Forecasting the global shipping network and the future of marine biological invasions

Anthony Sardain

Department of Biology
McGill University
Montreal, Quebec, Canada

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Dedication

To my father, who taught me how to think; to my mother, who taught me how to love; and to my sister, who taught me how to live. I love you all dearly.

General Abstract

Increasing global trade and maritime traffic are the dominant facilitators of spread of economically- and ecologically-harmful invasive marine species worldwide. Recent efforts to forecast the spread of marine invasive species through the global shipping network have done so under the assumption that the network will remain unchanged, despite historical evidence that this is extremely unlikely. In this manuscript, I develop a model that uses basic socio-economic indicators and predicts vessel traffic for the 7 major ship types at a macro-ecoregional level. Our model outperformed three other competing models, explaining 87% of the variation, using a validation dataset. I apply our model to generate 5 scenarios of global maritime traffic in 2050, based on the IPCC's Shared Socioeconomic Pathways quantitative projections of global economic development. Our model predicts increasingly high amounts of vessel traffic calling at Asian ports, the continued decline of Northern Europe in terms of relative global importance, and the emergence of South Asia as an important source and destination of vessel traffic in the future. Finally, I employ our scenarios of future shipping traffic in conjunction with IPCC projections of global climate change, and use established probabilistic models of shipping-mediated invasion to estimate changes in probabilities of invasion across ecoregions. I conclude that Asia, particularly North-East Asia, will continue to grow as a major donor and recipient of invasions, particularly with North America and the Mediterranean, as well as with Southern and Eastern Africa, albeit to a lesser degree. Generally, regions that are currently experiencing lower amounts of traffic, particularly the Eastern Indo-Pacific islands, are not expected to see any notable increase in invasion risk by 2050. I also find that shipping increase had a far greater effect on invasion risk globally than climate change.

Résumé

La croissance du commerce mondial et du trafic maritime sont les principaux moteurs de propagation d'espèces marines invasives dans le monde entier. Récemment, certaines études ont tenté à prévoir la propagation de ces espèces sous l'hypothèse que le réseau maritime international restera inchangé, malgré le fait que la tendance historique indique que cela est très improbable. Dans ce manuscrit, nous développons un modèle qui utilise des indicateurs socio-économiques et prédit le trafic maritime pour les 7 principaux types de navires au niveau écorégional. Notre modèle surpasse trois autres modèles alternatifs et explique 87% de la variation, en utilisant un ensemble de données de validation. Nous appliquons notre modèle pour générer 5 scénarios de trafic maritime en 2050 à l'échelle mondiale, appuyant sur les Shared Socioeconomic Pathways, une série de projections de développement socio-économique mondial créé par la GIEC. Notre modèle prédit une augmentation de trafic maritime dans les ports asiatiques, le déclin continu de l'Europe du Nord en termes d'importance relative et l'émergence de l'Asie du Sud comme source et destination importante de mouvements de navires dans le futur. Enfin, nous utilisons nos scénarios de trafic maritime futur en conjonction avec des projections de changements climatiques développées par la GIEC et des modèles probabilistes d'invasion pour évaluer les changements de probabilités d'invasion parmi les écorégions. Nous concluons que l'Asie, en particulier l'Asie du Nord-Est, continuera à croitre en tant que source et destinataire important d'invasions, en particulier avec l'Amérique du Nord et la Méditerranée, ainsi qu'avec l'Afrique occidentale et orientale, mais à un moindre degré. D'une manière générale, les régions qui connaissent actuellement des quantités plus faibles de trafic, en particulier les îles orientales de l'Indopacifique, ne devraient pas voir une augmentation notable du risque d'invasion d'ici 2050. Nous constatons également que l'augmentation de trafic maritime

aura un effet beaucoup plus important sur le risque d'invasion à l'échelle mondiale que le changement climatique.

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conditions; d) the highest traffic scenario (SSP5) and current environmental conditions; e) the lowest traffic scenario (SSP3) and current environmental conditions. Rows designate source SER while columns designate recipient SER.

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Preface and Contribution of Authors

This thesis was prepared in traditional monograph style following the 'Thesis Submission Guidelines' provided by McGill University's Faculty of Graduate and Postdoctoral Studies Office. Project design, data acquisition, and analysis were undertaken by Anthony Sardain under the guidance and supervision of Dr. Brian Leung from the Department of Biology at McGill University.

General Introduction

Biological invasion is a pressing, global environmental problem (Bellard et al. 2016). Although most introductions of non-indigenous species (NIS) by human activity are relatively benign, in some cases they can result in detrimental impacts to ecological systems (Pimentel et al. 2005) and cause immense economic losses (Pimentel et al. 2005, Colautti et al. 2006, Aukema et al. 2011, Walsh et al. 2016).

The globalization of trade has played a sizable role in accelerating the spread of NIS. Although some commercial activities such as fish stocking and the seed trade depend on the purposeful translocation of species outside of their native range, NIS are often spread unintentionally, as inadvertent hitchhikers along human transportation networks (Lodge et al. 2006). Of these transportation pathways, the global shipping network (GSN) is widely recognized as the dominant global vector for the spread of marine NIS (Molnar et al. 2008). Cargo ships typically transport marine NIS in one of two ways. The first of these is through the ship's ballast water, which is taken up to stabilize the vessel at sea, and usually contains a diversity of species that are released into the environment at the site of ballast discharge (Ruiz et al. 2015). The second pathway for NIS spread is through biofouling, whereby species will attach and accumulate on the hulls of ships (Sylvester et al. 2011). Together, these two pathways of spread are believed to account for between 60% and 90% of marine bioinvasions (Hewitt et al. 2009).

Given that preventing the introduction of NIS remains the most effective strategy to curtail invasions (Sylvester et al. 2011), considerable effort has been made in recent years to understand the network's structure, its dynamics, and its implications for the spread of NIS (Banks et al. 2015; Kaluza et al. 2010; Kölzsch and Blasius 2011; Xu et al. 2014). Other studies have gone further forecast invasion through the network over the coming decades (Floerl et al. 2013; Seebens et al. 2016; Ware et al. 2014). Many of these studies consider ecological and environmental factors, notably global climate change, which is expected to impact the range and distribution of species, and thereby differentially alter regions' susceptibility to invasion. However, as of yet, no study has considered the possibility of changes in propagule pressure, either through changes in shipping intensity or through a reorganization of the structure of the GSN itself.

To assume that the GSN will remain unchanged over the coming decades goes against the historical trend. Indeed, in just 15 years, global demand for ship-carrying capacity increased almost 75%, from 30,823 ton-miles in 2000 to 53,589 ton-miles in 2015 (Asariotis et al. 2016). As an added complication, growth in global shipping has shown to occur non-uniformly across space. For instance, although both Western Europe and Japan had experienced dramatic increases in shipping traffic between 1960 and 1970 followed by a period of stagnation, only Western Europe experienced another boom in traffic two decades later, while Japan has continued to experience marginal growth to the present day (Stopford 2009). Similarly, change in shipping traffic does not occur uniformly across ship types: container ships and ships catering to specialized cargo – such as liquid natural gas (LNG) and automobiles – have experienced considerable growth over the past decades, while general cargo ships have decreased in relative numbers (Stopford 2009).

The primary driver of these changes in the GSN are largely socio-economic (Asariotis et al. 2016). Imbalances in global supply and demand causes nations to trade goods and services that are locally available for ones that are not, and with 80% of traded goods transported by sea, shifts in supply and demand drives changes in shipping movement patterns. As a consequence, maritime traffic will generally follow trends in the macroeconomic landscape, and reflect tendencies in economic growth, industrial activity and merchandise trade. The close relationship between economy and shipping largely explain the sudden 25% drop in sea trade volume following the stock market crash of 1929, its dramatic upswing during the post-WWII economic boom, and the decline in maritime trade triggered by the 1973 and 1979 oil price shocks. The most significant event in recent years, however, has been the rapid economic development of China which has drastically affected global shipping: between 1990 and 2006, China's share of world maritime trade increased from 1% to 10% (Stopford 2009).

Given the apparent importance of economy in determining dynamics of global maritime traffic, it would be instructive to develop a deeper understanding of the links between the two for the purposes of forecasting future shipping-mediated invasion. Such knowledge would allow us to benefit from extensive research on socioeconomic scenarios (e.g. Nakicenovic et al. 2000; Rounsevell and Metzger 2010; Kok et al. 2015) to generate associated projections of shipping-mediated invasion. Further, a nuanced characterization of the ties between economic development and shipping would allow, for instance, to forecast at the level of individual ship-types, which is important from the perspective of biological invasion, as not all ships are associated with the same invasion risks. For instance, bulk cargo ships tend to release more ballast water than ro-ro cargo ships, resulting in a greater likelihood of species introduction (Seebens et al. 2013).

In this manuscript, I fill a gap in the current invasion literature by demonstrating the predictability of shipping dynamics, by developing scenarios of possible GSN futures to 2050, and by forecasting how these futures will impact biological invasions globally. Specifically, I link maritime traffic to socio-economic indicators at a macro-regional level, and employ quantitative projections of global development and climate change, as well as established probability models of ship-mediated invasion to predict change in invasion risk over the coming decades. The resulting image of global invasion risk differs substantially from previous forecasts that have focused solely on climatic drivers of change.

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CHAPTER 1

Introduction

The spread of non-indigenous species (NIS) by human activity has emerged as a pressing, global environmental problem (Bellard et al. 2016). While most NIS do not cause problems, those few that do can have immense economic impacts (Aukema et al. 2011; Pimentel et al. 2005, Colautti et al. 2006, Walsh et al. 2016). Further, it is estimated that 42% of endangered species are at risk, in part, due to pressures imposed by invasive NIS (Pimentel et al. 2005).

NIS are largely transported as a byproduct of trade, and the globalization of trade has accelerated their spread. Indeed, invasive NIS are typically introduced in one of two ways (Lodge et al. 2006). The first is through the commerce of living organisms: the seed trade, fish stocking, and the pet industry represent at least partially-deliberate avenues for the establishment of non-native species. However most invasive species are introduced unintentionally as hitchhikers on human transportation pathways, much of it linked to the global shipping network (GSN). Numerous insect species, for instance, have spread globally transported in the packing materials of transported goods (Work et al. 2005); for marine invasive marine species, however, it is typically the ships themselves that are responsible. Ships' ballast water, taken up to stabilize the vessel at sea, usually contains a diversity of marine and/or aquatic species that are released into the environment at the site of ballast discharge (Ruiz et al. 2015). In addition, ships have been found to translocate numerous organisms that attach and accumulate on their hulls (Sylvester et al. 2011). Cargo ships have been so effective in facilitating biological invasions worldwide that the GSN is now widely recognized as the dominant global vector for the spread of marine NIS (Molnar et al. 2008).

Until recently, little was understood about the structure of the GSN due to an absence of comprehensive information about shipping traffic. However, the standardization of Automatic Identification Systems (AIS) for merchant vessels engaging in international trade recently allowed for a reconstruction of the GSN by Kaluza et al. (2010), and subsequent studies have brought greater understanding of the network's structure (Banks et al. 2015; Kölzsch and Blasius 2011; Xu et al. 2014). This newfound understanding has led to a number of studies venturing to forecast the spread of invasive species through the GSN. Most of these forecasts focus on climate change as an important driver to consider when forecasting spread (e.g. Floerl et al. 2013; Seebens et al. 2016; Ware et al. 2013), and for good reason: global climate change is expected to alter the range and distribution of many species, such that the risk of invasion of certain areas linked through the GSN may also change (Bellard et al. 2013). However, as global climate projections are undertaken at the scale of multiple decades, one must consider that perhaps the structure of the GSN itself will also change over the coming years, and that these changes need to be taken into consideration.

Indeed, historically, the GSN has not been static: between 2000 and 2015, global demand for ship-carrying capacity increased almost 75%, from 30,823 ton-miles to 53,589 ton-miles (Asariotis et al. 2016). Nor does increase in shipping traffic occur uniformly across regions. For instance, Western Europe and Japan had both experienced dramatic increases in shipping traffic between 1960 and 1970 followed by a period of stagnation. But, whereas Western Europe saw another surge two decades later, Japan has continued to experience marginal growth to the present day (Stopford 2009). Different ship types have also historically grown at different rates: between 2000 and 2007, the annual growth rate of the global fleet of LNG tankers (in terms of deadweight tonnage, DWT) was 11%, 5% for ro-ro cargo ships, and 2% for bulk carriers (Stopford, 2009).

