MANAGEMENT OF VESSEL-BORNE BIOLOGICAL INVASIONS: POLICY, ECONOMIC, AND TECHNOLOGY ASSESSMENT

by

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ABSTRACT

Global shipping activities account for 90% of global trade and play an important role in the world economy and welfare, but vessels generate different negative environmental impacts meanwhile, by air emissions, greenhouse gas emissions (GHG), and species invasion. The four studies in this work aim to inform related policymaking at international and regional levels to reduce the negative impacts from international shipping.

The first study examines the container vessel diversion pattern to trans-Arctic shipping routes and GHG emission abatement potential under climate change and ice retreat in the Arctic area. Literature shows inconsistent conclusions on the economic feasibility of the trans-Arctic routes, which motivates this work to examine the potential general diversion patterns of the global shipping traffic. While we find some trans-Arctic routes are economically feasible, the diversion potential of trans-Arctic routes may be overestimated. The sample in this work contains 522,691 shipping moves, and only 83 moves would reduce distance, and 45 would save sailing time through the Arctic; however, 20 moves would reduce shipping cost. Though few diversions may happen, we find that 20 economically feasible trans-Arctic diversions reduce GHG emissions. Their average fuel consumption reduction through the Arctic is 264 metric tons (MT) (reduced by 26%); the range is 125-328 MT. The average CO2e emission is 767 MT (reduced by 24%); the range is 359-954 MT. Most of these voyages are between North America and East Asia. These results inform ship

operators a possible operating way to achieve the GHG abatement goal by making a diversion to the trans-Arctic routes for voyages between certain geographical areas.

The second work starts to examine the policies to manage ballast water discharge to decease aquatic species invasion from the perspective of the technology. Ballast water treatment systems (BWTS) are the technology to comply with the ballast water regulations but generate great compliance costs, which may increase the shipping cost. Therefore, to balance the effectiveness and cost of ballast water treatment, this work evaluates technological strategies that include conventional vessel-based and alternative barge-based technologies. We also propose a potential policy scenario under which California makes efforts to provide additional protection from ballast discharge invasion risk. We construct a vessel-versus-barge compliance cost framework to examine the available technological strategies. The results show that the stringency of the regulations matters the technology selection a lot. If a single global standard is a weak standard, then adopting vessel-based compliant technology is less costly than centralized barge-based compliance. This work considers these findings to apply generally beyond the California context. Specifically, if some region or all regions adopt standards different from current global standards (i.e., stricter), barge-based systems can be less costly than retrofitting world fleets.

The third work continues to global ballast water management and further balance the compliance cost and potential negative impacts on the economy and global trade. We employ an integrated shipping cost and global economic modeling method to examine the impacts of ballast management regulations on bilateral trade, national economies, and shipping patterns. Given the potential need for more stringent regulation at regional hotspots of species invasions, this work considers two ballast

water treatment policy scenarios: implementation of current international regulations, and a possible stricter regional regulation that targets ships traveling to and from the United States while other vessels continue to face current standards. We find that ballast water management compliance costs under both scenarios lead to modest negative impacts on international trade and national economies overall. However, stricter regulations applied to U.S. ports are expected to have large negative impacts on the bilateral trade of several specific commodities for a few countries. Trade diversion causes decreased U.S. imports of some products, leading to minor economic welfare losses.

The fourth work further moves the ballast water regulations forward with integrated analysis with a risk-policy-economic-technology nexus. The work uses a ballast water-borne biological invasion risk assessment model based on a higher-order-network. (1) By quantifying the ballast water treatment efficacy of BWTS under the IMO and stricter global standards, the work reveals that stricter regulation is needed to further reduce invasion risks. Given the revealed uneven distribution risks at different ports, the work finds that regional regulations are needed to target high-risk ports. (2) By cluster analysis, the work reveals both intra- and inter-cluster species introduction pathways and identifies “hub ports” connecting several clusters. Targeting such hub ports is the key to break down the inter-cluster connection not only can protect high-risk ports, but also reduce worldwide risks with lower costs by changing the inter-cluster species introduction pattern. (3) Then the work combines a technology cost model to find the least costly way to compliance different “regional stricter regulatory scenarios” since the new policy may choose different numbers of ports to strictly regulate. By varying the number of higher-risk ports selected to do

stricter regulations, the model simulates 4257 policy cases. The work finds the vessel-based method is least costly under the IMO regulations under every policy case, while the port-based method becomes important to lower the compliance cost for stricter regulations. The identifies the threshold of the number of ports regulated more strictly for compliance technology selection: when the number of high-risk ports is smaller than 2882, the port-based method at high-risk ports combining the vessel-based method is the least costly strategy; when the number is larger than 2882, the port-based method at all world ports is least costly. This implies the geopolitical shifts in global ballast water management since the IMO is the agency to regulate ships while it cannot make requirements for ports.

Chapter 1

INTRODUCTION

1.1 Background and Motivation

Shipping activity, as one of many uses of the ocean, accounts for 90% of global commercial trade, but it generates different environmental issues. Vessels combust marine fuels emitting air pollutants and greenhouse gases. Air emissions harm people's health and cause global warming. Ships also take on ballast water to maintain stability and adjust the trim for optimal steering and propulsion, meanwhile carrying organisms via ballast water. Once the organisms become established at destination ports, they cause damage to the environment, human health, and resources (Carlton, 1985, Drake et al., 2007). This dissertation focuses on GHG emission reduction and ballast water management.

Regulations are in place to manage these environmental issues. Most emissions are regulated by Annex VI of MARPOL, developed through the International Maritime Organization (IMO) that establishes legally binding international standards. As for GHG emissions, in April 2018, IMO's Marine Environment Protection Committee (MEPC) for the first time adopted an initial strategy on the reduction of GHG from shipping which will reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008. IMO has adopted mandatory measures to reduce emissions of greenhouse gases from international shipping, under IMO's pollution prevention treaty (MARPOL) - the Energy Efficiency Design Index (EEDI) mandatory for new ships, and the Ship Energy Efficiency Management Plan (SEEMP).

Besides, ship operators may take operational measures to reduce GHG emission, such as slow steaming and shipping route optimization.

For example, due to climate change and ice retreat in the Arctic area, new trans-Arctic shipping routes are emerging and changing the global shipping pattern. Trans-Arctic routes may reduce shipping distance and the resulted fewer fuel consumption may contribute to GHG emission abatement goals. To study the potential role of trans-Arctic routes in GHG abatement, we need to know the global diversion pattern to the Arctic. New trans-Arctic routes seem promising with the support from related research in navigation risk assessment, technology development, geographical politics, and environmental impact analysis. Shipping companies could assign vessels to divert to trans-Arctic routes to pursue higher profits, enlarge the market share, or expand service (Beveridge et al., 2016, Lindstad et al., 2016, Furuichi and Otsuka, 2015). However, recent studies draw different conclusions on the economic feasibility of trans-Arctic routes, which makes the evaluation of potential Arctic diversion difficult. Therefore, an economic model that can be generally applied for all shipping moves is necessary.

The species invasion issues caused by ballast discharge is regulated by the International Convention on the Control and Management of Ship's Ballast Water and Sediments (the BWM Convention). The BWM Convention came into force on September 8, 2017. As of January 2020, 81 states had ratified the Convention, accounting for 80.76% of the world tonnage (The IMO, 2020). The BWM Convention includes two discharge standards: Ballast Water Exchange (D-1 Standard) and Ballast Water Performance Standard (D-2 Standard). D-1 Standard requires ships to exchange at least 95% of the ballast water within open ocean areas, and D-2 Standard specifies

the maximum amounts of viable organisms allowed to be discharged, including specified indicator microbes harmful to human health. The BWM Convention explicitly disavows preventing a State Party from taking, individually or jointly with other State Parties, more stringent measures with respect to the prevention, reduction or elimination of the transfer of Harmful Aquatic Organisms and Pathogens through ships' Ballast Water and Sediments, consistent with international law (The IMO, 2004). Parties may also, consistent with international law, require ships to meet a specified standard or requirement for certain areas if necessary (The IMO, 2004).

Current IMO BWM standards are species concentration-based, instead of risk-based. Risks are not clearly mitigated by current standards, so there is a need for more stringent location-specific regulations at invasion hotspots (Verna and Harris, 2016, Saebi et al., 2019). Therefore, risk-based policymaking is needed, and regional stricter regulations are needed to better manage the ballast discharge and protect the coastal ecosystem. However, better management generates higher compliance costs for the world fleet and may have negative impacts on the ship operations, national economy, international trade, and shipping pattern. Therefore, cost-effective solutions are necessary.

This dissertation examines four issues in environmental policymaking to reduce negative impacts from international shipping: (1) the potential diversion pattern of containerships to trans-Arctic routes and the GHG emission reduction potential; (2) cost-effectiveness analysis of ballast water treatment strategies to achieve current IMO standards and potential regional stricter regulations; (3) potential impacts of ballast water management regulations on international trade, shipping pattern, and the global economy; and (4) risk-based policymaking to inform better protection from species

invasion. Independently, each of them addresses a key challenge in the environmental management of global shipping. Combined, these essays help develop a coupled human-natural system to cost-effectively move policymaking forward. This is within the consideration of the trade-off between shipping environmental performance and economic feasibility. We not only need the most stringent standards, but the standards should be achievable. We not only want to reduce the pollution from ships but need to maintain the normal operation of shipping activities to maintain the global trade and economic development.

1.2 Overview of Dissertation

This dissertation is composed of four independent but connected articles, aiming to propose cost-effective ways to inform the next step policymaking to reduce pollutions from international-going ships.

The first paper examines the potential diversion pattern of containerships to the trans-Arctic routes under climate change and the potential of those routes to reduce GHG emissions (Wang et al., 2020b). This modeling exercise uses a large dataset of historic shipping moves. This paper builds a time- and cost-based diversion feasibility framework and obtain the number and geographic pattern of diversions among all container moves in one year. This work then discusses the environmental impacts of trans-Arctic diversions based on the potential diversion pattern.

The second article examines the cost-effective strategies for the world fleet to comply with ballast water regulations, by considering both traditional vessel-based ballast water treatment methods and port-based alternatives (Wang and Corbett, 2020). Since the BWM Convention explicitly disavows preventing a State Party from taking more stringent measures and the United States (U.S.) is not a party to the BWM

Convention, the work includes a proposed regulatory scenario that the U.S. adopts a stringent regulation following California's interim numeric standards and all other countries follow the IMO standards. The work introduces the advantages of vessel- and barge-based treatment methods and proposes several strategic combinations of these two methods to achieve current and proposed policy scenarios. By establishing a compliance model, this work identifies cost-effective technological strategies to achieve the regulations.

The third article examines the potential impacts of ballast water regulations, including the impacts on international trade, shipping patterns of three vessel types, and national economies of the top 20 trade countries (Wang et al., 2020a). The work also includes two policy scenarios, but it does not predict future policies but propose scenarios to explore the viability to drive policies forward. The work establishes an integrated shipping cost and global economic modeling approach. The shipping cost model estimates changes in transport costs resulting from ballast regulation, which are employed as exogenous shocks to the marine transportation sector in the economic model to quantify changes in bilateral commodity trade and corresponding changes in national economies. Simulated changes in bilateral trade then serve as inputs for the shipping traffic accumulation model, which identifies potential changes in global shipping traffic. This work shows the potential negative impacts of ballast water management, which indirectly show the benefit of ballast management is much higher than the negative impacts.

The fourth article further moves policymaking forward with a risk-based method. The risk assessment model used is improved with higher-order-network (HON) by the coauthor. The risk assessment reveals that ballast water treatment can reduce the risks

of shipping moves and ports global, which informs that global regulation is needed. The risk assessment also shows that ballast water management can change the higher-order-network and the species flow cluster pattern, and stricter regulations further reduce the HON feature and reduce the inter-cluster species flow risk. Based on the risk assessment results, this work includes all 4257 ports in the world and includes 4257 regional stricter regulatory cases and performs cost-effectiveness towards different ballast treatment technological strategies. This work helps make policymaking risk-based and identifies the high-risk ports. This work further reveals a broadly applied technology selection for different policy scenarios.