Socio-economic factors largely underlie the changes in the GSN (Asariotis et al. 2016). As wealth and population increase, so comes a growing need for goods and services for which the supply may not be available locally. Imbalances between supply and demand create conditions for trade and interdependence between nations. The transport of goods traded between the world's commercial partners is the GSN's *raison d'être*, and, as a consequence, "seaborne trade volumes have generally moved in tandem with economic growth, industrial activity and merchandise trade" (Asariotis et al. 2016). These close links between economy and shipping underlie the 25% drop in global shipping during the 1930's recession and 640% increase over the 25-years of post-WWII economic boom (Stopford, 2009). Looking at more recent years, it is evident that the rapid economic development of China has had a profound impact on maritime shipping: between 1990 and 2013, China's economy grew 830% and its share of the world's total container throughput surged from 1.4% to 20.1% (Wang 2015). In view of this variability in trade and shipping patterns – both in terms of magnitude and distribution – over the past few decades, it is clear that the assumption of an unchanging GSN warrants greater scrutiny when venturing to forecast shipping-mediated invasion into the next century.

Moreover, given the importance of socioeconomic factors in driving change in global shipping, it is instructive to investigate how well traditional socioeconomic indicators predict changes in shipping patterns, as well as what other factors must be considered to this end. All other things equal, trade between nations is known to increase proportionally with the product of their gross domestic products (GDP), and decrease as the distance between them increases (Silva and Tenreyno 2006); one may expect similar relationships to hold for shipping traffic, although to what extent remains an open question. Indeed, we should not expect the links with trade to be mirrored perfectly. For instance, all else being equal, contiguous nations engage in more trade (Silva and Tenreyno 2006), but may see less shipping traffic due to the availability of overland transport options. In addition, different ship types carry different cargoes, therefore we should expect the relationships between socioeconomic development and maritime traffic to vary by ship type. This is particularly important from the perspective of biological invasion, as not all ships are associated with the same invasion risks. For instance, bulk cargo ships tend to release more ballast water than ro-ro cargo ships, resulting in a greater likelihood of species introduction (Seebens et al. 2013).

Linking changes in shipping traffic to their socioeconomic drivers has the additional advantage of allowing us to benefit from, and build upon, extensive research on socioeconomic scenarios (e.g. Nakicenovic et al. 2000; Rounsevell and Metzger 2010; Kok et al. 2015). The Shared Socio-economic Pathways (SSP) framework is among the most recent set of comprehensive forecasts of global development. Developed as part of the International Panel on Climate Change's (IPCC) AR5, the SSPs present five possible global futures, matched with qualitative narratives and corresponding quantitative pathways of socioeconomic variables, such as GDP and population (Riahi et al. 2016). In addition to forming the basis for the IPCC forecasts of global greenhouse gas emissions, mitigation options and policies, the SSPs have been used in forecasting studies in the domains of land-use (Riahi et al. 2016) and agricultural production (Wiebe et al. 2015), water consumption (Bijl et al. 2016), public health (Chen et al. 2017), and vulnerability to extreme weather events (Alfieri et al. 2015; Yuan et al. 2016). To add global shipping, and concomitant biological invasions, to this list further advances the scenarios themselves by adding to their dimensionality, thereby contributing to a higher resolution image of the future.

In this manuscript, I fill an important gap in the current invasion literature by demonstrating the predictability of shipping dynamics, by developing scenarios of possible GSN futures to 2050, and by forecasting how these futures will impact biological invasions globally. More specifically, I demonstrate that macroeconomic factors can be successfully used to explain worldwide maritime traffic at the level of individual ship types, and that these predictions consistently outperform ones based solely on historical shipping patterns. Mapping our model onto quantitative scenarios of global macroeconomic development (SSPs) and overlaying forecasts of global climate change, I employ methodologies from the literature to assess likelihood of invasion by marine NIS and demonstrate how forecasted changes in world shipping patterns lead to vastly different predictions of global biological invasion than have been previously reported.

Methods

I begin by presenting our proposed predictive shipping model, hereafter referred to as the Residual Adjusted Unconstrained Gravity (RAUG) model. The RAUG model takes as input various macroeconomic variables and provides as output an expected amount of traffic. Historical values for both of these datasets were required for fitting of the model. Using these vessel traffic projections, I forecast global invasion risk using the methodology described in Seebens et al. (2013). In addition to data on vessel traffic, Seebens et al.'s model uses data on ballast water release and environmental data on seawater temperature and salinity at ports of call.

Data

For fitting of the RAUG model, I acquired data on ship movements from the IHS Sea-web reference tool (www.sea-web.com). Sea-web provides data on movements (port of call, arrival and departure dates, hours in port) and ship attributes (e.g. ship size, ship type) for over 207,183 vessels. I collected data on all movements occurring during 2006-2014, consisting of over 50 million voyages of 81,305 ships between 3,872 ports.

With respect to macroeconomic predictors, I obtained GDP and population data from the World Bank Databank (http://databank.worldbank.org/), and data on inter-country distance, regional trade agreements, common language, common border, common colonial history through CEPII Research Centre's Geodist and Gravity datasets (Mayer and Zignago 2011; Head and Mayer 2014). I acquired forecasted GDP and population values from the International Institute for Applied Systems Analysis (IIASA) Shared Socioeconomic Pathways (SSP) database (https://tntcat.iiasa.ac.at/SspDb/).

Data on ballast water releases were collected from the National Ballast Information Clearinghouse (NBIC) Online Database (National Ballast Information Clearinghouse 2016). The NBIC collects data on ballast water discharge volumes for all ships calling at ports within the U.S. and is the most comprehensive database of its sort available globally. I collected data on all ballast water releases recorded by the NBIC between the years 01-01-2006 and 31-12-2014.

I determined current and forecasted environmental conditions for all ports listed in the Sea-web database using the AquaMaps Environmental Dataset (Kaschner et al. 2016). The AquaMaps database lists dozens of environmental variables at a scale of 0.5 degree latitude x 0.5 degree longitude cells worldwide, providing forecasted values based on projections from IPCC Scenario A2. Each port was matched with the nearest AquaMaps environmental cell.

Before parameterizing the RAUG model, I performed a number of filtering steps on the data. First, I processed the raw shipping files by compiling counts of inter-country movements, disregarding any port call lasting less than 2 hours (the minimum time window recorded by Sea-web). Ship movements to Panama and Egypt were disregarded due to the high number of movements attributable to canal transit rather than to trade specific to these countries. In these cases, the previous and subsequent ports-of-call are taken as the source and destination, respectively.

I then categorized the world's marine-coastal countries into 16 different socio-ecoregions (hereafter SER; Table 1). In addition to excluding those countries that did not share a border with an ocean or sea, as well as those for which data was missing in at least one of the four datasets mentioned above. This filtering step resulted in the exclusion of 40 coastal countries, most of which were small island states. The remaining 140 countries accounted for 99.3% of all port calls. I define SERs as regions of the world displaying primarily marine biogeographic and ecological similarity, roughly matching Spalding et al.'s (2007) 'realm' bioregionalization, but also socio-economic similarity when possible. When countries could be said to belong to 2 SERs (e.g. France), the country was categorized based on which SER's coast received the most shipping traffic.

Predictive model

The model I propose is an adaptation of the gravity model of trade. Inspired by Newton's law of universal gravitation, the original formulation of the gravity model of trade states that bilateral trade flows between two countries are proportional to the product of the size of their economies and inversely proportional to the distance between them (Anderson 1979). Since then, the gravity model of trade has been broadly adapted in the literature to include more variables that may impact the resistance to trade, such as common colonial ties or contiguity (e.g. Anderson Wincoop 2003, Silva and Tenreyno 2006, Gómez-Herrera 2013, Buongiorno 2016), and used to explore other types of bilateral flows such as migration (Anderson 2011), commuting behavior (Eaton and Kortum 2002), and service offshoring (Head et al. 2009). Given the close link between trade and shipping, gravity models also form a natural structure to predict shipping traffic.

The formulation of the gravity model I used was the following:

$$logX_{IJst} = \beta_{s0} + \beta_{s1}logGDP_{It} + \beta_{s2}logGDP_{Jt} + \beta_{s3}logPop_{It} + \beta_{s4}logPop_{Jt} + \beta_{s5}logDist_{IJt} + \beta_{s6}CL_{IJt} + \beta_{s7}CB_{IJt} + \beta_{s8}CCH_{IJt} + \beta_{s9}RTA_{IJt} + \varepsilon_{IJst} \quad (1)$$

where X_{IJst}designates ship movements of ship type s from source SER I to destination SER J in year t, GDP is the gross domestic product, Pop is population, $Dist$ is distance, and CL, CB, CCH and RTA are values from 0 to 1 denoting the proportion of pairs between each of I and J's member countries that share a common official language, common border, common colonial history, and regional trade agreement, respectively.

GDP and Pop are the sum of gross domestic product and population, respectively, of all countries within an SER. Because I was interested in invasions at the SER level, which are comprised of multiple countries, $Dist$ is calculated based on mean latitude and longitude of all countries within an SER, weighted by each country's population, e.g.:

$$latitude_I = \sum_{i \in I} latitude_i \cdot \frac{Population_i}{\sum_{i \in I} Population_i} \tag{2}$$

where i is a country in SER I, and $Population_i$ is the average population of country i over the course of the RAUG model's fitting years. With each SER's latitude and longitude values, I calculated inter-SER distances as great circle distances on an ellipsoid between geographical point locations (R package: geosphere, function: distVincentyEllipsoid). CL, CB, CCH and RTA are typically binary values for each pair of countries. To convert these to SER-level parameters, I calculated the mean of binary values for each combination of countries present in each pair of SERs.

The model was fit for each ship type, for two measures of ship movements – total number of ship movements, and total deadweight tonnage (DWT) of ships displaced. In each case, forward selection of model variables was performed to determine which ones should be retained.

Our model accounts for changes in each of the predictor variables but fails to account for the myriad of other factors intrinsic to each bilateral connection that may impact movement flows. To correct for this, I incorporated inter-regional fixed effects by calculating a "between-SER-specific offset" (i.e., the "Residual-Adjustment" component of the RAUG model). I reasoned that deviations from the mean expectation reflect systematic, repeatable differences between country pairs, and in such a case, the residual structure contains predictive information and should be preserved. The effect of this is similar to using dummy variables for each country, but has important consequences for forecasting. First, country-specific dummy variables will capture much of the variation due to predictors (e.g., GDP), which can yield a good fit, but will have strong effects for forecasting if the predictor has a real effect. Adjusting using residual has the advantage of attributed effects first to the predictors. Second, using dummy variables requires additional parameters to be fit for each country, whereas residuals require no additional parameters. Given the log-linear formulation of the gravity model, this back-transformed offset was multiplicative and was calculated as follows:

$$e^{\varepsilon} = \frac{\hat{X}_{IJs2014}}{\hat{X}_{IJs2006-2009}} \cdot X_{IJs2006-2009} \tag{3}$$

I performed model validation by fitting model parameters to four years of data (2006-2009), and then predicting ship movements in 2014. I evaluated the strength of the prediction using the squared deviation from the 1:1 line of our predicted values ($\hat{y}$) vs. observed values (y) – i.e. the mean squared error, MSE, as a proportion of the variation in observed values: R^2_{MSE}.

$$R^2_{MSE} = 1 - \frac{\sum(y-\hat{y})^2}{\sum(y-\bar{y})^2} \tag{4}$$

This is a more conservative measure than the conventional R^2, which generates residuals from the best fitting regression line. By forcing the relationship between predicted and observed values through the 1:1 line, R^2_{MSE} results in values that will always be less than or equal to R^2.

I compared this model against three alternative models. In all cases, the years 2006-2009 were used as fitting years and 2014 as the validation year. The first alternative model (Alternative Model I) resembled our proposed model, but did not use the multiplicative offset calculation. Instead, dummy variables are added to the original formulation for each source and destination SER and all time-invariant variables are omitted. This expression of the gravity model of trade is a widely-used formulation that attempts to capture multilateral resistance occurring within the system of interest (see Baldwin and Taglioni 2006; Bacchetta et al. 2012). The second of model (Alternative Model II) was a naïve history model that assumed shipping traffic would remain unchanged from mean values between the years 2006 and 2009. The third (Alternative Model III) was a historical model with an applied constant growth rate. For this model, I used mean traffic between 2006 and 2008 as the historical baseline and traffic data for 2009 to calculate an annual rate of growth, which was assumed to remain constant to 2014.

Forecasting

I then forecasted ship movements to 2050 by fitting our model parameters to 9 years of data (2006-2014) and using GDP and population projections under each of the 5 marker SSPs.

The IIASA's SSPs were developed as part of the IPCC's AR5 and present 5 different narratives of future socio-economic developments (Riahi et al. 2016). SSP1 ("Sustainability") foresees a world where global emphasis shifts from economic growth to human well-being, and lower resource and energy intensity, leading to lower inter- and intra-country equality. SSP2 ("Middle of the road") projects a continuation of the historical trend: uneven global development, moderate population growth, and slow progress in mitigating environmental degradation and reducing resource and intensity. SSP3 ("Regional rivalry") forecasts a rise in global protectionism, resulting in slow economic development and current levels of inequality or worse, where population growth is low in developed nations and high in developing ones. SSP4 ("Inequality") is characterized by high intra- and international stratification of power, wealth, and opportunity, split between a capital-intensive and well-connected society and a fragmented collection of lower-income societies. SSP5 (“Fossil-fueled development”) proposes a world that embraces resource- and energy-intensive practices coupled with effective management of social and ecological systems, in which I see rapid global economic growth and increasingly integrated global markets.

Associated to each of the 5 SSPs are decadal GDP and population forecasts going to 2100 and covering 181 countries, which included all the countries I examined. Each SSP presents a single population projection and 3 differing GDP projections, one of which is designated the representative “marker” for that SSP. For this study I used the population and marker GDP projections for each of the 5 SSPs.

RTAs were kept unchanged from their 2014 values. The same multiplicative offset calculation was performed for the forecast.

Probability of invasion

Using these projections of global shipping, I forecasted changes in probabilities of invasion between SERs using the methodology outlined by Seebens et al. (2013). Seebens et al. decompose the probability of a species invading a certain port due to a given vessel movement into independent probabilities of a species being alien to the destination port, of the species actually being introduced by the vessel, and of that species successfully establishing. For every inter-port movement, I calculated the probability of that movement leading to species invasion from the origin port to the destination port. I obtained model parameters from Seebens et al. (2013), which were calculated based on global introduction and establishment records.

Following Seebens et al. (2013), the likelihood that a native species in donor port i is non-native in recipient port j is a function of biogeographical dissimilarity:

(5)

$$\Pr(Alien) = (1 + \frac{\gamma}{d_{ij}})^{-\beta}$$

where d_{ij} is the distance between the ports, and γ and β are constants. The likelihood that a species is introduced from source i to destination j on ship route *r* was:

$$\Pr(Introduction) = \rho_r\left(1 - e^{-\lambda B_r}\right)e^{-\mu \Delta t_r} \quad (6)$$

In this formulation, the probability of introduction increases with the amount of released ballast water B_r that is taken up at source port i and released at destination port j, and decreases with mortality rate of the species μ, and travel time Δt_r. λ is a characteristic constant, while ρ_r is a scaling factor representing possible ballast water treatment, which I set to 1. For each set of connections, Δt_r was set as the number of days between port calls. Following Seebens et al. (2013), I set $\mu = 0.2$ day^{-1}, which is the measured median mortality rate for various taxa in untreated ballast water. It should be noted that Seebens et al.'s formulation appears to consider only ballast water introductions, and exclude hull fouling as a potential mechanism for species introduction. Indeed, Seebens et al. found that inclusion of hull fouling as another bioinvasion vector did not yield improved model fits.

Ballast water released was calculated as follows:

$$B_r = zW_r\left(1 - \frac{zW_r}{V_r}\right)^{\delta_r} \quad (7)$$

where W_r represents the amount of released ballast water, V_r denotes the volume of a ship's ballast tank, δ_r is the amount of intermediate stopover routes on route r, and z is the fraction of zero-releases a ship typically makes. These values were approximated from regression fits on U.S. ballast water release data from the NBIC, using ships size (DWT) and ship-type as predictors.

The probability of establishment followed a Gaussian function of standardized differences of water temperature and salinity between donor and recipient ports (Seebens et al. 2013):

$$\Pr(Establishment) = \alpha e^{-0.5[\left(\frac{\Delta T_{ij}}{\sigma_T}\right)^2 + \left(\frac{\Delta S_{ij}}{\sigma_S}\right)^2]} \tag{8}$$

where $\frac{\Delta T_{ij}}{\sigma_T}$ and $\frac{\Delta S_{ij}}{\sigma_S}$ represent the standardized differences in temperature and salinity, respectively, between the source port i and destination port j, and α represents the basic probability of establishment, where $\sigma_T = 2°\text{C}$, $\sigma_S = 10\text{ppt}$, and $\alpha = 0.00015.$

The above equations were used to calculate the probabilities of invasion between SERs:

$$\Pr(Invasion)_{IJ} = 1 - \prod_{i \in I} \prod_{j \in J} \prod_{s_{ij}} \left[1 - \Pr(Alien)_{ij} \Pr(Introduction)_{s_{ij}} \Pr(Establishment)_{ij}\right] \tag{9}$$

where s_{ij} denotes all vessel movements from a port i located in SER I to port j located in SER J, and $\Pr(Invasion)_{IJ}$ was the complement of remaining uninvaded, given all introductions between I,J.

To forecast inter-port invasion risk to 2050, I recalculated probabilities of invasion using forecasted environmental values, and then applied an exponential coefficient based on the projected increase in traffic for the corresponding SER-pair. Given the multiplicative probability of remaining uninvaded, an exponential coefficient was the appropriate formulation to model increases the number of trips by the projected increase in traffic between the corresponding SERs:

$$\Pr(Invasion)_{IJ2050} = 1 - \left[\prod_{i \in I} \prod_{j \in J} \prod_{s_{ij2014}} \left[1 - \Pr(Alien)_{ij} \Pr(Introduction)_{r_{ij2014}} \Pr(Establishment)_{ij2050}\right]\right]^{n_{IJ2050}} \tag{10}$$

$$n_{IJ2050} = {}^{X_{IJ2050}}/_{X_{IJ2014}}$$

where again s_{ij} denotes all vessel movements from a port i located in SER I to port j located in SER J and n_{IJ2050} represents the ratio of traffic between SERs I and J in 2050 compared to 2014.

Results

The current shipping network

Between 2006 and 2014, 7 of the 29 ship types accounted for between 94% and 96% of total primary vessel movements between countries, with container ships and general cargo ships being the most common (Table 2a). Thus, worldwide shipping can largely be characterized by a small number of ship types. Each of these ship types have seen large increases in traffic, with a cumulative 184.29% increase in inter-country movements. However, the different ship types have increased differently, ranging between 94.25% to 402.55%. This suggests that it is important to consider changes in different ship types explicitly.

Shipping traffic varied considerably by SER (Table 2b), with most traffic calling at ports in Northern Europe, although decreasingly so, and the least in the Eastern Indo-Pacific and in African SERs. Rates of growth in shipping traffic across SERs are equally heterogeneous, ranging between 14.47% and 623.47% among the 5 highest traffic SERs in 2006. This high spatial variability, witnessed over the course of just 9 years, is further evidence that the global maritime traffic is unlikely to remain static, or grow uniformly, over the coming decades.

Considering DWT displaced as the measure of traffic rather than number of vessel movements yields largely similar results, but with some differences, namely a greater representation of bulk carriers and crude oil/oil products tankers over general cargo ships, and Asian SERs over Northern Europe and the Mediterranean (see Supplementary Material).

Model validation and comparison

I found the RAUG model was more predictive than all three alternative models in all cases, generating predictions based on traffic from 2006-2009, and predicting 2014. Compared with using historical values, our model improved predictions by 24% when aggregating across ship types, (Table 3). When breaking down by ship type, our model also outperformed all three alternative models for all ship types by a considerable – albeit less drastic – margin. The mean difference in R^2_{MSE} between our model and the next best performing model was 0.167. While the RAUG Model performed the best, interestingly the second most predictive model was simply using unaltered historical values (Alternative Model II). The two other alternative models, yielded systematic underpredictions in the case of Alternative Model I (using source and destination dummy variables) and drastic overpredictions in the case of Alternative Model III (historical values with an applied constant growth rate). Nonetheless, given the substantial benefits of using macroeconomic predictors, and the availability of such data, there were clear reasons to use the RAUG Model.

Predictor variables

Across all ship types, GDPs of source and destination SERs, distance between SERs, prevalence of common languages between SERS, and prevalence of regional trade agreements were found to be important predictors in our model (Table 4). I found that source GDP, destination GDP, common language, and regional trade agreements had a positive relationship with vessel traffic, while distance and had a negative relationship with vessel traffic. Other predictor variables were important in some cases and not in others. Where these variables were included, shipping traffic was invariably found to have a positive relationship with common colonial history, and a negative relationship with source population and degree of contiguity. The relationship of vessel traffic with destination population varied by ship type.

Forecasting shipping traffic to 2050: Regional patterns

Ship traffic is projected to differ across scenarios (SSPs), SERs, and ship types, and interactions between these three components. In all cases, the *fossil-fueled development* (SSP5) scenario yields the largest increases in shipping traffic, followed by SSP1, which predicts a world emphasizing *sustainable development* (Table 5). SSP2, the *status quo* scenario, yields generally larger increases in traffic than SSP4, characterized by increasing *global inequality*, but not in all cases. SSP4 saw higher increases in shipping traffic than SSP2 for connections between North America and the Mediterranean, Northern Europe, North East Asia, and Australia/New Zealand; North-East Asia with Australia/New Zealand, Northern Europe, and Russia; and Australia/New Zealand with all SERs other than West, South, and East Africa. Of all the scenarios, SSP3, *regional rivalry* or global protectionism saw the smallest increase in traffic across all connections, except for some relatively minor connections with African SERs, for which the increase was slightly lower than SSP4. All scenarios saw increases in shipping traffic from 2014 levels, except for traffic to and from islands in the Eastern Indo-Pacific. Although growth rates differences appear modest between scenarios (Table 5), the cumulative effect over time can be quite large (Figure 2).

The greatest growth in shipping traffic is forecasted to take place around Asian SERs (North-East Asia, South Asia, South-East Asia), which will increasingly dominate the landscape of maritime transport (Figure 2). Of the 20 highest traffic shipping routes in 2014, 8 of 16 had at least one of these three SERs as either source, destination, or both; in 2050, it will increase to 12, regardless of the development scenario. This increase is largely attributable to a boom in traffic in South Asia, particularly between South Asia and South-East Asia. Traffic between these two SERs, which between 2006 and 2014 grew from approximately 2,350 vessel movements each way to 13,250, are expected to grow to between 56,000 and 152,000, thereby increasing from the fifth-most to the second-most travelled in 2050, after the routes between South-East and North East-Asia.

Of the other connections, those that link with faster growing economies – such as those in Asia – are projected to experience higher rates of growth, while those linking with large, developed economies, or slower-growing developing economies are expected to see more moderate growth rates. Namely, connections with the Mediterranean and Northern Europe, which presently experience among the highest traffic, are expected to decline in relative importance as a result of more moderate future growth; connections between African SERs and South and South-East Asia, by contrast, are poised to experience relatively high increases in traffic over the coming decades.

Vessel traffic along routes connecting with currently small economies are not expected to increase to any globally-significant scale by 2050, despite some high growth rates in some cases. Shipping routes to the Eastern Indo-Pacific islands, in particular, are projected to remain relatively low traffic and retain a similar structure, with Australia/NZ expected to remain the primary partner, and with whom traffic is expected to increase from 450 to 575-1450 vessel movements between 2014 and 2050.

Forecasting shipping traffic to 2050: Patterns across ship types

Container ships are expected to experience the greatest increase in traffic, increasing between 254-809% from 2014 values, followed by bulk carriers (181%-682%), general cargo ships (152%-519%), chemical/products tankers (137%-466%), ro-ro cargo ships (101-338%), crude oil tankers (113%-337%), and finally LNG tankers (40%-133%). Increases in traffic for all of these ship types is expected to be highest along routes connecting to the three Asian SERs, and especially between the three Asian SERs themselves. General cargo ships are an exception, where substantial increases in shipping traffic are also expected between the Mediterranean and the Black Sea, and the Mediterranean and Northern Europe.

Probabilities of invasion

In 2014, Asian SERs, particularly South and South-East Asia, were the highest risk donors and recipients of invasive species globally (Table 6). SERs experiencing high traffic but occupying more temperate areas, such as North America, Northern Europe and the Mediterranean, were slightly less likely to be invasion risk zones. Meanwhile, smaller traffic areas, such as Southern South America, African SERs, and the Eastern Indo-Pacific were lowest risk invasion zones, regardless of environmental conditions.