This dissertation is composed of six chapters. Chapters 2, 3, 4, and 5 each address the above issues as stand-alone articles. The final chapter concludes the results and policy implications.

Chapter 2

CONTAINER VESSELS DIVERSION PATTERN TO TRANS-ARCTIC ROUTES AND GHG EMISSION ABATEMENT POTENTIAL[1]

2.1 Introduction

Global shipping patterns are widely used in the economic and environmental analysis (Corbett et al., 2010, Seebens et al., 2016, Lam and Yap, 2011). Due to climate change and ice retreat in the Arctic area, new trans-Arctic shipping routes are emerging and changing the global shipping pattern. New trans-Arctic routes seem promising with the support from related research in navigation risk assessment, technology development, geographical politics, and environmental impact analysis. Shipping companies could assign vessels to divert to trans-Arctic routes to pursue higher profits, enlarge the market share, or expand service (Beveridge et al., 2016, Lindstad et al., 2016, Furuichi and Otsuka, 2015).

Many studies have examined the economic feasibility of trans-Arctic routes with different conclusions. During 2006 to 2018, one article is about LNG vessel (Falck, 2012), one is about tanker (Juurmaa, 2006), two are about general cargo vessel (Lasserre and Pelletier, 2011, Wergeland and Østreng, 2013), three are about bulk vessel (Falck, 2012, Pruyn, 2016, Schøyen and Bråthen, 2011), and 17 are about

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container vessel (Arpiainen and Kiili, 2006, Juurmaa, 2006, Somanathan et al., 2007, Borgerson, 2008, Dvorak, 2009, Somanathan et al., 2009, Verny and Grigentin, 2009, Chernova and Volkov, 2010, Liu and Kronbak, 2010, Srinath, 2010, Xu et al., 2011, Wergeland and Østreng, 2013, Lasserre, 2014a, Furuichi and Otsuka, 2015, Zhao and Hu, 2016, Solakivi et al., 2017, Wan et al., 2018b). This work focuses on container vessels and finds that different results on the economic feasibility of container vessels: 9 articles show the trans-Arctic routes are profitable (Arpiainen and Kiili, 2006, Juurmaa, 2006, Borgerson, 2008, Srinath, 2010, Liu and Kronbak, 2010, Xu et al., 2011, Wergeland and Østreng, 2013, Furuichi and Otsuka, 2015, Zhao and Hu, 2016), 6 articles get unprofitable results (Somanathan et al., 2007, Somanathan et al., 2009, Verny and Grigentin, 2009, Dvorak, 2009, Chernova and Volkov, 2010, Solakivi et al., 2017), and 2 articles get varied conclusions (Lasserre, 2014a, Wan et al., 2018b).

This analysis of potential containership diversion through Arctic routes updates the contexts and approach used previously in two aspects. First, economic analyses depend on a complex set of variables and assumptions that may be different among studies. The case studies in the literature selected different routes with different origin and destination ports, and/or vessels in different sizes (i.e., different economies of scale). Indeed, the fleet of potential vessels for diversion to trans-Arctic routes across diverse port-pairs is heterogeneous. Second, some articles estimate profits based on a year-round operation while single voyage costs in other work do not consider route service time advantages. Typically, a vessel that completes more turnovers (round trips) can transport more cargo if sailing time is saved, which can generate more profit (Liu and Kronbak, 2010, Lasserre, 2014a, Furuichi and Otsuka, 2015, Wan et al., 2018b). These differences need to be considered in the cross-study comparison.

This work examines the general pattern of the global shipping traffic and identifies how many of them may make a feasible diversion to the Arctic and better understand the potential diversion of trans-Arctic routes. This modeling exercise uses a large dataset of historic shipping moves. This paper builds a time- and cost-based diversion feasibility framework and obtain the number and geographic pattern of diversions among all container moves in one year.

Based on the potential diversion pattern, this work further discusses the environmental impacts of trans-Arctic diversions. Even though a small number of shipping moves may divert, some of the diversions to the Arctic routes may contribute substantially to the GHG abatement goal of the shipping industry. This work focuses on the cost-effectiveness of abating GHG emissions and a brief exposition is included on emissions of Sulphur oxides (SOx,) Nitrogen oxides (NOx), Black Carbon (BC) and the reduction of ice cover.

2.2 Methods

This work firstly identifies the trans-Arctic diversion pattern by evaluating the saved time and saved cost from potential trans-Arctic routes—two defining characteristics that firms use when considering feasibility. Second, we identify the port pairs of these diverted voyage segments and establish the liner shipping bilateral connectivity index (LSBCIP) to compare the trade importance of those port pairs. Third, we compute GHG emission abatement potential with consideration of implied carbon pricing effects.

This analysis inserts no new assumptions about voyage strings or other structural realignments of shipping patterns and presumes trade and freight rates (i.e., revenues) would be unchanged. Complex shipping circuits are split into simpler vessel

moves. These simple vessel moves include direct port-to-port trade and transshipment traffic. Such a general routing study controlled to examine only the diversion segments for all containerships can provide insight into diversion potential and derived energy savings.

2.2.1 Studied Voyages, Shipping Routes, and Shipping Moves

In our study, we include all the voyages A-B, B-C, A-C, and A-B-C, if there are any of them (Figure 2.1), and our examined objects are shipping moves comprising a whole voyage., i.e. the shipping moves ‘a’, ‘b’, ‘c’, ‘x’, and ‘y’. For example: if shortcut ‘a’ through the Arctic is preferred, vessels along voyage A-B will use ‘a’ as a replacement of ‘b’, and all vessels along voyage A-B-C will go through ‘bc’, instead of ‘ac’. In this way, these vessels can still meet the demand of Port B and Port C. In other words, by focusing only on two-port origin-destination pairs of each shipping move, we compare whether the voyage between Port A and Port B would find some advantage in the potential diversion. While simplistic, this does not preclude or disrupt voyage between Port B and Port C. Port pairs A-B, B-C, and A-C are called shipping routes, and each route may be traveled for several times, generating several shipping moves.

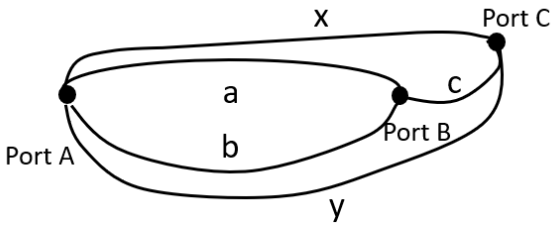

Figure 2.1 Shipping moves maintaining the many-to-many container network

In this construct, container demand at all ports in a string can be held constant (assumed to remain satisfied) even if potential trans-Arctic diversion routes between

Port A and Port B are equal to or less than the duration or cost of the default routes. Our study design maintains implicitly the many-to-many port network. By examining each origin-destination port pair for historical actual movements, we are not imposing any loss of container service to other ports in a string of origin-destination port pairs.

2.2.2 Solving for least shipping duration and least distance routing

Sailing time can be obtained with distance and speed estimations for conventional and trans-Arctic routes. Distances derive from a GIS-based modeling approach that solves multiple port pair routes using our geospatial waterway network. What we identify as the Universal Marine Transportation Model (UMTM) is a high-resolution navigable ocean network model laying over the entire globe, built from a web of lines representing potential marine travel paths, incorporating necessary navigable global rivers and lakes. The network model establishes nodes for identified shipping ports to provide waterborne connectivity. Every potential intersection point on UMTM can be accessed during a shipping move; this provides robust replication of voyage distances. The UMTM can be adjusted to present different shipping lane scenarios by imposing route barriers prohibiting or restricting movements, to show the impact of sea-ice, weather events, war and pirate zones, canals, and policy requirements. A key feature of the UMTM is that we can design scenarios that could include new or emerging port pairs for scenario analyses.

For the non-navigable/navigable Arctic scenarios in this work, UMTM can present the potential trans-Arctic distances by putting/removing a barrier in the Arctic area. See Figure A1 and Figure A2 in Appendix A.1. When calculating the distance, we add the port nodes with port coordinates and link the port nodes with the nearest points on the UMTM network. With the vessel move data (providing origin and

destination port coordinates), the model can record the distance and direction of each line segment and report the shortest paths for conventional and trans-Arctic routes. The UMTM works well for a set of moves at one time to get the distance changes and visualize the global shipping patterns. We apply UMTM using the shortest distance optimization. Sailing speeds of conventional routes are assigned according to container vessel size, and the data are from the 3rd IMO GHG Study (The IMO, 2014). The sailing speed of Arctic routes is slower than conventional routes. We assume the average speed in the whole trans-Arctic route is 90% of the speed in conventional routes. This average speed is determined by the speed in conventional routes, speed in the Arctic area (under ice or severe weather condition), and the proportion of distance of the Arctic area of the whole trans-Arctic routes. For example, if we pick the conventional speed of 20 knots for container speeds (Lasserre, 2014a), vary the Arctic distance portion from 0 to 50%, and vary the Arctic area speed from 12 knots to 18 knots. We found the average speed of all scenarios is about 90% of conventional routes, with a range of 80% - 99%.

2.2.3 Solving for least cost routing

The total shipping cost for a shipping move between two ports is calculated with daily shipping cost and sailing time. Sailing time can be obtained from Section 2.2. Daily shipping costs are calculated with our Container Shipping Cost Model (CSCM). CSCM contains two separate calculations and can return the daily costs for conventional and Arctic routes, respectively. The calculations share a similar shipping cost composition: capital, operating, fuel, canal/ice-breaker fee, and port cost (Stopford, 2009). The application of CSCM does not include port charges, maintenance, diesel oil, and lubricating oil costs because we assume they are common

– i.e., these charges do not change with diversion routes for the same origins and destinations (Zhao and Hu, 2016).

We select the least cost route among all alternative routes. Cost is the determinant for route selection because revenue per TEU and trade are assumed to be the same for both routes without considering customer preferences for saved transportation time (Lasserre, 2016). To obtain potential container vessel diversion patterns and shipping traffic, we apply CSCM to all shipping moves in the year 2012-2013.

The least costly routes are not always the shortest routes, particularly for Arctic shipping. Ice conditions and ice-safe voyages in the Arctic area and other characteristics result in different cost components for conventional routes and trans-Arctic routes, shown in Table 2.1. The detailed technical discussion of CSCM is in Appendix A.2 and A.3, including the data source, estimation method, and the validation for each cost component in Table 2.1. In our scenarios, the Arctic area is assumed to be navigable in all seasons. Ice-breaker escort is necessary at all times for safety consideration, and the ice-breaker fee applies to all Arctic navigations. Vessels are strengthened for Arctic navigation with extra capital and operating cost, according to regulations of the International Code for Ships Operating in Polar Waters (Polar Code).

Table 2.1 Container shipping cost modeling for conventional and trans-Arctic routes

Cost component	Conventional routes	Trans-Arctic routes
Capital cost	Base daily cost	Base cost + premium cost for ice-classed vessels
Operating cost	Base daily cost	Base cost + premium cost for more labors and insurance

Fuel cost	Base daily cost = Daily fuel oil consumption*fuel price	Adjustment for daily fuel consumption due to increased SFOC and decreased sailing speed. Higher fuel price for low freezing point fuel oil
Others	Panama/Suez Canal toll	Ice-breaker fee

We further include the social cost of carbon (SCC) in the shipping cost. The SCC is the marginal cost to society of carbon dioxide emissions, which is about \$50/MT CO_2 (IWG, 2010). We include an SCC of \$125/MT CO_2 to represent a high impact.