By 2050, the world will see some marked differences (Table 6). South and South-East Asia are expected to remain important source and destination SERs for invasive species, however both will be overtaken by North-East Asia regardless of development scenario. Further, North-East Asia is anticipated to primarily act as a donor of invasive species rather than a recipient. By contrast, of all the temperate SERs, the Mediterranean is expected to also see increasing invasion risk, primarily being a recipient of invasive species, but not a donor. Lower invasion-risk SERs in 2014 are expected to remain relatively low risk in 2050, albeit with some slight increases in relative risk of being invaded.

Examining individual connections provides a more nuanced picture of how invasion risk will change globally (Table 7a, 7b). The greatest increase in invasion risk by 2050 will be between South and South-East Asia, although the magnitude of this growth is strongly contingent upon the development scenario. The increase in invasion risk between these two SERs is not expected to be mirrored in their connections with the rest of the world, however. By contrast, North-East Asia's connections globally are expected to see the greatest increase in exchange of invasives, particularly with the South Asia, the Mediterranean, and North America. Somewhat surprisingly, invasion risk between North-East Asia and South-East Asia is not expected to increase substantially, despite the surge in vessel traffic expected along this already high-traffic shipping route. I expect moderate increases in invasion risk between Africa and Asia, however these will differ by region: East Africa will see greater exchange of invasives with South Asia, while Southern Africa will be more at risk from North-East Asia.

Risk of invasion across inter-SER connections is largely expected to increase or remain stable by mid-century, regardless of development scenario. Those few connections that will see a marginal decrease will concern currently low-risk, low-traffic connections. This is largely due to the fact that shipping traffic is anticipated to be the primary driver of invasions over the coming decades.

Indeed, by contrast, environmental changes are expected to have a relatively marginal effect on invasion. The mean projected change in invasion risk associated with environmental changes alone (Table 7c) is between 7 and 21 times smaller than the mean change in projected invasion risk associated with change in shipping traffic alone (Table 7d, 7e), depending on the global development scenario. Further, comparing cases where environmental changes are accounted for (Table 7a, 7b) with cases where they are not (Table 7d, 7e), it is apparent that forecasted environmental changes may in fact temper some of the more extreme values of invasion risk associated with shipping growth.

Discussion

Our results suggest that the GSN in 2050 will differ substantially from current patterns regardless of global development trajectory. Traffic is expected to increase to historically unprecedented levels, even under the most conservative scenario. Traffic in Asia, especially, will see dramatic increases, particularly between Asian SERs, but ultimately all connections with Asia will see significant growth. By contrast, connections with historically high traffic areas, namely the Mediterranean and Northern Europe, will experience more moderate increases. Areas currently experiencing smaller amounts of traffic will not see much growth regardless of scenario.

These results largely reflect the degree of economic growth expected in these areas. Indeed, just as increasing GDP has been found to be positively related with increasing trade (Bergstrand 1989; Silva and Tenreyno 2006), our results show that increasing economic activity (GDP) is a driving force increasing shipping traffic. The relationship between the other variables in the RAUG model and vessel traffic also largely match observed relationships with trade (Buongiorno 2016; Gómez-Herrera 2013; Silva and Tenreyno 2006), which might be expected given the close association between trade and shipping. One exception is contiguity, which I found to be inversely related to shipping, likely because greater contiguity provides more opportunities for overland transport.

It is worth noting that population was found to be negatively associated with shipping, although it was not found to be an important predictor in most cases. The relationship between population and trade is disputed, with positive (Brada and Mendez, 1983), negative (Leamer and Stern 1970; Linneman 1966; Carrere 2006), and equivocal (Martínez-Zarzoso and Nowak-Lehmann 2003; Egger and Pfaffermayr 2003) relationships having been documented in the trade literature. On the one hand, population is an estimate of a nation's market size, with population growth promoting greater division of labor and the creation of more tradable goods. On the other hand, however, a larger population may, by the same mechanism, be more self-sufficient and therefore less reliant on international trade (Oguledo and MacPhee, 1994). Furthermore, in the context of GDP, population reflects the degree of economic development (GDP per capita), meaning a negative population coefficient may be interpreted as a positive GDP per capita coefficient (Brun et al. 2005). These conflicting effects of population on trade may explain why population did not emerge as a significant predictor of vessel traffic.

How will biological invasions change in 2050?

Globally, biological invasions are likely to accelerate dramatically but non-uniformly, regardless of development scenario. Moreover, these changes in invasion risk are expected to be driven primarily by increases in shipping traffic; environmental change, although undeniably important, is expected to have a relatively small effect by comparison. Our results suggest that the biggest increase in invasion will be between South and South-East Asia, however North-East Asia will see the greatest increase in invasions globally, particularly along its connection with North America, the Mediterranean, and South Asia.

Contrasting these results with previous studies is challenging as forecasting efforts have largely been local in scope (e.g. Floerl et al. 2013; Ware et al. 2014). The only global study I am aware of (Seebens et al. 2016) factored in environmental changes but not changes in shipping traffic, and reported markedly different results from our own, which factored in both. When applying the model to forecast global invasion risk of 97 known invaders, Seebens et al. (2016) found ambivalent effects of environmental change. Certain temperate areas, particularly the

United States and Canada, were predicted to see a considerable increase in invasion risk, while more tropical regions such as South and South-East Asia, the Panama Canal area, and the Malacca Strait saw decreases in invasion risk.

Comparison with Seebens et al.'s analysis is difficult because of differences in grouping of ecozones (given the primacy of economic predictors in our model, our grouping necessarily incorporated national boundaries – i.e., socio-ecoregions, SER). Additionally, their study applies a modified version of the model so that it would work for a specific set of species, while I focused our analyses on general species, following Seebens et al. (2013). Nonetheless, I could draw some parallel conclusions, by forecasting environmental change while holding traffic constant at 2014 values, which notably drops relative invasion risk for South and South-East Asia. As stated before, however, it is apparent that the effect of vessel traffic increase will outweigh the effect of environmental change several fold, resulting in increases in invasion risk globally, with the exception of certain areas, such as the Eastern Indo-Pacific islands, which will see little change in invasion risk. Such a result is particularly interesting, considering the attention many of these island nations have garnered with respect to environmental threats, and particularly biological invasions (Kingsford et al. 2009). Environmental change will, of course, undeniably play a role in future shipping-mediated invasions: indeed, environmental dissimilarity can be seen to act as an invasion buffer along those routes projected to experience substantial increases in traffic, such as the connection between North-East and South-East Asia. However, ultimately, our results suggest that shipping traffic will change by orders of magnitude, and that far greater attention must be paid to the effect of changes in vessel traffic on the rate of biological invasions than has hitherto been given in the literature.

More generally, these results underline the importance of proper consideration of human drivers of change in socio-ecological systems. With respect to invasion biology, this does not simply require a greater involvement of social scientists and general emphasis on multidisciplinarity, but more broadly a willingness of natural scientists to branch out and tackle problems and topics beyond their traditional spheres of knowledge. Efforts of this sort, such as the estimation of the effect of the expansion of the Panama Canal (Muirhead et al. 2015) and the development of the American LNG industry (Holzer et al. 2017) on biological invasions in the United States, have brought to light infrequently discussed considerations and yield interesting conclusions.

Alternative drivers of change in the GSN

Within the context of the purposes of this study, it is apparent that future endeavors to forecast shipping-mediated invasion should lend more consideration to potential changes in the GSN. Historically, drivers of change in the GSN have fallen into one (or several) of four categories. The first of these, economic drivers, was the focus of this study.

The second of these are technological drivers. These drivers of change mainly impact cost-effectiveness of maritime transport, either by improving its reliability or efficiency. Improvements to sailship technology allowed for the European discovery of continental America, while the advent of steamships and refining of inland transportation systems created a boom in trans-Atlantic trade. Later on, containerization would revolutionize transport efficiency in the post-WWII era.

The third of these drivers of change are geophysical. The building of the Panama and Suez Canals, for instance, dramatically reduced intercontinental nautical distances for ships travelling between the Atlantic and Pacific Oceans and Arabian and Mediterranean Seas, respectively, through the removal of natural land barriers. Geophysical drivers may also seriously disrupt the GSN, as was seen in the aftermaths of Hurricane Sandy and the 2011 Japanese earthquake, which saw major ports put out of operation for several months.

The fourth of these drivers is political. Wars, economic sanctions, and embargoes have historically caused significant obstruction to global maritime transport. For instance, the six-day war that led to the closure of the Suez Canal between 1967-1975 saw shipping cargo either detoured around the Cape of Good Hope or transported overland (Lundgren, 1996). Similarly, the Iranian Revolution triggered the 1979 oil crisis, which disrupted oil exports from the Organization of the Petroleum Exporting Countries, pushing oil importing countries to obtain their oil from other exporters.

Despite this apparent diversity in potential drivers of change, the sole reliance on macroeconomic projections to forecast future shipping over the coming decades, as I have done, is defensible. With regards to political drivers, many of these are factored into economy. Indeed, by their very nature, macroeconomic scenarios inherently aggregate specific socio-economic and political factors that are individually unpredictable, hence their inclusion in our methodology. For instance, the impact of the political drivers that caused the 1979 oil crisis are reflected in the GDP growth slumps in developed, oil-importing countries, and surges in oil-exporting countries that made up for the supply shortage, like Saudi Arabia and Iraq.

I purposefully exclude geographic drivers of change in our study, as, to our knowledge, only two are on the horizon. The first is the construction of the Nicaragua Canal, which is unlikely to have a significant effect on global shipping patterns (Chen and Liu, 2016). The second is the opening up of Arctic passages due to the melting of polar ice caps, which has garnered much attention in recent years (Chan et al. 2013; Ho 2010; Miller and Ruiz 2014). However despite studies showing that Arctic avenues may open up by mid-century (Smith and Stephenson 2013, Melia et al. 2016), the problems posed by: i) sea-ice irregularity in an industry dominated by logistical constraints and strict delivery schedules, ii) a dearth of intermediate ports for stopovers, and iii) the substantial increase in navigation risks and associated insurance premiums mean that Arctic maritime traffic is likely to remain largely destinational rather than navigational until mid- to late-century (Lasserre and Pelletier 2011; Lasserre 2014; Meng et al. 2017). While these other categories of drivers of change may play a role in the coming decades, their arrival and impact are unpredictable at this time. Still, given all these considerations, macroeconomic forecasts are a useful, and demonstrably necessary, central element for projections of future shipping patterns.

Limitations

I acknowledge certain limitations in the methodology of this study. First, regionalization of the world's ports places certain limits on the ability to forecast shipping-mediated invasion. Indeed, although our model predicts changes in inter-SER travel, the model design retains elements of the current network architecture by assuming that the relative rankings of ports engaging in inter-SER travel within a given SER will remain constant. As history shows, this is unlikely to hold true (AAPA, American Association of Port Authorities), and Kaluza et al. (2010) use theoretical simulations to show how connectivity structure can have important consequences on how quickly species may spread through the network. Furthermore, our study does not account for growth in traffic *within* a given SER, although this, too, would necessarily affect invasives' spread.

Second, certain non-linearities in the response of shipping traffic to socio-economic drivers may be underestimated by the RAUG model. There is evidence to suggest that the positive relationship between a country's wealth and its resource consumption may saturate and even inverse at higher levels of national wealth (Duarte et al. 2013). Such non-linearities with respect to consumption would likely diffuse into the relationship between socioeconomic drivers and maritime trade. Further, non-linearities specific to shipping are possible, for instance as a result of infrastructural limitations that may limit the abilities of ports to accommodate traffic above a certain threshold amount. The RAUG model, being log-linear, does take into account non-linearities and therefore allows for saturation, however it is possible that the effect is even stronger than is accounted for.

Third, this forecast does not take into account changes in the per-vessel transport risk of invasive species. Indeed, imminent mandatory requirements for 'vessel hygiene', such as those put forward by New Zealand (Ministry for Primary Industries 2014) and the state of California (California State Lands Commission 2017), as well as increasing compliance with the IMO's guidelines for minimizing spread of invasive species are likely to drive down the invasion risk posed by a single ship in the future. By and large, however, biosecurity standards remain highly variable across locations, and in many cases their biological efficacy remains to be determined (Davidson et al. 2016). As a consequence, considerations of changes in per-vessel transport risk were excluded from the forecast; however, future studies seeking to include them could achieve this by altering the $\rho_r$variable in the calculation of $\Pr(Introduction)$.

The task of forecasting decades into the future is one that is fraught with complications, and projecting a complex, global, dynamic network such as the GSN is no exception. Here, I have made the case that conceivable changes to the GSN would have demonstrably dramatic effects on biological invasions. Yet, much work remains to be done to continually improve and refine models of the future GSN. Future efforts should seek to improve the resolution of GSN projections and their effects on biological invasions, while also considering other drivers of change that may determine the future of the GSN. Such endeavors would allow for the application of alternative models, some of which are more complex, that examine network topology and structure, and their implications for the spread of invasive species, as has been done for the current shipping network (Banks et al. 2015; Xu et al. 2014). The work I have presented here may be viewed as laying a foundation for such ventures to build upon.

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General Conclusion

The GSN is widely recognized as the most important transport vector facilitating the spread of marine invasive species (Molnar et al. 2008). Following the reconstruction of the GSN by Kaluza et al. (2010), numerous studies have attempted to predict shipping-mediated invasions over the coming decades (Floerl et al. 2013; Seebens et al. 2016; Ware et al. 2014). Given the large time scales involved, many of these studies rightly take into account the potential effects of environmental change. However, to date little consideration has been given to the fact that shipping dynamics may themselves change, despite substantial evidence of such change in recent history.

In the present work, I demonstrate that large-scale shipping dynamics can be reliably modeled using standard macroeconomic variables, and that these model predictions consistently outperform predictions based purely on historical shipping patterns. Further, applying this model to forecast global shipping to midcentury reveals that global shipping traffic is expected to grow to historically unprecedented levels, even under the most conservative scenario. This increase is anticipated to be most pronounced in Asia, particularly in South Asia, and less so in currently high-traffic regions such as Northern Europe.

Applying established models of invasion probability to these predictions, and mapping on projections of global climate change reveal substantial anticipated increases in invasion risk globally. Invasions between Asian ecoregions are forecasted to increase dramatically, with North-East Asia expected to become a prominent source and destination of global invasions, particularly along its connections with North America and the Mediterranean. Regions currently experiencing relatively low risk today, such as the Eastern Indo-Pacific islands, are expected to see the smallest increases in invasion risk.

Finally, I find that increases in shipping traffic, driven by global development patterns, will be primarily responsible for the change in invasion risk globally. While environment is an indisputably crucial determinant of invasion risk, these results suggest that socioeconomic factors, which have been underappreciated in the invasion literature, are most important and warrant greater attention.

The results presented in this manuscript are relatively large-scale. Future efforts to forecast the GSN should seek to increase the resolution of invasion risk projections, while simultaneously considering other drivers of change that may impact the future of maritime traffic: political, economic, technological, or geophysical. The application of alternative models, such as ones grounded in network theory which have been used to analyze the current GSN (Banks et al. 2015), may also yield interesting additional insights.

More broadly, future explorations of other well-characterized invasion pathways – such as the aquarium trade (e.g. Gertzen et al. 2008) and the seed trade (Dehnen-Schmutz et al. 2007) – may also seek to investigate the socioeconomic factors that underlie them and drive them to change. Such a task need not necessarily be fraught with complexity: as this study and others (e.g. Leung et al. 2014; Leprieur et al. 2014) have shown, using even basic socioeconomic indicators can yield powerful and informative results. Ultimately, more routine pairing of socioeconomic and environmental considerations into our conceptualizations and characterizations of these other invasion pathways would result in more accurate estimations of the associated invasion risks, and lead to a deeper and more nuanced understanding of the invasion pathways themselves.

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Tables

Table 1. Socio-ecoregions with associated countries used in this study.

Socio-ecoregion	Associated countries
(1) North America	Canada, United States
(2) Central America, Caribbean, & Northern South America	Aruba, Bahamas, Barbados, Belize, Brazil, Colombia, Costa Rica, Cuba, Dominican Rep., El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Venezuela
(3) Southern South America	Argentina, Chile, Ecuador, Peru, Uruguay
(4) Northern Europe	Belgium, Denmark, Estonia, Finland, France, Germany, Iceland, Latvia, Lithuania, Netherlands, Norway, Poland, Sweden, United Kingdom
(5) Mediterranean	Albania, Algeria, Croatia, Cyprus, Greece, Israel, Italy, Lebanon, Libya, Malta, Montenegro, Morocco, Portugal, Slovenia, Spain, Syria, Tunisia, Turkey
(6) Western Africa	Angola, Benin, Cabo Verde, Cameroon, Congo, Côte d'Ivoire, Dem. Rep. of the Congo, Equatorial Guinea, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mauritania, Nigeria, Sao Tome and Principe, Senegal, Sierra Leone, Togo
(7) Southern Africa	Namibia, South Africa
(8) Eastern Africa	Comoros, Kenya, Madagascar, Mauritius, Mozambique, United Rep. of Tanzania
(9) South Asia	Bahrain, Bangladesh, Djibouti, Eritrea, India, Iran, Iraq, Jordan, Kuwait, Maldives, Myanmar, Oman, Pakistan, Qatar, Saudi Arabia, Somalia, Sri Lanka, Sudan, United Arab Emirates, Yemen
(10) South-East Asia	Brunei Darussalam, Cambodia, Indonesia, Malaysia, Papua New Guinea, Philippines, Singapore, Solomon Islands, Thailand, Timor-Leste, Vietnam
(11) Australia/New Zealand	Australia, New Zealand
(12) North-East Asia	China, China Hong Kong SAR, Japan, Rep. of Korea
(13) Eastern Indo-Pacific	Fiji, French Polynesia, New Caledonia, Samoa, Tonga, Vanuatu
(14) Russia	Russian Federation
(15) Black Sea	Bulgaria, Georgia, Romania, Ukraine

Table 2a. Percentage of total *inter-country* shipping traffic attributable to each ship type for 2006 and 2014. Growth expressed as percentage increase of traffic between both years. Shipping traffic measured as number of ship movements.

Ship type	**2006**	**2014**	**Growth (%)**
Bulk Carrier	8.54	15.27	402.55
Chemical and Chemical/Products Tanker	11.13	12.08	205.25
Container Ship	24.33	25.74	197.49
Crude Oil/Oil Products Tanker	6.27	6.81	205.42
General Cargo Ship	27.82	22.09	123.34
LNG Tanker	2.70	3.99	315.69
Ro-ro Cargo Ship	13.45	9.29	94.25
Total	**94.23**	**95.26**	**184.29**

Table 2b. Percentage of total *inter-country* shipping traffic attributable to each SER for 2006 and 2014. Growth expressed as percentage increase of traffic between both years. Shipping traffic measured as number of ship movements.

SER	**2006**	**2014**	**Growth**
North America	5.69	3.78	90.09
Central America, Caribbean, & Northern South America	2.27	4.81	508.01
Southern South America	0.56	1.71	773.59
Northern Europe	55.63	22.21	14.47
Mediterranean	6.14	14.68	585.21
Western Africa	0.06	2.27	10842.39
Southern Africa	0.64	0.71	218.34
Eastern Africa	0.00	0.55	81000.00
South Asia	4.97	8.69	400.81
South-East Asia	5.22	13.17	623.47
Australia/New Zealand	0.44	1.75	1035.75
North-East Asia	15.20	18.94	257.22
Eastern Indo-Pacific	0.00	0.13	114000.00
Russia	1.61	3.50	522.46
Black Sea	1.56	2.85	423.51

Table 3. Predictive performance of the proposed model and three alternative models at the ship type level. Values are expressed as R^2_{MSE} of predicted shipping traffic in 2014 after fitting to the years of 2006-2009. Bold values indicate which model was most predictive. The final column compares the aggregated model predictions across all ship types against the true sum of ship movements.

	Bulk Carrier	Chemical and Chemical/ Products Tanker	Container Ship	Crude Oil/Oil Products Tanker	General Cargo Ship	LNG Tanker	Ro-ro Cargo Ship	All Ships
Proposed Model	**0.6685092**	**0.8322772**	**0.8763442**	**0.739729**	**0.9311899**	**0.5940681**	**0.7506133**	**0.8721857**
Alternative Model I	-8.742025	0.1902814	0.6974064	0.5400013	0.24065432	0.2957496	0.635261	-0.5011395
Alternative Model II	0.3608236	0.6564815	0.7130451	0.5684313	0.8197343	0.4348355	0.6692433	0.6386451
Alternative Model III	0.1765243	-0.03899773	0.2845635	0.08110701	-3.8297225	-0.0816734	0.6049333	-0.4041242

Table 4. Parameter values and fits for the proposed model. Values were fit on vessel traffic data for the years 2006-2009. Green cells denote positive valued parameters; red cells denote negative ones.

	Bulk Carrier	Chemical and Chemical/Products Tanker	Container Ship	Crude Oil/Oil Products Tanker	General Cargo Ship	LNG Tanker	Ro-ro Cargo Ship
Intercept	-32.4257272	-18.4128371	-30.6845859	-18.6905757	-17.4302083	-11.7295334	-19.4786459
GDP.i	0.9142528	0.713227	0.7645234	0.6132747	0.7730449	0.4076933	0.5778473
GDP.j	0.8128876	0.655912	0.7600527	0.5931071	0.6980196	0.4098852	0.5768308
Pop.i	-0.2302503	-0.159121	NA	NA	-0.1836319	NA	NA
Pop.j	-0.1171944	-0.0968979	NA	NA	-0.127595	NA	NA
Distance	-0.7216482	-1.4885959	-1.1106999	-1.5004292	-1.7527839	-1.1429323	-1.2821611
CB	-1.3679874	-6.3090807	-5.6119506	-4.4844703	NA	-8.2751919	-5.851839
CL	0.721071	1.046572	2.2093864	1.1787687	0.9036002	0.8085308	2.0891099
CCH	NA	5.8145941	6.5326617	6.7407325	1.8129753	2.186447	7.2432487
FTA	1.2926779	1.6830894	1.7822042	0.6295324	1.5437802	1.6438121	0.8414773
R2 Fit 2006-2009	0.6642365	0.6565487	0.5509978	0.685824	0.7121338	0.5314216	0.5999651

Table 5. Inter-SER traffic annual growth rates between SERs between 2014 and 2050 under the 5 SSP scenarios (interpolated).

Scenario	Max	Min	Mean
SSP1	1.129	0.916	1.049
SSP2	1.116	0.900	1.041
SSP3	1.103	0.887	1.031
SSP4	1.107	0.892	1.037
SSP5	1.140	0.940	1.058

Table 6. Relative risk of invasion of each SER as sources and recipients of invasions. Rows sum to 1.

2014	**N Am**	**CAm/Cb/NSA**	**SSA**	**N Eur**	**Med**	**W Af**	**S Af**	**E Af**	**S As**	**SE As**	**Aus/NZ**	**NE As**	**C P Isl**	**Rus**	**Blk Sea**
As source	0.12206863	0.06330668	0.01028374	0.05748245	0.02713271	0.01343779	0.01731479	0.02584381	0.21682353	0.24725548	0.04674842	0.14253973	0.00226654	0.00461244	0.00288325
As destination	0.14158561	0.06429795	0.01296202	0.04615933	0.03100827	0.01318762	0.02576467	0.02961147	0.24181135	0.22289072	0.05889836	0.09909149	0.00228813	0.00644919	0.00399379
2050: SSP5															
As source	0.10456355	0.04855312	0.0179642	0.01800903	0.032061	0.01639996	0.02197434	0.03948186	0.22134454	0.1983997	0.03425554	0.24095321	0.00089471	0.00212127	0.00302398
As destination	0.09356889	0.04773648	0.03204317	0.03298949	0.08494467	0.01811428	0.0363156	0.05051743	0.21655192	0.1857932	0.04021654	0.15382262	0.00099349	0.00251697	0.00387524
2050: SSP3															
As source	0.10957783	0.05472812	0.02074906	0.01909631	0.03455363	0.01331566	0.02002522	0.03035638	0.21455008	0.1890688	0.02935803	0.25880361	0.00080947	0.00219941	0.00280838
As destination	0.1034774	0.05368539	0.03724625	0.03414122	0.09040193	0.01478975	0.03451117	0.03876901	0.21697835	0.18057118	0.0339027	0.15421255	0.00091363	0.00269995	0.00369953

Table 7. Increase in probability of invasion between 2014 and 2050 under: a) the highest traffic scenario (SSP5) and projected environmental conditions; b) the lowest traffic scenario (SSP3) and projected environmental conditions; c) 2014 traffic scenario and projected environmental conditions; d) the highest traffic scenario (SSP5) and current environmental conditions; e) the lowest traffic scenario (SSP3) and current environmental conditions. Rows designate source SER while columns designate recipient SER.

a)