2.2.4 The Liner Shipping Bilateral Connectivity Index

Sections 2.2.2 and 2.2.3 identify the port pairs between which the vessels may divert to the trans-Arctic route. Here we establish the liner shipping bilateral connectivity index between ports (LSBCIP) to compare the trade importance of those port pairs and identify the port pairs mostly impacted by the diversions.

UNCTAD has several maritime transport indicators to describe connectivity, and the most relative two to LSBCIP established in this work are country-level bilateral shipping index and port connectivity index. Neither of them is bilateral connectivity between ports. We follow the method of country-level liner shipping bilateral connectivity (UNCTAD, 2019) and adapt the components to calculate the port level connectivity. LSBCIP includes four components: (1) The number of moves between port pairs. All the moves between port pairs are direct moves, so the number of moves in the article includes both direct trade between single-move voyage and trade between multi-moves voyages. Each shipping move adds one more option to multi-moves/single-move voyages. The more moves mean the better connection of two ports and more total trade with each other; (2) The number of vessels operating

between port pairs. We use this number to represent the competition level. The higher competition level is an incentive for vessels to decrease the transportation costs and increase the trade (Fugazza and Hoffmann, 2017); (3) Total TEU capacity between port pairs. It represents the infrastructure of the shipping route between port pairs; (4) The size of the largest vessel operating between port pairs. It can represent both infrastructure and the economics of scale of shipping routes. LSBCIP is obtained by averaging these four components after they are normalized to be index unit free (UNCTAD STAT).

2.2.5 Cost-effectiveness Analysis of GHG Emission Abatement with Potential Emission Trading System

IMO aims to reduce total annual GHG emissions by at least 50% by 2050 compared to 2008 (MEPC, 72nd Session, 9-13 April 2018). The study of the cost-effectiveness of GHG emission abatement can reveal the potential contribution of trans-Arctic diversion to the IMO goal. Also, the potential for trans-Arctic routes to reduce energy use and GHG emissions could make the route diversion more attractive.

This section considers primary gaseous pollutants: CO_2, CH_4, and N_2O. GHG emissions can be estimated with fuel consumption and emission factors. GHG emissions then are converted to CO_2-equivalent (CO_2e) with the Global Warming Potential (GWP). GWP is used to compare components with differing physical properties using a single metric (IPCC, 2014). The 100-year GWP (GWP100) was adopted by the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol and is now used widely as the default metric.

Will an Emission Trading System increase the cost-effectiveness of GHG emission abatement? In an ETS market, a shipping company seeks to minimize its

compliance costs and abates its emissions until its marginal cost equals the market price of an allowance. Even though shipping is not included in any trading system, for now, the largest carbon market, European ETS, will move to include shipping from 2023 if IMO progress is considered insufficient (Revision of the EU ETS 2021-2030, EU). We assume the European ETS applies to the shipping industry.

If the marginal abatement cost of a shipping move is lower than the highest market carbon price, voyages containing this shipping move would be likely to make a diversion to trans-Arctic routes and sell the abatement credits to the market. The market price in ETS changes over time, and we use the data from the World Bank Group for illustration in this study. The ETS prices for 19 jurisdictions vary from \$1/MT CO_2e to \$25/MT CO_2e on April 1, 2019 (World Bank Group, 2019). The highest market price is \$25/MT CO_2e of EU, so all shipping moves with a marginal cost of less than \$25/MT CO_2e can trade in the market and be cost-effective to reduce GHG emission.

2.2.6 Data

The vessel moves, vessel specifications, and port information are from 2012-2013 Lloyds moves dataset (Lloyds Maritime Information System, 2013). It includes all shipping routes with port pair names provided. A separate Lloyds places dataset provides port coordinates. Records for containerships that year include 18,766 unique routes/port pairs and 522,691 unique shipping moves with identified origin and destination ports. All cost data used are from recent years or are adjusted to be consistent with the current condition.

Emission factors of different GHGs are from the Third IMO GHG Study (The IMO, 2014). To comply with the 2020 Sulphur limits, the most popular options are

using Scrubber and high sulphur fuel oil (HSFO) and low sulphur fuel oil (LSFO). The emission factors for CO_2, CH_4, N_2O of LSFO and HSFO are the same: 3.114, 0.00006, and 0.00016 g/g fuel (The IMO, 2014). In Arctic navigation, the Canadian Coast Guard also requires Naval Distillate Fuel (NDF) or P50 (Lasserre, 2014a). NDF is a kind of distillate fuel, which is most similar to Diesel oil included in the classification in the Third IMO GHG study, so we use Diesel oil to estimate carbon emission factors for low freezing point fuel oil used in the Arctic area. The emission factors for CO_2, CH_4, N_2O of Diesel Oil are 3.206, 0.00006, 0.00015 g/g fuel.

GWP values have been updated in successive IPCC reports, and this work uses the latest GWP100 values from the IPCC Fifth Assessment Report (1 g CO_2=1 g CO_2e; 1 g CH_4=28 g CO_2e; and 1 g N_2O=265 g CO_2e) (IPCC, 2014).

2.3 Results

2.3.1 The Shipping Diversion Pattern to the Trans-Arctic Routes

We identify the number of diversions and the shipping pattern to the trans-Arctic routes with UMTM and CSCM. Figures 2.2 and 2.3 illustrate the ports distribution and the density of potential diverted trips to trans-Arctic routes. Fewer trips will divert to the Arctic when considering shipping costs, and the port pairs are more concentrated in North America, Europe, and East Asia.

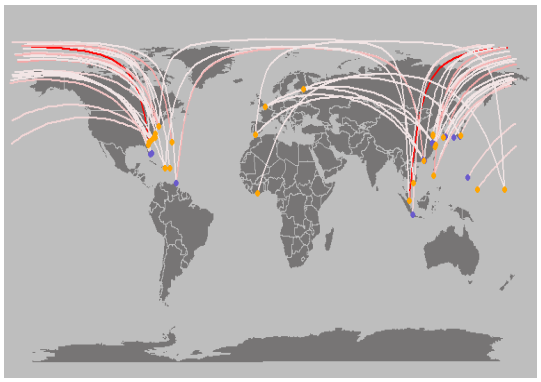

Figure 2.2 Ports distribution for 83 shipping moves with UMTM

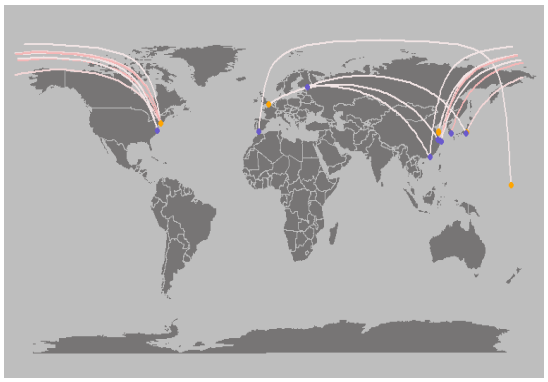

Figure 2.3 Port distribution for 20 shipping moves with CSCM

The number of trans-Arctic diversions is small: 83 moves reduce distances through the Arctic. They reduce by 0.8% to 42.5% compared to conventional routes, and 38 moves only reduce the distance by less than 10%. By applying vessel speeds typical of containership design and sailing route (ice-navigation speeds for trans-Arctic segments), we find 45 can save sailing time. It is 0.01% of the total trips. These 45 shipping moves can save 3 days on average, which is about 10% of the total duration of a trip. See Figures 2.4 and 2.5.

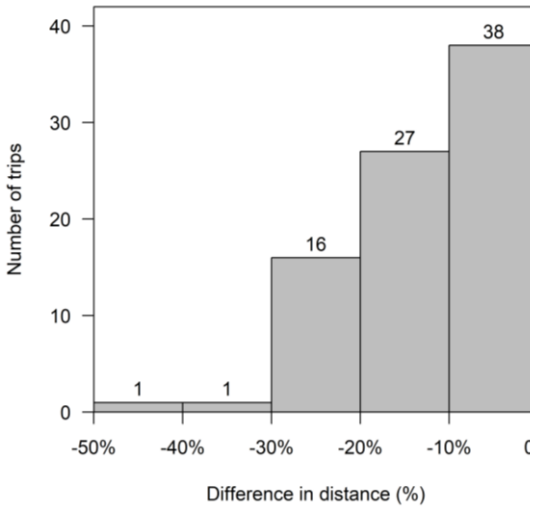

Figure 2.4 83 shipping moves save distance through trans-Arctic route

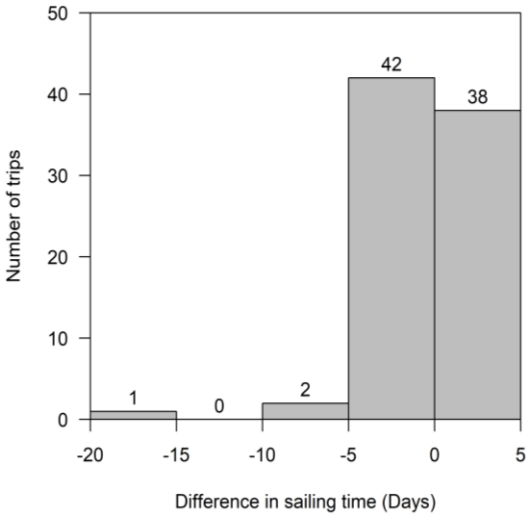

Figure 2.5 45 shipping moves save duration through trans-Arctic route

The diversion number decreases to 20 moves when considering shipping costs. The cost difference is positively related to the distance difference. With more distance reduced through the Arctic, the shipping moves tend to reduce more cost (Figure 2.6). The shipping cost will go down if the distance reduction through the Arctic is greater than 20%.

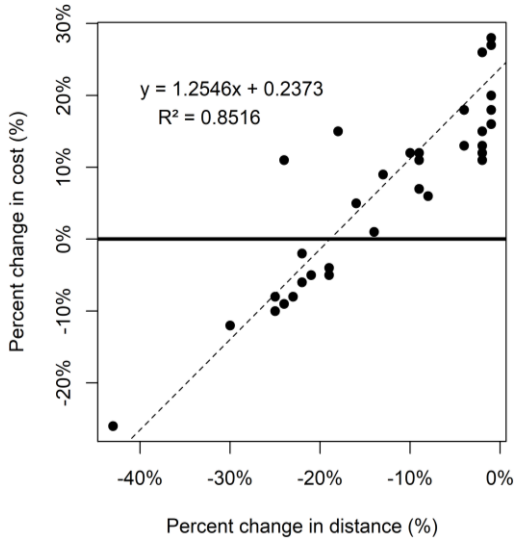

Figure 2.6 Cost saving is positively related to distance saving through Arctic

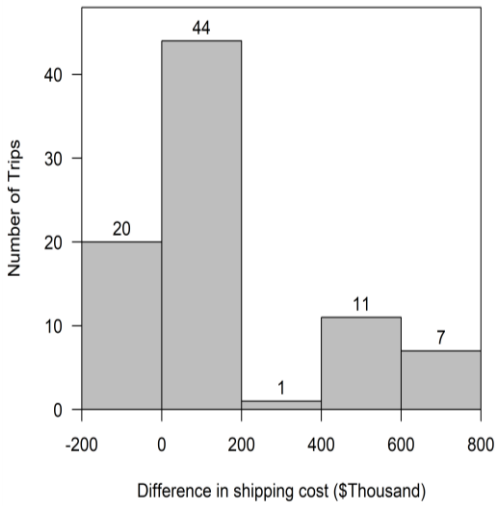

Figure 2.7 20 shipping moves can save costs of the 83 moves saving distance

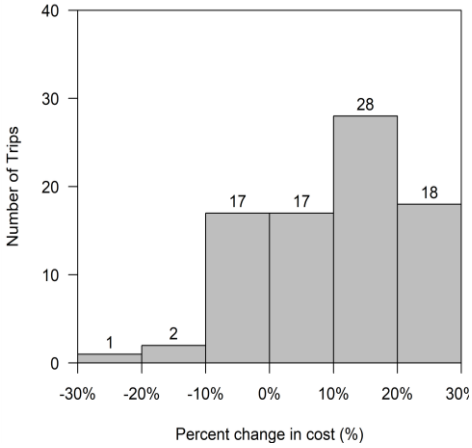

Figure 2.8 Percentage change in shipping costs

Figures 2.7 and 2.8 illustrates the cost differences for those 83 moves, of which 20 moves can save shipping cost by diverting. In contrast, most of the trans-Arctic shipping routes may increase the shipping cost, and about one-fifth of shipping moves would witness increases in shipping costs of more than $400,000—a 28% increase compared to conventional routes. This shows the small economic diversion potential of the trans-Arctic routes. In Figure 2.7, the range [200, 400] has the minimum number of shipping moves. For the shipping moves falling in ranges [-200, 400], vessels' TEUs are between several thousand to 50,000, and the TEUs jump to more than 100,000 for the moves falling in ranges [200, 800]. This makes the shipping costs jump from about $750,000 to $1,970,000. Therefore, the cost reductions jump directly from less than $170,000 to over $500,000 unless one shipping move, which falls in the range [200, 400].

Considering SCC in the shipping cost, the diversion number with reduced cost becomes 21 when the SCC is $50 ~ $117/MT CO_2 and 33 when the SCC is $118~ $180/MT CO_2.

2.3.2 Shipping Routes and Port Pairs

This section shows the port pairs of the revealed diverted trips. To compare the trade importance of those port pairs and identify the port pairs that are most impacted by the diversions, we calculate their LSBCIP and rank the shipping routes (port pairs) by the LSBCIP.

Table 2.2 lists the port pairs and origin and destination countries of the shipping routes with short distance through the Arctic. The 83 shipping moves saving distance through the Arctic are among 36 shipping routes. They are marked with 'Yes' in columns 5 and 6 if they also can save sailing time or shipping cost, respectively.

Among them, 45 shipping moves can save sailing time and they are comprised of 19 unique shipping routes. The 20 shipping moves saving shipping costs are comprised of 12 unique shipping routes and they all save sailing time.

Table 2.2 Port pairs for shipping moves saving distance sailing through the Arctic

Shipping routes/Port pairs		Country[1]		Save sailing time	Save shipping cost	Liner shipping bilateral connectivity between port pair
Origin port	Destination port	Origin (UN code)	Destination (UN code)			
Savannah	Tanjung Pelepas	USA	MYS			1.00
Busan	New York	KOR	USA	Yes	Yes	0.38
Yangshan	New York	CHN	USA	Yes	Yes	0.33
Nansha	Dover Strait	CHN	GBR	Yes		0.27
Tanjung Pelepas	New York	MYS	USA			0.26
Charleston	Tanjung Pelepas	USA	MYS			0.25
Port of Spain	Mawan	TTO	CHN			0.22
Shanghai	New York	CHN	USA	Yes	Yes	0.21
Yokohama	New York	JPN	USA	Yes	Yes	0.18
Norfolk	Qianwan	USA	CHN	Yes	Yes	0.16
Chaguaramas Anch.	Mawan	TTO	CHN			0.13
Miami	Yangshan	USA	CHN			0.12
Bermuda	Manila	BMU	PHL	Yes		0.12
Yangshan	Norfolk	CHN	USA	Yes	Yes	0.12
Port of Spain	Yangshan	TTO	CHN			0.11
Norfolk	Qingdao	USA	CHN	Yes	Yes	0.11
Hong Kong	New York	CHN	USA	Yes	Yes	0.11
Ciwandan	Morehead City	IDN	USA			0.11
Busan	Savannah	KOR	USA	Yes		0.09
Yangshan	Algeciras	CHN	ESP			0.08
Manila	Bermuda	PHL	BMU	Yes		0.07
Manila	Fernandina	PHL	USA	Yes		0.07
Algeciras	Majuro Atoll	ESP	MHL	Yes	Yes	0.07
Majuro Atoll	Abidjan	MHL	CIV			0.07
Shanghai	San Juan	CHN	PRI			0.07
Caucedo	Ho Chi Minh City	DOM	VNM			0.05
Caucedo	Ningbo	DOM	CHN			0.05
Kobe	Caucedo	JPN	DOM			0.05
Changzhou	Dover Strait	CHN	GBR	Yes	Yes	0.05
Freeport	Gwangyang	BHS	KOR			0.04
Fernandina	Manila	USA	PHL	Yes		0.03
Guam	Wilmington	GUM	USA			0.03
Wilmington	Chuuk Islands	USA	FSM			0.03
Hong Kong	Vysotsk	CHN	RUS	Yes	Yes	0.02
Vysotsk	Tokyo	RUS	JPN	Yes	Yes	0.02

Shipping routes/Port pairs		Country[1]		Save sailing time	Save shipping cost	Liner shipping bilateral connectivity between port pair
Origin port	Destination port	Origin (UN code)	Destination (UN code)			
Manila	Charleston	PHL	USA	Yes		0.00

1: UN country codes use ISO 3166-1 alpha-3 format (https://unstats.un.org/unsd/tradekb/Knowledgebase/50347/Country-Code).

The shipping route of Savannah-Tanjung Pelepas is the most important in bilateral trade (LSBCIP=1.00; see Table 2.2), but it may not be largely impacted by the new trans-Arctic routes because it cannot save sailing time or shipping cost. On contrast, the shipping route of Busan-New York may be largely impacted due to its trans-Arctic diversion potential and it has the highest LSBCIP other than Savannah-Tanjung Pelepas.

2.3.3 Fuel Consumption, GHG Emission Abatement, and potential ETS credits

This section reveals the fuel consumption and GHG emission abatement potential of the possible trans-Arctic diversion shipping moves. All the 20 moves with reduced shipping costs can reduce fuel consumption and CO_2e emission. Their average reduction of fuel consumption through the Arctic is 264 MT (reduced by 26 %). The range is 125 - 328 MT (21% - 44%). The average CO_2e emission is 767 MT (reduced by 24%). The range is 359 - 954 MT (19% - 43%) due to speed reduction and different fuels used in the Arctic area. The CO_2e emission from the 20 moves is 50,157 MT.

ETS may make more shipping moves become cost-effective if shipping moves can sell the CO_2e emission reduction to make a profit. We further analyze the 83 moves with reduced distance. The CO_2e emission reduction marginal costs of all the 83 moves with shorter distance vary from -$218/MT CO_2e to $8566/MT CO_2e. See Figure 2.9. The positive marginal costs mean that the diversion to the trans-Arctic

route costs more than conventional routes when reducing GHG emissions. 63 moves are with positive marginal costs, meaning the increased shipping costs to reduce GHG emissions. 20 shipping moves can reduce shipping costs and GHG emissions at the same time.

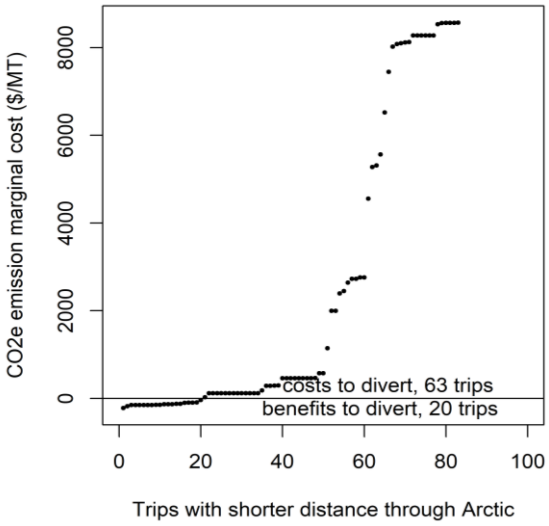

Figure 2.9 GHG emission marginal cost for 83 diversion

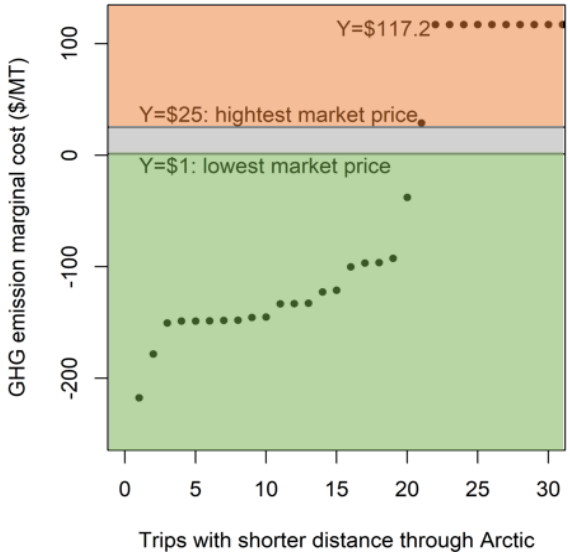

Figure 2.10 Zoom in (emission marginal cost less than $100/MT)

In ETS, if the shipping moves can reduce GHG emission abatement at a marginal cost less than the highest market price, they can find at least one market to sell the reduced GHG emission and make profits. However, if the marginal cost of GHG emission abatement is higher than the highest market price, even though the shipping moves can sell all the reduced GHG emissions at the market with the highest price, the shipping moves cannot cover the cost through the ETS ($25/MT CO_2e). Therefore, under ETS, the threshold line is not when GHG emission marginal cost is 0, but when the marginal cost equals the highest market price. In Figure 2.10, the shipping moves in the yellow shadow have marginal costs higher than the highest

market price (‘positive’ marginal cost), so they cost more to reduce GHG by diverting to the trans-Arctic route. There are 20 shipping moves below the highest market price (‘negative’ marginal cost), in the green and grey shadow, and they are cost-effective with the ETS. Since these 20 moves are all below the lowest market price (in the green), the GHG emission abatement from these shipping moves can be traded in any market, even at the lowest market price of \$1/MT CO_2e in Shenzhen and Chongqing, China. The shipping moves in the grey shadow means the increased number of shipping moves becomes cost-effective through the Arctic due to ETS. In this case, no move is added. We can see no move will be added even the highest market price goes up to \$117.

Most of the shipping moves are between ports in Asia, North America, and Europe. The shipping moves from Yangshan to New York, and from Busan to New York are best fits for GHG emission trading. The traffic between these port pairs might increase because shipping companies may allocate the shipping moves operating between these port pairs to trans-Arctic routes to abate GHG emission cost-effectively and contribute to 50% GHG emission reduction goal of IMO.

2.3.4 Sensitivity Analysis of Variable Values on the Diversion Pattern

Uncertainties may exist in the value of variables used in CSCM. To reveal a robust analysis, we apply sensitivity analysis to common variables and find the number of diverted trips fluctuate between 1 and 46. See Table 2.3. The sensitivity analysis confirms the small number of diversions to the trans-Arctic routes. Especially, we vary fuel price from \$188/MT to \$966/MT (the lowest and highest price for marine fuel oil and marine gas oil [MGO] from March 2009 to Dec 2017). This price range

allows for the expectation that cleaner fuels under MARPOL VI Sulphur limits in 2020.