	N Am	CAm/Cb/NS	SSA	N Eur	Med	W Af	S Af	E Af	S As	SE As	Aus/NZ	NE As	C P Isl	Rus	Blk Sea
N Am		0.0349439	0.00620632	0.00347643	0.00960821	0.00061866	0.00159055	6.5846E-06	0.0111743	0.00016853	0.00184493	0.11316231	4.9726E-05	-0.0002075	3.6896E-05
CAm/Cb/NSAm	0.03486285		0.01804391	4.9807E-05	0.00219011	0.00380306	0.01322597	7.0352E-05	0.00272306	0.00017629	3.9575E-05	0.00476398	9.3324E-05	-3.418E-08	-8.567E-08
SSA	0.00456955	0.01718596		0.00050645	0.00323124	3.3468E-05	0.0028067	6.9404E-07	1.0577E-05	2.7481E-05	6.195E-05	0.0035898	1.8159E-09	5.8761E-07	1.1822E-05
N Eur	0.00243577	8.9734E-05	0.00210358		0.00757344	0.00065315	0.00012079	-2.245E-09	5.1163E-05	9.5053E-05	0.00034885	0.00509639	-6.106E-15	0.00142992	0.00076156
Med	0.01682085	0.00099104	0.01154339	0.00770083		0.00253557	0.0016954	-3.089E-06	0.00036436	4.1773E-06	0.00011892	0.00892937	-2.082E-09	0.00161803	0.00359937
W Af	0.00076836	0.01048383	2.366E-05	0.00032439	0.00422076		0.0004092	0.00086492	0.00436444	0.00664018	9.0931E-05	8.4828E-05	-3.607E-10	7.8002E-08	1.7042E-06
S Af	0.00057429	0.0077454	0.00122588	5.0764E-05	0.0011621	0.00142543		0.00247196	0.00648841	0.00026619	0.00028734	0.01652579	-1.812E-07	8.8448E-09	1.7355E-06
E Af	1.1429E-05	0.0004036	6.3838E-07	6.9271E-09	-1.303E-06	0.00132489	0.00557816		0.04584205	0.01624376	-1.369E-05	0.00085578	-4.704E-10	-6.263E-13	-3.464E-13
S As	0.00800779	0.00063952	3.8184E-06	3.5835E-05	0.00038924	0.00297398	0.00943871	0.0546725		0.25863681	0.00290476	0.0907449	1.8919E-06	1.4E-09	5.6005E-08
SE As	0.00021335	0.00023141	8.4873E-06	0.00010219	8.5096E-06	0.01779273	0.00030873	0.01831466	0.2517723		0.02364259	0.04015982	0.00095968	-1.221E-15	-1.621E-14
Aus/NZ	0.00142457	6.6831E-05	6.5562E-06	1.5052E-05	3.5711E-05	0.00036076	0.00014009	3.4079E-05	0.0037269	0.01100405		0.0376572	0.00028261	4.9819E-06	2.5682E-08
NE As	0.09313257	0.00931012	0.02251937	0.04107365	0.13331741	0.00153563	0.03214065	0.01930884	0.10754097	0.04988206	0.03740984		2.4898E-05	0.00044646	0.00215474
C P Isl	6.6194E-05	2.0765E-07	3.8327E-09	-3.22E-15	-5.202E-10	-9.032E-10	1.2801E-09	-4.259E-09	-1.837E-07	0.00041096	0.00025622	0.00042034		0	0
Rus	-9.652E-05	-8.112E-08	3.3445E-06	0.00121191	0.00116661	2.2183E-09	7.6571E-07	-2.768E-13	1.5502E-09	-1.776E-15	7.7092E-07	0.00049366	0		0.00014142
Blk Sea	4.1272E-05	-1.703E-08	2.8358E-05	0.00069601	0.00319758	1.4162E-07	1.1294E-06	-4.138E-13	7.5038E-08	-6.661E-15	2.0906E-07	0.0009595	0	0.00013203	

b)

	N Am	CAm/Cb/NS/	SSA	N Eur	Med	W Af	S Af	E Af	S As	SE As	Aus/NZ	NE As	C P Isl	Rus	Blk Sea
N Am		0.01207547	0.00232605	-0.0035641	0.00368092	0.0001369	0.00063102	-2.592E-06	0.00421017	5.6203E-05	0.00050345	0.04372625	1.1592E-05	-0.0003322	1.1546E-05
CAm/Cb/NSAm	0.01221363		0.00916848	2.1758E-05	0.0005808	0.00109078	0.00465727	4.6237E-06	0.00105017	5.194E-05	1.3808E-05	0.00175365	-5.07E-05	-3.457E-08	-1.071E-07
SSA	0.00178908	0.00872665		0.00021564	0.00129343	1.2229E-05	0.00117757	9.8894E-10	4.3464E-06	1.263E-05	1.6885E-05	0.00148347	1.4127E-08	1.2948E-07	4.0913E-06
N Eur	-0.0053373	3.7821E-05	0.0009586		0.00304814	0.00021397	3.2591E-05	-2.869E-09	1.895E-05	3.2917E-05	0.00012482	0.00197108	-6.106E-15	0.0005539	0.00031647
Med	0.00744469	8.5133E-05	0.00558446	0.00316085		0.00072118	0.00041619	-3.739E-06	7.6542E-05	-4.228E-06	1.5062E-05	0.00342299	-2.082E-09	0.00032798	0.00104263
W Af	0.00010646	0.00283531	7.8729E-06	0.00010823	0.00130275		-9.695E-05	0.00019339	0.0012369	0.0020696	1.886E-05	6.9954E-06	-9.594E-10	2.0061E-08	4.4578E-07
S Af	0.00020255	0.00285898	0.00043624	3.9769E-06	0.00027153	-1.099E-06		0.00050186	0.0020408	5.1543E-05	1.9374E-05	0.00606008	-1.812E-07	8.1732E-10	5.1522E-07
E Af	7.0608E-07	0.00012048	1.7506E-07	7.9919E-10	-1.411E-06	0.00027465	0.00110664		0.01271573	0.00458766	-1.865E-05	0.00018295	-4.704E-10	-6.263E-13	-3.468E-13
S As	0.00335194	0.00020005	1.5798E-06	7.0174E-06	7.8349E-05	0.00081883	0.00290684	0.01437601		0.07761733	0.00073784	0.03320569	2.0725E-07	5.1285E-10	1.8254E-08
SE As	6.2851E-05	5.871E-05	3.7221E-06	3.5308E-05	-1.549E-06	0.00547595	5.5225E-05	0.00497868	0.0719971		0.0063386	0.01188258	0.00025781	-1.221E-15	-1.621E-14
Aus/NZ	0.00048977	2.0475E-05	3.8434E-07	3.4145E-06	9.4604E-06	8.6063E-05	3.2943E-05	3.0337E-06	0.00117152	0.0032891		0.00795522	1.135E-05	9.4607E-07	8.0294E-09
NE As	0.03479035	0.00316035	0.00998248	0.01701312	0.05795242	0.00044632	0.01210737	0.00562857	0.03844185	0.01391208	0.00662983		-1.538E-05	0.00015547	0.0007549
C P Isl	1.2922E-05	1.5662E-08	7.2877E-08	-3.442E-15	-5.202E-10	-1.686E-09	1.2801E-09	-4.259E-09	-2.22E-07	7.5238E-05	1.4472E-05	1.9247E-05		0	0
Rus	-0.0002308	-8.156E-08	3.6165E-07	0.00046987	0.00026875	2.899E-10	1.3725E-07	-2.768E-13	5.8559E-10	-1.776E-15	4.078E-07	0.00018308	0		1.2081E-05
Blk Sea	1.2919E-05	-2.109E-08	1.1236E-05	0.00025628	0.00101513	4.5732E-08	-1.002E-07	-4.159E-13	2.5693E-08	-6.661E-15	6.0421E-08	0.00032356	0	4.3638E-06	

c)

	N Am	CAm/Cb/NS/	SSA	N Eur	Med	W Af	S Af	E Af	S As	SE As	Aus/NZ	NE As	C P Isl	Rus	Blk Sea
N Am		0.00184945	0.00018617	-0.0065984	0.00154835	-0.0001318	3.283E-05	-3.538E-06	0.00040867	2.6794E-06	-0.000152	0.0056949	1.0601E-05	-0.000321	-4.766E-06
CAm/Cb/NSAm	0.00227126		0.00302218	2.1252E-06	-0.0005196	-0.0002162	-0.0001215	-1.374E-05	-7.915E-06	-2.273E-05	1.0459E-06	-3.158E-07	1.102E-05	-3.473E-08	-1.192E-07
SSA	0.00027245	0.0027315		3.3902E-05	6.4784E-05	1.9287E-06	-4.692E-06	-1.764E-07	1.2218E-06	2.1308E-06	1.7975E-07	-0.0001064	1.413E-08	-5.659E-08	-1.636E-07
N Eur	-0.008843	3.4835E-06	0.00011442		0.00141471	1.358E-05	-2.139E-05	-3.081E-09	-2.836E-06	-7.482E-07	-5.616E-06	0.00012858	-6.106E-15	0.00041254	4.8853E-06
Med	0.0037435	-0.0004316	3.4061E-05	0.00147577		-2.975E-06	-0.0001011	-3.969E-06	-4.507E-05	-7.554E-06	-1.865E-05	-4.353E-05	-2.082E-09	-0.0001037	6.4253E-05
W Af	-0.0001788	-0.0003697	9.5458E-07	1.1258E-05	6.7148E-05		-0.0002999	-2.33E-05	-4.645E-05	7.2417E-05	-6.613E-07	-2.141E-05	-4.62E-10	-4.075E-09	-1.032E-08
S Af	3.0198E-05	6.0892E-05	-3.911E-05	-2.419E-05	-7.796E-05	-0.0005382		-0.0002409	3.5111E-05	-4.894E-05	-3.701E-05	-9.718E-05	-1.812E-07	-1.553E-09	-2.882E-08
E Af	-2.577E-06	-2.272E-05	-2.378E-08	-9.055E-10	-1.445E-06	-4.743E-05	-0.000456		-3.418E-05	-2.684E-05	-1.256E-05	-2.426E-05	-4.704E-10	-6.263E-13	-3.466E-13
S As	3.5417E-05	-7.268E-06	4.3682E-07	-8.405E-06	-5.091E-05	-4.845E-05	0.0001698	6.5109E-05		-0.0157519	9.0292E-05	0.00116006	1.221E-07	5.749E-10	2.9546E-09
SE As	6.8343E-07	-3.11E-05	5.8416E-07	-1.092E-06	-6.164E-06	0.00017626	-6.004E-05	-6.188E-05	-0.0200626		0.00042225	-0.0009784	-3.691E-05	-1.221E-15	-1.621E-14
Aus/NZ	8.2046E-05	-8.738E-07	-6.873E-07	2.1913E-07	-7.471E-07	6.1714E-06	-7.082E-06	-5.431E-06	8.7553E-05	8.2845E-05		-0.0030129	-7.813E-06	1.8077E-07	1.0848E-09
NE As	0.00305459	-0.0001666	-0.0002194	0.00024217	-0.0002238	-4.653E-05	-8.818E-05	-0.0001387	0.00182075	-0.0020487	-0.0038249		-2.255E-05	0.00010019	-1.863E-05
C P Isl	4.7317E-06	1.8858E-08	7.2886E-08	-2.776E-15	-5.202E-10	-1.405E-09	1.2801E-09	-4.259E-09	-1.454E-07	-3.604E-05	-9.359E-06	-2.171E-05		0	0
Rus	-0.0002084	-8.168E-08	-8.375E-07	0.00035573	-2.841E-06	-3.339E-10	-1.702E-07	-2.768E-13	6.079E-10	-1.776E-15	4.236E-07	0.00014134	0		-7.583E-06
Blk Sea	-1.201E-06	-2.356E-08	-1.957E-07	1.8093E-05	0.00014752	4.2058E-09	-5.651E-07	-4.16E-13	3.1975E-09	-6.661E-15	1.3104E-09	-1.432E-05	0	-8.081E-06	

d)