Table 2.3 Sensitivity analysis of common variables

Variable	Range	Number of diverted shipping moves
Vessel operation period per year	16 years ~ 24 years	From 20 to 21
Down payment	80%*ship price ~ 120 % *ship price	From 20 to 21
Financing maturity	12 years ~ 16 years	From 20 to 21
The operating cost	3%*capital cost ~ 10%*capital cost	No change
Fuel price	$188/MT ~ $966/MT	From 21 to 20
Ballast and laden ratio	90% ~ 60 %	No change

Due to the special nature of the Arctic, capital cost, operation cost, and fuel consumption in the estimation for trans-Arctic shipping cost could be different. The sensitivity analysis in Table 2.4 reveals the impact of these variables. The results show that the ice-breaker fee, sea speed, and capital cost of Arctic sailing have greater influences on the diversion number as they highly rely on the ice condition. The ice-breaker fee has the largest effect. When an ice-breaker is not required, the ice-breaker cost would be 0 and the diversion number would rise to 46 moves. However, if the ice-breaker fee is as high as $15/GT, most trips will not divert to the Arctic.

Table 2.4 Sensitivity analysis of variables in trans-Arctic routes

Variable	Range	Number of diverted shipping moves
Capital cost change	100% ~ 120%	From 35 to 20
Operating cost change	100% ~ 120%	From 21 to 20
SFOC change	100% ~ 120%	From 21 to 20
Sailing speed change	100% ~ 80%	From 3 to 36
Ice-breaker fee	0 ~ $15/GT	From 46 to 1

The increased traffic through the Arctic will in itself contribute to the more rapid melting of the sea ice. When all ice in the Arctic is melt, the capital cost and operating cost will not increase, no ice-breaker is needed, and the sailing speed may

achieve the same to conventional routes. In this situation, all 83 shipping moves with reduced sailing distance can save shipping cost through the Arctic.

The route diversion will increase the emissions to the new area (Wang and Peng, 2019). The number of diversion routes depends on the fuel price with respect to the emission charge. We also test the emission in the Arctic against the percentage change of the fuel price. When the fuel price is 50% of the current price, the diversion number becomes 21, and the CO_2e emission to the Arctic increases to 52,400 MT. When the fuel price fluctuates between 75% to 300% of the current price, the diversion number and CO_2e emission to the Arctic maintain the same. An emission charge will increase the fuel price, meaning the emission charge will not change the emission to the Arctic.

2.4 Discussion

With generally applied sailing time and shipping cost methods to evaluate trans-Arctic diversion for single vessel moves between port pairs, our results identify a small diversion potential of containerships. Our interest here is to identify feasible route diversions for a given market demand among ports and holding freight rate constant; in this regard, these results inform the necessary and evolving firm-level analyses for maximizing profit.

Our work performs well in examining the general diversion pattern to the Arctic, though we simply assume the Arctic routes can be navigable at all seasons with ice-breakers, without detailed modeling on the relationship of ice and speed, or ice and cost. The sensitivity analysis of 'no ice-breaker' and 'no premium for capital and operating cost' represents the open water scenario of the Arctic. Even though the weather condition in the Arctic is as good as conventional routes in our work, the

largest diversion number is 83, which is the number of shipping moves that can reduce distance. Other more severe conditions will make the diversion number smaller. Our models will benefit from more detailed modeling on the relationship of climate-ice-speed in the Arctic (Melia et al., 2016).

The sailing time and shipping costs are compared for single moves without consideration of year-round turnover times. We recognize that the single moves may be part of more complex voyage circuits or strings, and the shipping lines might generate positive profit with year-round profit analysis. However, the more turnover times of a voyage can only be achieved by saving sailing time, and our results indicate 45 shipping moves can save sailing time. Hence, even though year-round profit analysis is done for all the 522,691 moves, 45 moves at most will gain profit. This proves the time- and cost-based methods in the work are reasonable and the diversion results are robust.

The diversion pattern is impacted by vessel size and age. These remind shipping companies to consider vessel specifications when allocating new vessels to achieve cost-saving and GHG emission abatement. For example, vessels in different sizes may benefit from the shorter distance through the Arctic, while the very small or very large vessels may not save shipping cost through the Arctic. The diverted vessels obtained with UMTM are from 300 to 8000 TEUs, and vessels obtained with CSCM are from 900 to 5000 TEUs. This is because the shipping costs of very small vessels are impacted most by the ice-breaker fee, which would increase their unit costs; and the very large vessels would have very high capital cost adjustment for Arctic navigation. In terms of vessel age, the diverted vessels identified with UMTM are as old as 40 years, and the oldest vessel identified with CSCM as 18 years old. Hence,

older vessels may save distance via the trans-Arctic routes, while they cannot save shipping cost.

The diversion pattern also informs related authorities to respond to the new trans-Arctic routes. For example, the sensitivity analysis implies that most shipping moves will not divert with an ice-breaker fee of $15/GT, so the Northern Sea Route Administration of Russia needs to set the ice-breaker fee carefully so that they can maximize the profit by balancing the shipping traffic and ice-breaker fee. This is important because trans-Arctic navigation will likely require ice-class vessels and some ice-breaking escort for decades. The situation is the same for the Panama Canal Authority. More shipping moves make a diversion from the Panama Canal than the Suez Canal. Among the 83 moves diverting to the trans-Arctic route with UMTM, 58 shipping moves are transferred from Panama Canal and 25 moves are from Suez Canal. Among the 20 moves diverting to the trans-Arctic route with CSCM, 17 shipping moves are from Panama Canal and 3 are from Suez Canal. That is, with UMTM and CSCM, 70% and 85%, respectively, of the total diversion shipping moves are from Panama Canal, with the caveat that the data are from pre-Panama Canal expansion. The new toll system after the Canal's expansion would cause more traffic to divert.

Even though this work does not consider the demand and trade dynamics, the benefits of reduced shipping cost, fuel consumption, and GHG emission may attract shipping companies to assign more vessels and shipping moves to the trans-Arctic routes. Those port pairs with larger connectivity tend to attract new traffic, such as Busan-New York and Yangshan-New York. Thus, these port pairs with higher LSBCIP would benefit most from trans-Arctic routes and may wish to develop port

services applicable to potential trade increases. For those ports with lower LSBCIP, i.e., with fewer current trade, the authorities of the ports could consider making use of the opportunity brought by trans-Arctic routes to promote their status in the liner shipping network, such as providing low freezing point fuel oil used in the Arctic sailing to attract shipping traffic. This strategy could also be used by the ports located along the trans-Arctic routes but not called by vessels for now.

The identified diversion pattern to the new trans-Arctic shipping pattern is important to the following risk analysis of the vessel-borne pollutants. (1) Diminishing sea ice has had a leading role in recent Arctic temperature amplification (Screen and Simmonds, 2010), and the ice surface can be physically reduced by the use of icebreakers. An icebreaker would open an area of water 10 km^2 over the entire Arctic cruise in summer (National Snow and Ice Data Center, 2012, Meier, 2020). This work shows 20 shipping moves may divert to the Arctic, which means no more than 200 km^2 of ice will be reduced each summer. This is a small impact on the ice cover decrease compared to over 9 million km^2 each year during its summer season. As to impacts upon the surrounding ice, icebreakers create very little direct disturbance to the sea ice outside of their immediate path (Mahoney, 2020a), including drifting pack ice and landfast ice (Hotzel and Noble, 1979, Cornett, 1982). The reduction in ice strength would only be temporary and ultimately the ice would become thicker and stronger (Cornett, 1982). Thus, icebreaker activity will only have negligible effects, if any, upon the sea ice (Mahoney, 2020b, Mahoney, 2020a). (2) SOx emission reduction removes their cooling effect and, thus, accelerates the effects of Climate Change (Lindstad and Eskeland, 2016). The energy-based emission factors (in g kW^{-1} h) for LSFO and MGO are 2.4 and 0.48 g kW-1h, and SFOC is 250 g kW^{-1} h (Sofiev et al.,

2018). The energy-based emission factor can be converted into fuel-based, and the fuel-based emission factors for LSFO and MGO are 0.0096 and 0.0019 g/g fuel. The average SOx emission of 20 diverted shipping moves decreases from 10 to 1.5 MT (by 85%). (3) The emission factors of HSFO and MGO in 2030 are 0.083 and 0.088 g/g fuel (The IMO, 2014). The average NOx emission of diverted shipping moves decreases from 86 to 59 MT (by 31%). (4) Black Carbon (BC) can significantly affect the Arctic climate because of its strong effect on reducing snow albedo (Zhang et al., 2019). We assume the emission factor of BC is 0.00035 g/g fuel for both conventional and the Arctic shipping (Comer et al., 2017, Corbett et al., 2010, Mjelde et al., 2014) and the GWP 100 of BC is 910 (Bond et al., 2013). The average BC emission of diverted shipping moves decreases from 0.36 to 0.27 MT (by 25%), and the average CO_2e of BC emission changes from 330 to 246 MT (by 25%).

2.5 Conclusion

We predict the potential shipping traffic to trans-Arctic routes with a general least shipping duration method and least shipping cost method. Our paper adds to a growing body of evidence that the Arctic through-routes offer a limited attraction for diversion of current trade patterns. Based on the revealed diversion pattern, we also find the substantial GHG emission abatement potential of the trans-Arctic routes. We do not model shared economics of a string of containership moves. Our study design doesn't, for example, examine the likelihood of latent demand that could emerge among new ports connected in trans-Arctic strings of shipping moves. Therefore, this study may conservatively estimate diversion potential for emerging port strings that could be served by trans-Arctic diversion routes. The potential trade change can be examined with a general equilibrium model or a discrete choice model in future work.

Chapter 3

SCENARIO-BASED COST-EFFECTIVENESS ANALYSIS OF BALLAST WATER TREATMENT STRATEGIES[2]

3.1 Introduction

Water was first used as ballast to maintain stability in navigation in the 19th century due to the invention of ballast tanks (Davidson et al., 2018), as a replacement for dry materials such as stones and sand. Water as ballast is free, abundant and can be easily handled by pumps among different tanks, compared to dry materials. However, ballast water is a major introduction vector of nonindigenous species and diseases (Carlton, 1985, Drake et al., 2007), which may have negative impacts on health, biodiversity, and economics (Pimentel et al., 2005, Lodge et al., 2006, Ruiz et al., 2000, McGeoch et al., 2010, Wan et al., 2016). Regulations and technologies are available to reduce the invasion risk caused by ballast water discharge.

3.1.1 Regulations towards ballast water discharge

The concern regarding invasive species is manifest in legislative instruments at different levels (Pam et al., 2013). The International Maritime Organization (IMO) primarily regulates ballast water management (BWM) at the international level and adopted the International Convention on the Control and Management of Ship's Ballast Water and Sediments (BWM Convention) in 2004. The BWM Convention

[2] Published with open access: Zhaojun Wang, James J. Corbett*, Scenario-based cost-effectiveness analysis of ballast water treatment strategies. Management of Biological Invasions. 2020, 11.

came into force on September 8, 2017. As of January 2020, 81 states had ratified the Convention, accounting for 80.76% of the world tonnage (The IMO, 2020). The BWM Convention includes two discharge standards: Ballast Water Exchange (D-1 Standard) and Ballast Water Performance Standard (D-2 Standard). D-1 Standard requires ships to exchange at least 95% of the ballast water within open ocean areas, and D-2 Standard specifies the maximum amounts of viable organisms allowed to be discharged, including specified indicator microbes harmful to human health.

Some regions have voluntary requirements, such as Mediterranean Sea (Regional Marine Pollution Emergency Response Centre for the Mediterranean Sea), North-East Atlantic and the Baltic Sea (OSPAR and Helsinki Convention members), and the Antarctic; some regions have mandatory requirements, such as Persian Gulf (Regional Organization for the Protection of the Marine Environment) and North Sea (Lloyd's Register, 2016). Article 196 of United Nations Convention on the Law of the Sea (UNCLOS) addresses the obligations of states concerning the implementation of all measures necessary for the prevention, reduction, and control of environmental pollution from intentional and unintentional introductions of alien and new species which may lead to harmful changes (UNCLOS, 1982, David et al., 2015).

Nationally, individual states also may establish regulations. The BWM Convention explicitly disavows preventing a State Party from taking, individually or jointly with other State Parties, more stringent measures with respect to the prevention, reduction or elimination of the transfer of Harmful Aquatic Organisms and Pathogens through ships' Ballast Water and Sediments, consistent with international law (The IMO, 2004). Parties may also, consistent with international law, require ships to meet a specified standard or requirement for certain areas if necessary (The IMO, 2004).

The United States (U.S.) is not a party to the BWM Convention. Ballast water discharge was historically regulated by two authorities in the U.S. - the Coast Guard (USCG) under CFR 151, and the Environment Protection Agency (EPA) by 2013 Vessel General Permit (VGP). On December 4, 2018, the Vessel Incidental Discharge Act of 2018 (VIDA 2018) was signed into law establishing uniform national standards and requirements (Title IX of Frank LoBiondo Coast Guard Authorization Act of 2018). VIDA requires EPA to develop new national standards of performance for commercial vessel incidental discharges (including ballast water) and the USCG to develop corresponding implementing regulations. The existing 2013 VGP remains in full force and effect beyond its expiration date until such time that the EPA and the Coast Guard finalize and implement the new regulations that VIDA requires. VIDA preempts individual U.S. states from setting new standards other than those contained in national regulations, but it gives them the right to work together to develop a regional Great Lakes basin standard. In addition, the current standards of individual states will be valid until a new, region-wide standard for ballast water is fully implemented (MEP, 2018). For example, California's interim and final performance standards, scheduled to be implemented by Jan 1st, 2030, and by Jan 1st, 2040, with different standards for organisms in different sizes, are stricter than the federal regulations (State of California, 2020).

3.1.2 Ballast water treatment technologies

The BWM Convention requires all vessels to conform to the D-2 Standards by September 8, 2024. The D-2 standard involves installing a ballast water treatment system (BWTS). BWTS used to comply with the Convention must be type-approved by or on behalf of a Flag State Administration taking into account the Guidelines for

approval of ballast water management systems (G8) (The IMO, 2004). Even though some claim that nearly all of the tests conducted for compliance with the microbe standards have been defective(Cohen and Dobbs, 2015), or some BWTS may fail to achieve the standards under certain conditions (Jing et al., 2012), approved BWTSs are the only choice for the shipping industry. BWTS may employ different treatment methods, including mechanical, physical, and chemical treatment (Tsolaki and Diamadopoulos, 2010, Karahalios, 2017).

The USCG has different type approval requirements than the BWM Convention; 25 BWTS are approved by Marine Safety Center and 16 more were under review as of January 29, 2020 (U.S. Coast Guard, 2020a). The USCG also approved 123 Alternative Management Systems (AMS) as of January 29, 2020 (U.S. Coast Guard, 2020b).

Besides shipboard BWTS, port reception facilities are considered as an alternative, as stated in Regulation B-3.6 of BWM Convention and Guidelines for ballast water reception facilities (G5) (resolution MEPC.153(55)) (The IMO, 2006, David et al., 2015). Port-based treatment facilities have advantages of better monitoring, better control of treatment operation, more available treatment alternatives, higher safety for the crew, and economy of scale in construction and operation (Pereira et al., 2010, Cohen and Weinstein, 1998, Cohen and Foster, 2000). Disadvantages of port-based treatment include port congestion arising from ballast collection and storage, high cost of land acquisition, and demand of pipe connection between the treatment plants and all the berths (Pereira et al., 2010, Gollasch et al., 2007). However, Pereira et al. conclude that the port-based treatment does not impact

the cargo capacity, occupation rate, or average queuing time at ports, even in those ports receiving high volumes of ballast water (Pereira et al., 2010).

Port-based reception facilities can be land- or barge-based (Maglić et al., 2015, The IMO, 2013, David et al., 2015). Barge-based BWTS may offer advantages over land-based BWTS: they can be used at different locations, can use systems that are not viable on land, and do not need land-based pipelines (Maglić et al., 2015). A study considering the cost and access options concludes that using a barge with a plant installed onboard is the most flexible port-based method (Brown and Coldwell, 2007). A case study conducted in California justifies the focus on barge-based treatment and finds its significantly lower cost and provides more economic and more certainty than centralized land-based treatment (Glosten et al., 2018b).

BWTS, no matter vessel- or port-based, approved by the IMO or the USCG can achieve the numeric standards required by the IMO (called 'IMO-BWTS'). To achieve more stringent interim goals, California State Lands Commission funded a study to assess the feasibility of a purpose-used barge-based treatment system (called 'Stricter-BWTS') (California State Lands Commission, 2018a). The cost of one BWTS can range from $640,000 to $947,000, depending on different capacities, methods, and sizes (King et al., 2009). The cost of purpose-built barge-based BWTS by California is even higher (Glosten et al., 2018a, COWI A/S, 2012, Maglić et al., 2015). The regulatory compliance cost imposed on the shipping industry may decrease the shipping service or be passed through to final consumers (Schinas and Stefanakos, 2012). Cost-effective treatment methods are needed to balance species invasion risk reduction and negative economic impacts.

3.1.3 Research question

Ballast water regulations are designed to protect regional ecosystems, while fleet managers seek compliance strategies that minimize cost across voyages to many ports (Firestone and Corbett, 2005). The key question motiving this paper is: what are the cost-effective technological compliance strategies? Broad studies discuss vessel-based system selection given space and resources onboard, cost, effectiveness, size, installation space, power, the safety of the crew, etc. (Karahalios, 2017, Ren, 2018, Šateikienė et al., 2015, Satir, 2014, Tsolaki and Diamadopoulos, 2010). However, they do not consider the potential economic benefits of port-based treatment. To this end, this work considers the conventional onboard and alternative strategies for the world fleet. We want to know whether and when the port-based reception treatment could be a feasible alternative from an economic perspective. Due to the reviewed advantages of barge-based BWTS over shore-based BWTS, we use barge-based BWTS to represent port-based BWTS.

The key question motivating regional standards is whether cost-effective treatment strategies better address invasive risk complexity. As the asymmetric risk of invasive species introduction varies among ports, one treatment standard may be less efficient or less effective than variable (stricter) regional standards (Saebi et al., 2019). If more stringent regulation standards are proposed after vessels take actions to meet the current standards, vessels could need to change the treatment method, incurring cost and fleet availability time loss. Hence, a robust and sustainable compliance strategy is needed for the world fleet under different regulatory scenarios.

Another question motivating this work is how much the ballast water management regulatory costs will add to the shipping costs for individual vessels. Each company faces challenges to navigate the way through environmental

regulations. The cost of running a ship is one of the key variables deciding financial performance for a shipping company (together with the revenue received from chartering/operating the ship and the method of financing the business) (Stopford, 2009).

3.2 Materials and Methods

The development and use of a set of scenarios is a strategy when facing uncertainty (Morgan, 2017). Our work models three policy scenarios due to the uncertainty of future ballast water management regulation. Under each policy scenario, this work proposes different technological solutions composed of conventional onboard treatment systems and barge-based alternatives and then compares them using cost-effectiveness analysis (CEA).

3.2.1 Policy scenarios

Three policy scenarios are proposed with different ballast water discharge standards and geographical scopes. The first scenario is ‘Consistent IMO Regulation’, where every port adopts the baseline BWM Convention standard. This is the current situation and practice of the industry.

The second one is ‘Inconsistent Regulation’, where most ports in the world follow the BWM Convention, and some regions adopt independent stricter standards. The stricter standards refer to the interim standards proposed by California.

The third one is ‘Consistent Stricter Regulation’, where all ports adopt the same stricter standards to the interim standards of California. It shows a boundary of the most stringent regulation by extending the scope of stricter standards to the whole

world. This policy also applies to the situation where the precautionary principle is used in the policy-making process.

This work selects the U.S. as a representative for regional/national regulation to illustrate the range of our analysis. The method can be applied to other regions to examine different regulatory scenarios.

3.2.2 Compliance strategy alternatives for each policy

This work considers both the conventional onboard option and a barge-based alternative to comply with different BWM scenarios. Table 3.1 illustrates possible cost-effective compliance technological alternatives.

Table 3.1 Possible cost-effective alternatives to comply with three policy scenarios

Policy scenario	Compliance Strategy[1]	Description[2]
1. Consistent IMO regulation	Strategy 1.1	IMO-BWTS on all vessels
	Strategy 1.2	IMO-BWTS at all ports
2. Inconsistent regulation: The U.S. adopts stricter standards	Strategy 2.1	Stricter-BWTS on Vessel-may-US[3] IMO-BWTS on Vessel-never-US
	Strategy 2.2	Stricter-BWTS at US Ports IMO-BWTS at non-US Ports
	Strategy 2.3	Stricter-BWTS at US Ports IMO-BWTS on all vessels
	Strategy 2.4	Stricter-BWTS on Vessel-may-US[3] IMO-BWTS at non-US Ports
3. Consistent stricter regulation	Strategy 3.1	Stricter-BWTS on all vessels[3]
	Strategy 3.2	Stricter-BWTS at all ports

1: The set of combinations does not include more expensive options that we can easily tell. For example, Stricter-BWTS on all vessels to comply with the first and second regulation scenarios, but the costs are much higher than IMO-BWTS.
2: Figure B1 in Appendix B.1 provides figure illustration for these strategies.
3: This work includes the case that Stricter-BWTS can be installed on vessels, even though the footprint of Stricter-BWTS may be too large for vessels. These potential strategies try to include future conditions due to technological innovation.

When the BWM regulation is uniform and consistent with IMO standards, the BWTS needed to meet the requirement is IMO-BWTS. The potential cost-effective strategies are to put the IMO-BWTS on all vessels or at all ports.

Under inconsistent regulation, Stricter-BWTS is required to achieve the standards at US Ports, so either US Ports need to install barge-based Stricter-BWTS or vessels that have a possibility to call at US Ports need to install Stricter-BWTS onboard. At non-US Ports, IMO-BWTS is enough to meet the requirement. Especially, under Strategy 2.4, vessel-may-US have two options when they call at non-US ports: they can either use vessel-based Stricter-BWTS or use barge-based IMO-BWTS to meet the IMO standards of non-US ports.

When the uniform regulation adopts California's stricter standards, the world fleet can either install Stricter-BWTS onboard every vessel or use barge-based Stricter-BWTS at every port.

3.2.3 Cost-effectiveness analysis for the world fleet

CEA compares alternatives in terms of costs to meet a single quantified effectiveness measure. It works well when the policy impact is unable to be monetized or the considerations are about human or ecosystem health. It also can be transformed into a cost-minimization problem with fixed effectiveness if the strategies have the same efficiency (Boardman et al., 2017). This is the case in this work in that all compliance strategies are proposed to meet certain regulatory standards. Therefore, we only need to find compliance strategies with the lowest cost. To this end, this work establishes compliance cost models to compare technological strategies.

We establish a world fleet compliance cost model and estimate the costs of technological strategies for the world fleet. The fleet compliance cost is calculated on a yearly basis. The compliance cost is calculated with Equation 1. Treatment cost depends on the treatment numbers and ballast water discharge volume each year.

$$\text{Fleet compliance cost} = \text{purchase} + \text{installation} + \text{operating} + \text{treatment cost} \quad \text{(Equation 1)}$$

If the BWTS is vessel-based, each item refers to the annual cost of BWTS. If the BWTS is barge-based, annualized purchase, installation, and operating cost also include those of barges, and treatment cost also includes the cost of tugs because tugs control the movement of barges. Table 3.2 illustrates the detailed compliance cost model for each policy scenario.