	N Am	CAm/Cb/NS	SSA	N Eur	Med	W Af	S Af	E Af	S As	SE As	Aus/NZ	NE As	C I P Isl	Rus	Blk Sea
N Am		0.02798093	0.00501866	0.03300465	0.00380844	0.00165157	0.00094302	2.6686E-05	0.00434803	0.00014249	0.00282991	0.05284066	2.4164E-05	0.00031018	0.00019745
CAm/Cb/NSAm	0.02614092		0.00179142	2.7851E-05	0.00584927	0.00656835	0.01415264	0.00013792	0.00289672	0.00049922	2.425E-05	0.00473146	7.5164E-05	8.666E-08	2.881E-06
SSA	0.00259807	0.00176938		0.00032126	0.00293123	1.3098E-05	0.00366596	1.6915E-06	9.4981E-07	1.2061E-06	5.8502E-05	0.00545177	-2.061E-11	7.2392E-07	1.3718E-05
N Eur	0.04116038	4.7827E-05	0.00092377		0.00283014	0.00035597	0.00032912	1.7366E-08	8.4732E-05	0.0001064	0.00024239	0.00247839	0	0.00028398	0.0006074
Med	0.00287282	0.00347546	0.01048732	0.00252083		0.00250379	0.00230763	2.8636E-05	0.00061628	4.2786E-05	0.00020751	0.00979538	-1.575E-12	0.00199959	0.00326312
W Af	0.00253806	0.01674389	1.5615E-05	0.00018718	0.00362603		0.00450278	0.00125415	0.00496243	0.00603074	9.3983E-05	0.00033154	1.618E-10	2.2978E-07	2.1141E-06
S Af	0.00038897	0.00730646	0.00161726	0.00038354	0.00178685	0.00757447		0.00570604	0.00635104	0.00083458	0.00041723	0.02199449	0	1.4864E-08	2.1526E-06
E Af	2.7941E-05	0.00095941	1.1701E-06	1.3911E-08	1.4877E-05	0.00199175	0.0107185		0.04521414	0.01665723	0.00012442	0.00111897	0	0	2.0228E-13
S As	0.00724905	0.00070335	2.2458E-07	0.00010988	0.00072344	0.00403034	0.00791137	0.05380443		0.38298505	0.00211073	0.0610585	1.5998E-06	2.3775E-10	4.6092E-10
SE As	0.00023347	0.00052879	7.8972E-07	0.00011396	4.8304E-05	0.01518064	0.00100286	0.01923398	0.39267796		0.02017892	0.04975809	0.00120482	9.77E-15	5.197E-13
Aus/NZ	0.00081521	7.3038E-05	6.3185E-06	1.4075E-05	4.0881E-05	0.00030639	0.00019613	8.294E-05	0.00219441	0.01041946		0.05745334	0.00030772	2.5712E-07	1.0865E-08
NE As	0.06825868	0.01071852	0.04987829	0.01885879	0.16939821	0.00566471	0.03611626	0.0254125	0.06890367	0.07033585	0.06342663		0.00010852	7.9503E-05	0.00263092
C I P Isl	5.2706E-05	1.448E-07	-1.191E-09	-1.554E-15	-9.537E-14	1.6661E-09	0	0	-3.963E-08	0.00053977	0.00028507	0.00048404		0	0
Rus	0.00030632	1.9666E-07	6.539E-06	0.00029174	0.00124675	4.7641E-09	2.5257E-06	1.3914E-12	9.4743E-11	7.2164E-15	2.5221E-07	6.546E-05	0		0.00015941
Blk Sea	4.2542E-05	4.4559E-07	3.1739E-05	0.00051773	0.00232661	3.17E-08	1.0118E-05	2.7782E-12	1.7818E-10	1.8652E-13	1.785E-07	0.00126629	0	0.0001523	

e)

	N Am	CAm/Cb/NS	SSA	N Eur	Med	W Af	S Af	E Af	S As	SE As	Aus/NZ	NE As	C I P Isl	Rus	Blk Sea
N Am		0.00861746	0.00177856	0.01031921	0.00098794	0.0005455	0.00036144	5.3072E-06	0.00155441	4.6696E-05	0.00088914	0.01834644	8.3275E-07	-9.959E-05	7.6192E-05
CAm/Cb/NSAm	0.0078881		0.00071105	1.1475E-05	0.00234858	0.00213262	0.00507558	2.8632E-05	0.00112741	0.00019175	8.0166E-06	0.00172177	-5.636E-05	2.5121E-08	1.0657E-06
SSA	0.0008049	0.0007144		0.00012674	0.00115811	4.3045E-06	0.0015649	3.656E-07	3.2335E-07	5.0721E-07	1.5656E-05	0.00232249	-6.434E-13	1.8756E-07	4.8698E-06
N Eur	0.01298359	1.9207E-05	0.00039187		0.00074552	0.00011075	0.00012813	4.0328E-09	3.4022E-05	3.7403E-05	8.9627E-05	0.00091794	-3.442E-15	3.0779E-05	0.00025217
Med	0.00078156	0.00126559	0.00505258	0.00068113		0.00072148	0.00068456	7.6105E-06	0.00018362	1.2338E-05	5.0522E-05	0.00378387	-3.028E-12	0.00050358	0.0009068
W Af	0.00070867	0.00519685	4.7757E-06	6.0181E-05	0.00106738		0.00131654	0.00030463	0.0014383	0.00186728	1.9814E-05	8.8183E-05	-7.941E-10	6.7587E-08	5.606E-07
S Af	0.00012274	0.00266015	0.00060804	0.00014888	0.00054226	0.00208583		0.00157055	0.00197422	0.00026606	7.2263E-05	0.00817858	0	3.2908E-09	6.6376E-07
E Af	6.1809E-06	0.00032589	3.5247E-07	3.0311E-09	3.9137E-06	0.00046615	0.00281095		0.01258539	0.00474681	2.5456E-05	0.00026919	0	0	-2.003E-13
S As	0.00309024	0.00022637	7.8718E-08	3.864E-05	0.00022107	0.00113902	0.00231083	0.01412818		0.13871744	0.00049002	0.02160447	7.8419E-08	6.3158E-11	1.4096E-10
SE As	7.6944E-05	0.00018686	3.1969E-07	4.0136E-05	1.5958E-05	0.00463185	0.00031701	0.00528569	0.14304092		0.00512783	0.01549053	0.00035653	2.9976E-15	1.6909E-13
Aus/NZ	0.0002475	2.3034E-05	2.6281E-07	3.0374E-06	1.1478E-05	6.8999E-05	5.34E-05	1.7954E-05	0.00064105	0.00304919		0.01536326	2.0774E-05	-8.406E-07	3.0373E-09
NE As	0.02395161	0.0037471	0.02254763	0.0077025	0.07470539	0.00176855	0.01368633	0.00755331	0.0235431	0.02170949	0.01606775		1.6543E-05	1.3159E-05	0.00091387
C I P Isl	6.6992E-06	-2.516E-09	-3.115E-12	-2.776E-15	-2.935E-13	-9.356E-10	0	0	-7.884E-08	0.00012667	2.6277E-05	4.4118E-05		0	0
Rus	-6.331E-05	4.2107E-08	1.8758E-06	4.2759E-05	0.00030303	1.1647E-09	8.296E-07	2.8755E-13	1.9346E-11	2.1094E-15	4.1495E-08	1.2252E-05	0		2.0014E-05
Blk Sea	1.483E-05	1.6351E-07	1.264E-05	0.00018209	0.00066662	9.5847E-09	3.0755E-06	5.2425E-13	5.4684E-11	6.0951E-14	5.0794E-08	0.00042954	0	1.2913E-05	

Figures

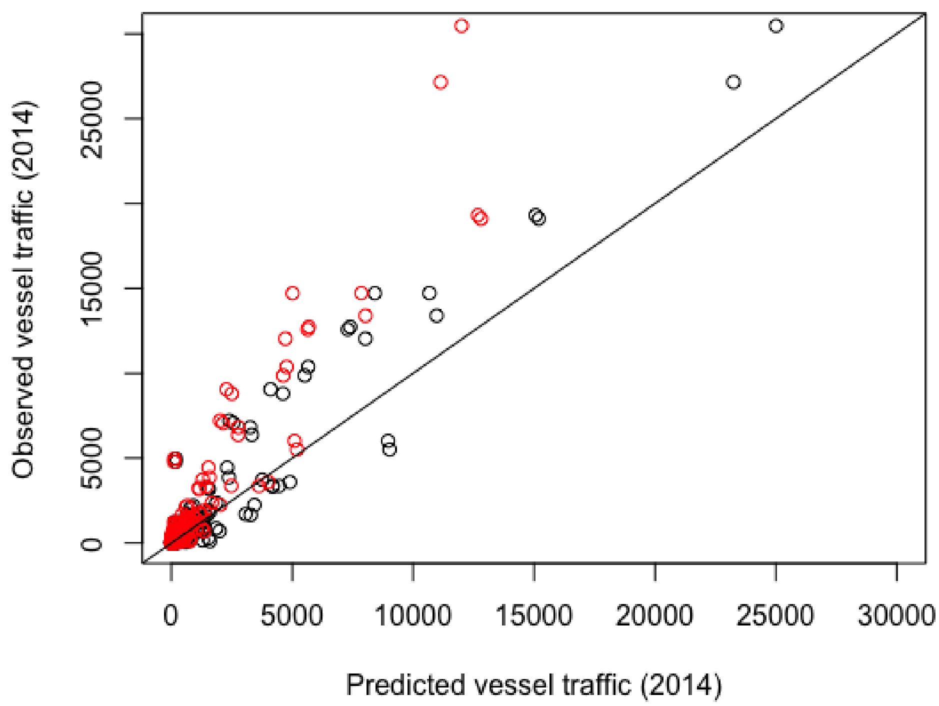

Figure 1. Predicted versus observed total vessel traffic in terms of vessel movements for the year 2014 using our proposed model (black) versus historical values (red). Both the proposed model and historical values model are based on data from 2006-2009.

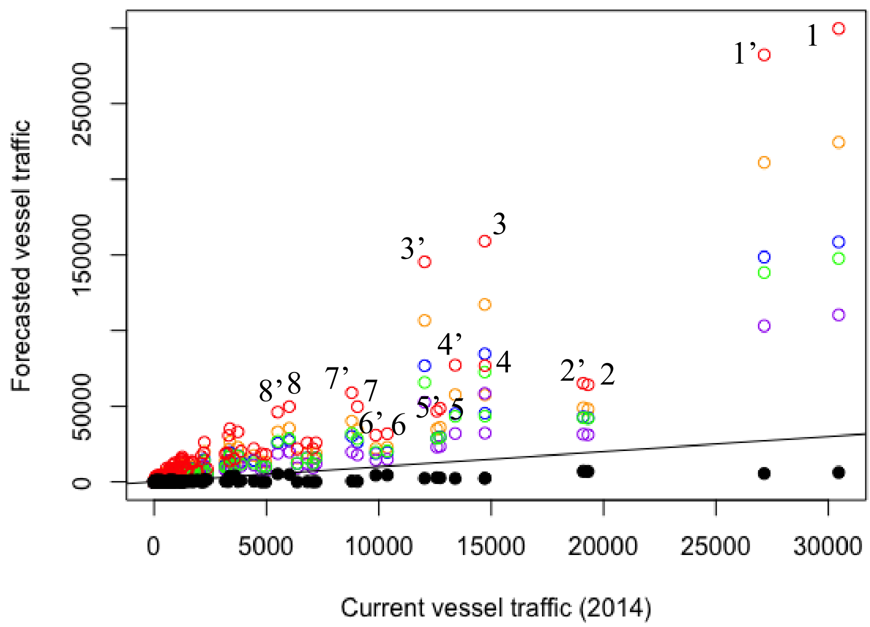

Figure 2. Forecasted vessel traffic under each of the 5 SSP scenarios: "SSP1, Sustainability" (orange), "SSP2, Middle of the road" (blue), "SSP3, Regional rivalry" (purple), "SSP4, Inequality" (green), and "SSP5, Fossil-fueled development" (red). The 1-to-1 line indicates no change, while the black points represent vessel traffic in 2006. Specific connections of interest are labelled. 1: North-East Asia to South-East Asia, 1': South-East Asia to North-East Asia, 2: Northern Europe to Mediterranean, 2': Mediterranean to Northern Europe, 3: South-East Asia to South Asia, 3': South Asia to South-East Asia, 4: Mediterranean to Black Sea, 4': Black Sea to Mediterranean, 5: Central and Northern South America to North America, 5': North America to Central and Northern South America, 6: Northern Europe to Russia, 6': Russia to Northern Europe, 7: Australia/New Zealand to South-East Asia, 7': South-East Asia to Australia/New Zealand 8: North-East Asia to North America, 8': North America to North-East Asia.

Appendix

Displaced DWT as a measure of vessel traffic

Considering DWT displaced as the measure of traffic rather than number of vessel movements yields a largely similar picture of historical change in shipping, but with some differences (Table S1). Northern Europe and the Mediterranean figure less prominently among global port calls, while Asian SERs figure more prominently. Bulk carriers and crude oil/oil products tankers account for a much larger share of traffic, while general and ro-ro cargo ships account for less. These differences highlight important attributes of maritime traffic for these ship types and these regions of the world. Namely that traffic in Northern Europe and the Mediterranean is characterized by a greater number of smaller size ships compared to Asian SERs, and that the bulk carrier and crude oil/oil products tanker markets are characterized by a smaller number of larger ships compared to the general and ro-ro cargo ship markets.