Table 3.2 World fleet cost model of compliance strategies

Alternatives	Annual capital cost, installation cost, and operating cost	Annual treatment cost
Strategy 1.1	$n_{allvessel} * (C_{imo} + O_{imo})$	$V_{allport} * T_{imo}$
Strategy 1.2	$n_{allport} * (C_{barge} + C_{imo} + O_{barge} + O_{imo})$	$V_{allport} * T_{imo} + T_{tug} * N_{allport}$
Strategy 2.1	$n_{v\_may\_us} * (C_{stricter} + O_{stricter}) + n_{v\_never\_us} * (C_{imo} + O_{imo})$	$(V_{vmayus\_to\_usport} + V_{vmayus\_to\_otherport}) * T_{stricter} + V_{vneverus\_to\_otherport} * T_{imo}$
Strategy 2.2	$n_{usport} * (C_{barge} + C_{stricter} + O_{barge} + O_{stricter}) + n_{otherport} * (C_{barge} + C_{imo} + O_{barge} + O_{imo})$	$V_{usport} * T_{stricter} + V_{otherport} * T_{imo} + T_{tug} * N_{allport}$
Strategy 2.3	$n_{all\_vessels} * (C_{imo} + O_{imo}) + n_{usport} * (C_{barge} + C_{stricter} + O_{barge} + O_{stricter})$	$V_{usport} * T_{stricter} + V_{otherport} * T_{imo} + T_{tug} * N_{usport}$
Strategy 2.4 (1) Use vessel-based BWTS when Vessel-may-US call non-US Ports	$n_{v\_may\_us} * (C_{stricter} + O_{stricter}) + n_{otherport} * (C_{barge} + C_{imo} + O_{barge} + O_{imo})$	$V_{usport} * T_{stricter} + V_{vmayus\_to\_otherport} * T_{stricter} + T_{tug} * N_{vneverus\_to\_otherport} + T_{imo} * V_{vneverus\_to\_otherport}$
Strategy 2.4 (2) Use barge-based BWTS when Vessel-may-US call non-US Ports	Same to above	$V_{usport} * T_{stricter} + V_{otherport} * T_{imo} + T_{tug} * N_{otherport}$
Strategy 3.1	$n_{allvessel} * (C_{stricter} + O_{stricter})$	$V_{allport} * T_{stricter}$
Strategy 3.2	$n_{allport} * (C_{barge} + C_{stricter} + O_{barge} + O_{stricter})$	$V_{allport} * T_{stricter} + T_{tug} * N_{allport}$

$C_{imo}, C_{stricter}, C_{barge}$: annual capital and installation cost of an IMO-BWTS/a Stricter-BWTS/a barge
$O_{imo}, O_{stricter}, O_{barge}$: annual operation cost of an IMO-BWTS/a Stricter-BWTS/a barge

$T_{imo}, T_{stricter}$: unit ballast water treatment cost of IMO-BWTS/Stricter-BWTS ($/ton)
T_{tug}: treatment cost of a tug ($/treatment; one treatment needs one tug)
$n_{allvessel}, n_{v\_may\_us}, n_{v\_never\_us}$: number of the world fleet, Vessel-may-US, and Vessel-never-US
$n_{allport}, n_{usport}, n_{otherport}$: number of world ports, US Port and non-US Ports
$V_{allport}, V_{otherport}, V_{usport}$: annual ballast water treatment volume from vessels to all ports/non-US Ports/US Port. The ballast water discharge probability of each voyage of 0.5 is considered
$V_{vmayus\_to\_usport}$: annual treatment ballast water volume from Vessel-may-US to US Port
$V_{vmayus\_to\_otherport}$: annual treatment ballast water volume from Vessel-may-US to Other-Port
$V_{vneverus\_to\_otherport}$: annual treatment ballast water volume from Vessel-never-US to Non-US Ports
$N_{allport}, N_{usport}, N_{otherport}$: annual treatment/discharge times at all ports/US Port/Non-US Ports. The discharge probability of 0.5 is considered.
$N_{vneverus\_to\_otherport}$: annual treatment times of Vessel-never-US at Non-US Ports

3.2.4 Compliance cost model for individual vessels

Even though the cost-effective alternatives identified may be the optimal options for the world fleet, it cannot reveal the cost difference among individual vessels. Therefore, the work further establishes individual vessel cost models. With the individual vessel compliance cost model, we further estimate the impacts of compliance costs on shipping costs. The individual vessel compliance cost model is shown in Table 3.3. Since the cost of Strategy 2.4 (1) is lower than strategy 2.4 (2), the following work uses Strategy 2.4 (1) and compare it with others. For all vessels, the individual vessel cost comprises capital, installation, operating, and treatment cost (the representative equation is the same to Equation (1). However, the details are different for Vessel-may-US and Vessel-never-US under the scenario of Inconsistent Regulation, so Table 3.3 shows different models for them.

Table 3.3 Cost model for individual vessels

Strategies	Annual capital, installation and operating cost		Annual treatment cost	
	Vessel-may-US	Vessel-never-US	Vessel-may-US	Vessel-never-US
Strategy 1.1	$C_{imo} + O_{imo}$		$V_v * T_{imo}$	
Strategy 1.2	$n_{allport} * (C_{barge} + C_{imo} + O_{barge} + O_{imo}) * V_v/V_{allport}$		$V_v * T_{imo} + T_{tug} * N_v$	
Strategy 2.1	$C_{stricter} + O_{stricter}$	$C_{weaker} + O_{weaker}$	$V_v * T_{stricter}$	$V_v * T_{imo}$

Strategy 2.2	$V_{v\_to\_usport} * n_{usport} * (C_{barge} + C_{stricter} + O_{barge} + O_{stricter}) / V_{vmayus\_to\_usport} + V_{v\_to\_otherport} * n_{otherport} * (C_{barge} + C_{imo} + O_{barge} + O_{imo}) / V_{otherport}$	$V_{v\_to\_otherport} * n_{otherport} * (C_{barge} + C_{imo} + O_{barge} + O_{imo}) / V_{otherport}$	$V_{v\_to\_usport} * T_{stricter} + V_{v\_to\_otherport} * T_{imo} + T_{tug} * N_v$	$V_{v\_to\_otherport} * T_{imo} + T_{tug} * N_v$
Strategy 2.3	$(C_{imo} + O_{imo}) + V_{v\_to\_usport} * n_{usport} * (C_{barge} + C_{stricter} + O_{barge} + O_{stricter}) / V_{vmayus\_to\_usport}$	$C_{imo} + O_{imo}$	$V_{v\_to\_usport} * T_{stricter} + V_{v\_to\_otherport} * T_{imo} + T_{tug} * N_{v\_to\_usport}$	$V_v * T_{imo}$
Strategy 2.4 (1)	$(C_{stricter} + O_{stricter}) + V_{v\_to\_otherport} * n_{otherport} * (C_{barge} + C_{imo} + O_{barge} + O_{imo}) / V_{otherport}$	$V_v * n_{otherport} * (C_{barge} + C_{imo} + O_{barge} + O_{imo}) / V_{otherport}$	$V_v * T_{stricter}$	$V_v * T_{imo} + T_{tug} * N_v$
Strategy 3.1	$C_{stricter} + O_{stricter}$		$V_v * T_{stricter}$	
Strategy 3.2	$n_{allport} * (C_{barge} + C_{stricter} + O_{barge} + O_{stricter}) * V_v / V_{allport}$		$V_v * T_{stricter} + T_{tug} * N_v$	

V_v: the annual discharged volume of vessel *v*, vessel *v* can be Vessel-may-US, or Vessel-never-US
$V_{v\_to\_usport}$: the annual discharged volume at US Port of vessel *v*
$V_{v\_to\_otherport}$: the annual discharged volume at non-US Port of vessel *v*
N_v: the annual treatment times at all ports of vessel *v*
$N_{v\_to\_usport}$: the annual treatment times at US Port of vessel *v*

Shipping costs are estimated for all container vessels, bulkers and tankers with shipping cost models (the database has 21,624 vessels of these three vessel types). The annual shipping cost for each vessel is estimated with daily shipping cost and voyage duration. Daily shipping cost is estimated with the method and data of Guide to Deep-Draft Vessel Operating Costs (US Army Corps of Engineers, 2002).

3.2.5 Data

The models mainly use three types of data: the cost and performance of BWTS, shipping traffic, and the ballast water discharge profile.

3.2.5.1 Cost and performance of BWTS

The work of King and Hagan includes cost data for IMO-BWTS (King et al., 2009). The information comes from technology vendors whose systems had been approved by the IMO as of May 2009, other industry representatives, and ship engineers. They present the preliminary costs for a 'typical' ship within each ship type/size category and include the cost variation caused by different BWTS treatment methods (i.e. chemical, physical, and mechanical). The range of the IMO-BWTS purchase and installation costs is between $0.7 to $1.1 million. Some vessels need small BWTSs and some use large BWTSs, so we use the average of lower and upper boundaries to calculate average fleet costs for available compliance strategies. Every vessel using the most expensive BWTS is the higher boundary and every vessel using the least expensive BWTS is the lower boundary.

The costs of some BWTS may decline due to technology advancement and large scale or production since more BWTS have obtained the type-approval certificate under the regulation of the IMO and the USCG. In considering whether to use 2009 ballast treatment cost data (King et al. 2009), we recognize that either cost may need upward adjustment to 2020 based on constant dollar differences or that fleet adoption experience over time may yield cost savings offsetting time-value increases. We interviewed a BWTS commissioning engineer from RMS Marine Service Company Ltd. about the lowest and highest market prices of a BWTS. We found the BWTS costs can be as low as $0.2 million, while they can still be high as $1.2 million for a VLCC (Zheng, 2020). We include the possible lowest IMO-BWTS costs of $0.2 million and 1.5 times of the highest cost ($1.8 million) in our analysis as a sensitivity analysis to show the robustness of cost-effective strategy facing technology uncertainty.

Delta Stewardship Council provides cost analysis for stricter-BWTS (Glosten et al., 2018a), including cost estimation for barges and tugs. Their reports consider the cost variation due to different sizes and capacities of BWTS and barges, and our work uses the upper and lower bounds to consider the data uncertainty.

The reports include 16 ports in California, and these ports use 24 barges in total. That is about 1.5 barges per port. The barges in different sizes are arranged for each port zone according to BWTS treatment capacities and vessel treatment demands (Glosten et al., 2018b). Capacities are measured in terms of ballast water discharge rate, i.e., 30,000MT discharged in 24 hours is similar to 15,000 MT discharged in 12 hours (Glosten et al., 2018a). Our work uses the same method and adjusts the number of barges needed for each port within the U.S. The average ballast water discharge volume of U.S. ports is 14% of the California average, and the average ballast water discharge/treatment events of U.S. ports is 55% of the California average, so 0.21 to 0.83 barge on average should be used in one U.S. port. We assume one barge per U.S. port if some fraction one barge is needed at a port. We include sensitivity analysis with 0.2 (several ports share one barge) to 3 barges per port (vessel arrival peak).

This work uses Delta Stewardship Council data to get annual costs: a BWTS lifetime of 30 years, a discount rate of 6%, and an annual inflation rate of 2.5%. Table 3.4 summarizes the annual capital cost, operating cost, and unit treatment cost for BWTS, barges, and tugs.

Table 3.4 Cost components of BWTS measures

Table 3.4a Costs of IMO-BWTS[1]

Scenarios[5]	Total capital and installation cost ($)	Annual capital and installation cost[2] ($)	Annual operating cost[3] ($)	Unit treatment cost[4] ($/MT)
Lower bound	658,000	35,776	9,000	0.02
Average cost	**901,000**	**48,989**	**13,500**	**0.135**

Upper bound	1,144,000	62,201	18,000	0.25

1: From (King et al., 2009)
2: Capital costs annualized: initial purchase and installation of a ballast water treatment system.
3: Fixed annual costs: does not vary with the volume of ballast water treated, including crew, consumables, parts, assistance, and technical support.
4: Variable annual costs: varies with the volume of ballast water treated, including crew, consumables, and fuel cost to run BWTS.
5: The lower and upper bound are the minimum and maximum costs of different treatment methods in the report.