Applying our proposed shipping model when using displaced DWT as the metric of traffic instead of total vessel movements yields similar results with respect to model performance (Table S2). Here, too, our model performed strongly (Figure S1), outperforming all other alternative models in all but one cases (Table S2). Compared to when using number of ship movements as the measure of traffic, unaltered historical values (Alternative Model II), performed worse, while a constant growth rate applied to historical values (Alternative Model III) performed slightly better.

Using DWT as the measure of shipping traffic largely resulted in the same variables being selected in the model by forward selection (Table S3), with population emerging as an unimportant predictor of shipping traffic in most cases. The relationship of each of these variables with shipping traffic was also conserved.

Applying the model to forecast changes in DWT displaced results in a similar image of future traffic (Figure S2). Links between the 3 Asian SERs are expected to continue to dominate global maritime traffic, particularly the route between North-East and South-East, which is projected to grow from 1,560,000,000 DWT displaced in 2014 to between 9,200,000,000 and 34,500,000,000 DWT by mid-century. However other SERs' links with Asia are also expected to experience considerable growth. This includes currently less-travelled links, such as from West Africa to South-East Asia, which is forecasted to grow from 104,000,000 to 980,000,000-4,200,000,000 DWT displaced.

Generally, traffic along routes not connecting to either the North-East, South, or South-East Asia are forecasted to experience more subdued growth. For instance, the route between Northern Europe and the Mediterranean, which at 460,000,000 DWT displaced was among the higher traffic routes in 2014, is expected to increase to between 880,000,000 and 2,500,000,000 DWT displaced.

For DWT displaced, forecasted changes in traffic are expected to be consistent with projections of number of ship movements in terms of which shipping routes will experience the most change, however they are anticipated to differ in terms of the relative importance of each ship type. By mid-century, crude oil tankers are expected to account for 32% of inter-SER travel, followed by bulk carriers (31%), container ships (25%), chemical/chemical products tankers (5%), general cargo ships (2%), LNG tankers (2%), and ro-ro cargo ships (2%) (see Table S1c for comparison with 2014 values).

Supplementary tables

Table S1a. Percentage of total *inter-country* shipping traffic attributable to each ship type for 2006 and 2014. Growth expressed as percentage increase of traffic between both years. Shipping traffic measured as total DWT displaced.

Ship type	2006	2014	Growth (%)
Bulk Carrier	18.97	28.80	518.36
Chemical and Chemical/Products Tanker	7.13	6.52	272.64
Container Ship	35.21	29.56	241.99
Crude Oil/Oil Products Tanker	19.76	21.42	341.60
General Cargo Ship	6.18	3.94	159.61
LNG Tanker	1.87	2.99	551.02
Ro-ro Cargo Ship	5.55	2.85	109.36
Total	**94.68**	**96.09**	**313.43**

Table S1b. Percentage of total **inter-country** shipping traffic attributable to each SER for 2006 and 2014. Growth expressed as percentage increase of traffic between both years. Shipping traffic measured as total DWT displaced.

SER	2006	2014	Growth (%)
North America	10.88	5.28	107.90
Central America, Caribbean, & Northern South America	3.24	5.85	674.09
Southern South America	0.80	2.15	1047.57
Northern Europe	36.50	12.03	41.04
Mediterranean	5.60	10.20	679.41
Western Africa	0.05	2.63	22893.88
Southern Africa	1.10	1.20	367.54
Eastern Africa	0.00	0.58	258911.78
South Asia	11.63	15.69	477.30
South-East Asia	9.06	16.36	673.05
Australia/New Zealand	0.85	4.30	2067.57
North-East Asia	18.27	19.99	368.32
Eastern Indo-Pacific	0.00	0.08	2646228100.00
Russia	0.97	2.42	971.72
Black Sea	1.05	1.20	387.01

Table S1c. Percentage of total **inter-SER** shipping traffic attributable to each ship type for 2006 and 2014. Growth expressed as percentage increase of traffic between both years. Shipping traffic measured as total DWT displaced.

Ship type	**2006**	**2014**	**Growth (%)**
Bulk Carrier	23.30	37.62	624.04
Chemical and Chemical/Products Tanker	5.68	4.92	288.52
Container Ship	36.37	22.76	180.62
Crude Oil/Oil Products Tanker	20.96	21.53	360.65
General Cargo Ship	3.88	2.89	233.83
LNG Tanker	2.07	3.41	637.37
Ro-ro Cargo Ship	2.77	1.69	173.20
Total	**95.04**	**94.82**	**347.39**

Table S2. Predictive performance of the proposed model and three alternative models at the ship type level. Values are expressed as R2MSE of predicted shipping traffic in 2014 after fitting to the years of 2006-2009. Bold values indicate which model was most predictive. The final column compares the aggregated model predictions across all ship types against the true sum of ship movements.

	Bulk Carrier	Chemical and Chemical/ Products Tanker	Container Ship	Crude Oil/Oil Products Tanker	General Cargo Ship	LNG Tanker	Ro-ro Cargo Ship	All Ships
Proposed Model	**0.6420917**	**0.7342681**	**0.7990583**	**0.8187119**	**0.9247012**	**0.6377575**	0.7860023	**0.8076939**
Alternative Model I	-19.5538139	-785.8240954	0.07707399	-261.4575495	-25.22548634	-0.59833555	-89.47168407	-67.293917
Alternative Model II	0.2916555	0.5713526	0.6217288	0.4665347	0.7607207	0.3638670	0.6842153	0.4218664
Alternative Model III	-0.4587374	0.4331777	0.7062118	0.7271206	-2.3108759	0.6308336	**0.8273728**	0.263075

Table S3. Parameter values and fits for the proposed model. Values were fit on vessel traffic data for the years 2006-2009. Green cells denote positive valued parameters, red cells denote negative ones, and NA is used to designate variables that were omitted as a result of forward selection.

	Bulk Carrier	Chemical and Chemical/ Products Tanker	Container Ship	Crude Oil/Oil Products Tanker	General Cargo Ship	LNG Tanker	Ro-ro Cargo Ship
Intercept	-35.570966832	-31.887166569	-38.757435228	-38.757435228	-38.757435228	-38.757435228	-38.757435228
GDP_i	1.1481589928	1.150103391	1.138538578	1.138538578	1.138538578	1.138538578	1.138538578
GDP_j	1.0234124780	1.002654352	1.145377217	1.145377217	1.145377216	1.145377217	1.145377216
Pop_i	-0.2739528141	-0.176577427	NA	NA	NA	NA	NA
Pop_j	-0.1424596010	NA	NA	NA	NA	NA	NA
Distance	-0.4554296289	-1.621686125	-1.866585681	-1.866585681	-1.866585681	-1.866585681	-1.866585681
CB	NA	-9.589078320	-12.441476642	-12.441476642	-12.441476642	-12.441476642	-12.441476642
CL	0.8201839262	1.683744004	4.476450462	4.476450462	4.476450462	4.476450462	4.476450462
CCH	NA	8.259727776	13.507442104	13.507442104	13.507442104	13.507442104	13.507442104
FTA	1.575575744	2.712902240	1.579338140	1.579338140	1.579338140	1.579338140	1.579338140
R2 Fit 2006-2009	0.660459336	0.615985466	0.5745336366	0.574533637	0.574533637	0.574533637	0.574533637

Supplementary figures

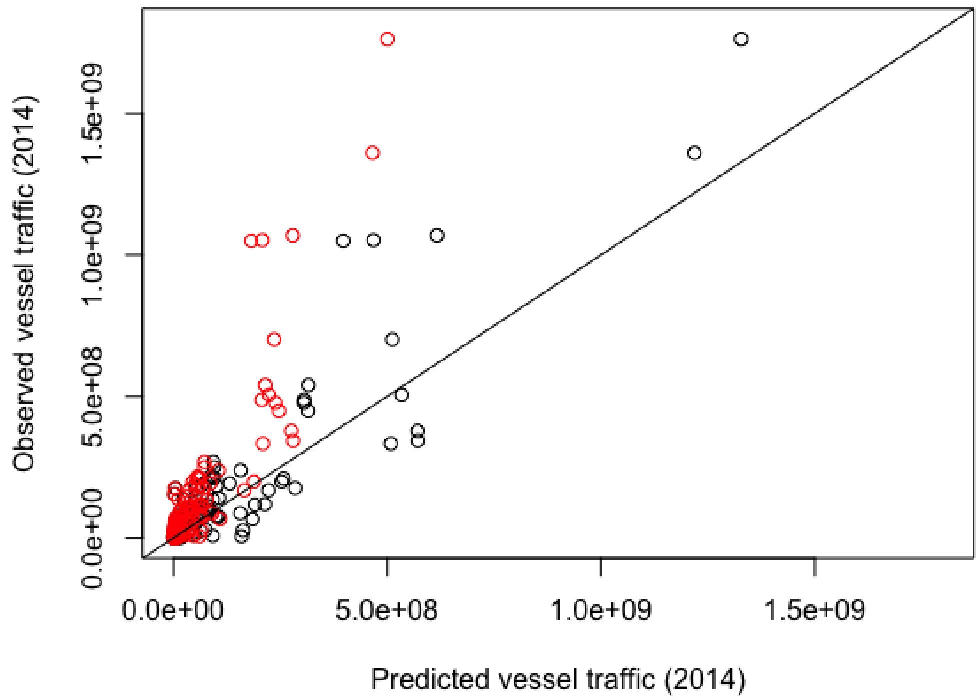

Figure S1. Observed versus predicted total vessel traffic in terms of DWT displaced for the year 2014 using our proposed model (black) versus historical values (red). Both the proposed model and historical values model are based on data from 2006-2009.

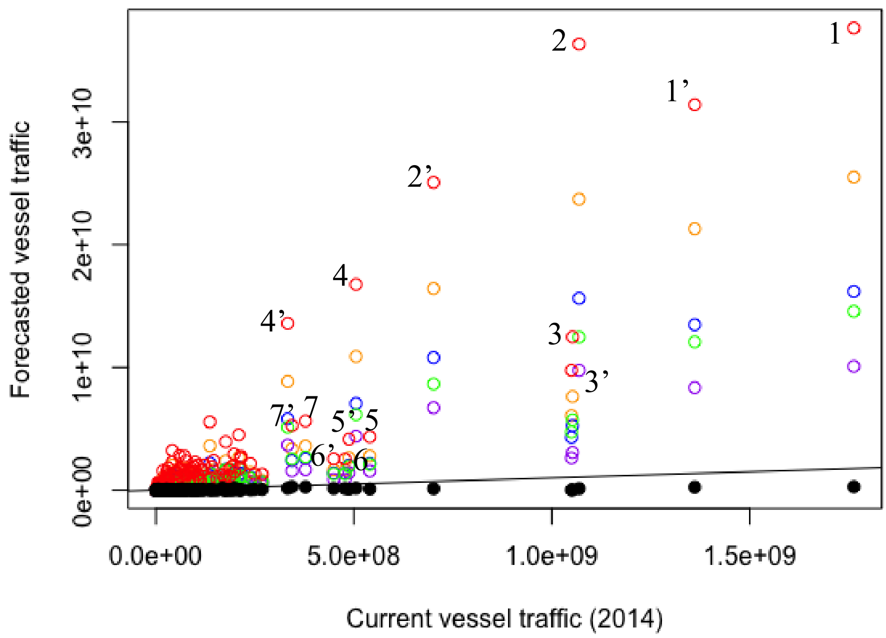

Figure S2. Forecasted vessel traffic in terms of DWT displaced under each of the 5 SSP scenarios: "SSP1, Sustainability" (orange), "SSP2, Middle of the road" (blue), "SSP3, Regional rivalry" (purple), "SSP4, Inequality" (green), and "SSP5, Fossil-fueled development" (red). The 1-to-1 line indicates no change, while the black points represent vessel traffic in 2006. Specific connections of interest are labelled. 1: North-East Asia to South-East Asia, 1': South-East Asia to North-East Asia, 2: South-East Asia to South Asia, 2': South Asia to South-East Asia,3: North-East Asia to Australia/New Zealand, 3': Australia/New Zealand to North-East Asia, 4: South Asia to North-East Asia, 4': North-East Asia to South Asia, 5: North America to Central and Northern South America, 5': Central and Northern South America to North America, 6: Northern Europe to Mediterranean, 6': Mediterranean to Northern Europe, 7: North-East Asia to North America, 7': North America to North-East Asia.