Table 3.4b Costs of Stricter-BWTS

Scenarios[4]	Total capital and installation cost[1] ($)	Annual capital and installation cost ($)	Annual operating cost[2] ($)	Unit treatment cost[3] ($/MT)
Lower bound	4,600,000	250,108	326,000	0.27
Average cost	**7,000,000**	**380,599**	**502,000**	**0.48**
Upper bound	9,900,000	538,276	678,000	0.68

1: *Treatment Plant* from Table 6 (Glosten et al., 2018a).
2: *M&R of system* from Table 14 is the annual operating cost of all BWTS in each zone (Glosten et al., 2018a). The cost for each BWTS is calculated with the number of barges in each zone (from Table 10).
3: *Operators* in Table 14 (Glosten et al., 2018a) is the total treatment cost of BWTS in each zone. The cost for the average tonnage of discharged ballast water is calculated with the discharge volume in each zone (from Table 12).
4: The lower bound is when all BWTS used are in small size, the upper bound is when all BWTSs are large.

Table 3.4c Extra costs if BWTS is installed on barges (the costs of barge and tug)

Scenarios[4]	Total capital and outfitting cost for one barge[1] ($)	Annual capital and outfitting cost for a barge ($)	Annual operating cost for a barge[2] ($)	Tug[3] ($/treatment)
Lower bound	6,300,000	342,540	231,000	11,400
Average cost	**10,100,000**	**549,150**	**231,000**	**11,400**
Upper bound	15,500,000	842,755	231,000	11,400

1: *Barge and Outfitting* in Table 9 (Glosten et al., 2018a). The barge hull size is the smallest to not only provide enough deck space for the BWTS but also enough tankage to provide adequate setting/flocculation of the ballast water prior to final treatment, so the cost of barges is assumed to be the same for IMO- and Stricter-IMO in this work.
2: The sum of *Barge berthing* and *Admin & Main Personnel* in Table 14 (Glosten et al., 2018a) is the annual operating cost of barges in each zone. Divide it by the number of barges in each zone and get $231,000 for one barge.
3: *Tug boat* cost in Table 14 (Glosten et al., 2018a) is the total tug cost to relocate barges at each zone. Divide it by total ballast water treatment times in each zone and then get the treatment cost for one tug.
4: The scenarios are determined in the same way to Table 3.4b.

3.2.5.2 Ship traffic and ballast water discharge profile

Table 3.5 provides the data of ship traffic and ballast water discharge profile.

The port, vessel and voyage data are from 2012-2013 Lloyd's Vessels Database and

Moves Database. These numbers provide a preliminary description of the demand for BWTS. The work assumes all ports and vessels need BWTS, and no vessel or port has installed BWTS before. The domestic shipping moves within the same origin and destination country are removed because IMO requires ships in *international* traffic to manage ballast water. There are 41,467 unique ships left and 9,088 of them have at least one record of calling at a U.S. port.

Table 3.5 Ship traffic and ballast water discharge profile in the year 2012-2013

The number of ports		The number of unique vessels		The number of discharges/treatments[1]		Modeled Discharge volume (MT)	
U.S. Ports	257	Vessels may go U.S.	9088	Vessel-never-US to non-US Ports	18,555	Vessel-never-US to non-US Ports	35,165,961
non-US Ports	3164	Vessels never go to U.S.	32379	Vessel-may-US to non-US Ports	118,991	Vessel-may-US to non-US Ports	256,769,311
World Ports	3421	World Fleet	41467	Vessel-may-US to US Port	535,540	Vessel-may-US to US Port	622,544,170

1: The fraction of port arrivals without ballast water discharge varies from 42% to 88% for different vessel types. We assume the discharge probability is 0.5 for simplification.

While some ships may choose to avoid U.S. ports in the future to obviate the need to have more robust treatment, we assume that each of the 9,088 vessels calling on U.S. ports—creating an upper bound—will need to install a stricter BWTS onboard or use barge-based stricter BWTS at the 257 ports in the U.S. This work also assumes ballast water discharge may happen at every port, so all ports are included in the analysis.

The ballast water discharge volumes are estimated with a regression method using DWT and ballast water discharge reported in the National Ballast Information Clearinghouse Database (NBIC) (Seebens et al., 2013). DWT data are from Lloyd's dataset and the average discharge volume is used for those vessels with missing DWT data. NBIC receives ballast water discharge reports that are required under U.S. law (U.S. Coast Guard, 2015). Furthermore, past reports on this database document

compliance with reporting requirements are near or above 80% of all reportable discharges of ballast water (Miller et al., 2007, Miller et al., 2011). Based on this information, this work treats the reported discharge volumes as valid enough for our analysis. We report the confidence of the regression fit of discharge volume and DWT in Table B1 in Appendix B.2.

3.3 Results and Discussion

3.3.1 Cost-effective compliance strategies for the world fleet

Table 3.6 shows the annual fleet costs for each compliance strategy. The cost-effective strategies are marked in bold. We can see the results remain the same under different cost scenarios, which reveals the robustness of the identified options.

Table 3.6 World fleet annual regulation compliance cost for technological strategies

Policy scenario	Strategy	Annual fleet cost (billion $)				
		Average	Lower bound	Higher bound	Lowest bound with lowest IMO-BWTS cost (Sensitivity analysis)	Highest bound with highest IMO-BWTS cost (Sensitivity analysis)
Consistent IMO regulation	**Strategy 1.1**	**2.7**	**1.9**	**3.6**	**0.8**	**5.0**
	Strategy 1.2	10.7	10.5	10.8	10.4	11.0
Inconsistent regulation: The U.S. stricter standards	Strategy 2.1	10.3	6.8	14.0	6.0	15.2
	Strategy 2.2	10.9	10.6	12.2	10.5	11.
	Strategy 2.3	**3.4**	**2.4**	**4.4**	**1.4**	**5.8**
	Strategy 2.4	17.0	14.0	20.2	13.9	20.3
Consistent stricter regulation	Strategy 3.1	37.0	24.1	51.1	24.1	51.1
	Strategy 3.2	**13.8**	**11.9**	**16.1**	**11.9**	**16.1**

Note: In the lower bound, all cost components, including capital, operating, and treatment costs of IMO-BWTS, stricter-BWTS, and barges use the minimum numbers in Tables 3.4. In the lowest bound of the sensitivity analysis, only the capital cost of IMO-BWTS is $0.2 million to show the extreme limit, and other cost components are the same to the lower bound.

Consistent IMO regulation is the current ballast water regulation practice. The most cost-effective strategy is to use the vessel-based BWTS (Strategy 1.1). This

optimal strategy verifies the current BWTS installation practice of the industry. In other words, this work confirms that the fleetwide vessel treatment is more cost-effective than port-based schemes to meet global treatment standards set by the IMO BWM Convention.

Under the policy scenario of inconsistent regulation when the U.S. adopts stricter regulation, the optimal compliance strategy is to install IMO-BWTS on all vessels and install Stricter-BWTS at US ports (Strategy 2.3). This result also suggests that regions can adopt stricter regulations than the BWM Convention without conflicting with current industry practice and requiring vessels to engage in retrofits on top of retrofits to come into compliance. Thus, these vessels will not be "grandfathered" at the expense of better environmental protection. Rather, the only update required will be a State's own ports to meet Stricter-BWTS. When vessels call at these ports, the ballast water will be treated by barge-based BWTS. When vessels call at non-US Ports, the onboard BWTS will be used. Such a strategy also does not require other countries to cooperate.

If all ports require stricter regulations, the barge-based strategy (Strategy 3.2) is more cost-effective than the vessel-based strategy (Strategy 3.1). Even though the capital cost of barge-based BWTS is much higher than vessel-based BWTS, the economies of scale make barge-based BWTS economically feasible for the world fleet. The average estimate of $13.8 billion provides the highest boundary of stricter regulation worldwide.

The last two columns of Table 3.6 show the fleet annual cost considering the capital cost uncertainty of IMO-BWTS. When we change the minimum IMO-BWTS cost to $0.2 million, Strategy 1.1, 2.3, and 3.2 remain the most cost-effective strategies

under all regulatory scenarios. The fleet costs of lower bound and lowest bound are the same for Strategy 3.1 and Strategy 3.2. This is because we only vary the capital cost of IMO-BWTS for the lowest bound and keep other cost components (operating cost of IMO-BWTS, costs of stricter-BWTS and barges, and treatment costs) the same to the lower bound, and these two technological strategies do not include IMO-BWTS. The same reason applies to the observation that the higher bound and the highest bound have the same costs for these two technological Strategies 1 and 2.The table also shows that the difference in the fleet compliance costs between Strategy 1.1 and Strategy 1.2 becomes bigger than the lower bound and the Average case, due to the cost advantage of IMO-BWTS over stricter-BWTS. When we change the maximum IMO-BWTS cost to $1.8 million, the cost-effective strategies remain the same. These results indicate that the identified cost-effective compliance strategies are robust within the possible cost ranges.

By examining the cost-effective strategies for each policy scenario, the vessel-based treatment method works well under current regulation, while the barge-based alternative is economically feasible if some regions adopt stricter regulation. Also, if the U.S. adopts stricter regulation in all the ports, the total cost will increase by $0.7 billion ($3.4 billion minus $2.7 billion from Column 3 of Table 3.6). The strategies proposed in Section 2.2 include the vessel-based Stricter-BWTS even though the footprint of Stricter-BWTS may be too large for vessels. We include this option to consider the future situation with technological innovation. The identified strategies under Policy 2 and 3 show that the Stricter-BWTS can be cost-effective when they are barge-based.

This work also considers the possible BWTS demand uncertainty due to the number of barges needed at the port and the fleet number. (1) By varying the number of barges used at one port, this work shows the same strategy selection results and reveals the robustness of the identified cost-effective strategies. The potential need for three barges per port demonstrates that the barge-based strategies remain feasible and preferred. (2) By varying the fleet number, we find that the demand for BWTS is inelastic. The compliance cost may be high enough to phase out some kinds of vessels, like small vessels operating in short-haul voyages, but the technological strategy selection will remain the same.

3.3.2 The compliance cost of individual vessels

Table 3.7 shows the cost difference of individual vessels for the identified cost-effective strategies. The unit ballast water treatment costs of individual vessels vary substantially. The ranges are from several dollars to several million dollars per ton of treated ballast water (Columns 2 and 3). The very high unit treatment costs are due to very little ballast water discharge volume from passenger and service vessels. When these vessels are removed, the highest unit treatment costs become much lower (Column 4). The maximum unit costs of Strategy 1.1 and 2.3 are the same if passenger and service vessels are excluded.

Table 3.7 Unit compliance costs of individual vessels of cost-effective strategies.

Strategy	Minimum unit compliance cost ($/MT)	Maximum unit compliance cost ($/MT)	Maximum unit cost（excluding passenger and service vessels） ($/MT)
Strategy 1.1	5	540,000	18,000
Strategy 2.3	5	1,200,000	18,000
Strategy 3.2	7	3,100,000	109,000

The proportions of compliance cost to total shipping cost for different vessels vary a lot. The vessels with very high percentages of compliance costs tend to be small or old vessels and tend to discharge less ballast water. Table 3.8 shows the average proportions of the compliance cost to the total shipping cost for individual vessels. The total shipping cost is composed of operating cost (14%), periodic maintenance (4%), voyage cost (40%), and capital cost (42%) (Stopford, 2009). The average ballast water management compliance cost is higher than the periodic maintenance cost.

Under Strategy 1.1, the compliance cost accounts for 4.6% of total shipping cost on average under current international ballast water regulation, and the percentage under the stricter U.S. regulation becomes 4.9% under Strategy 2.3. The difference is 0.3%, which is very small. As for the vessels with very high compliance costs, their firms may choose to speed up phasing out such vessels or improve their business strategies to satisfy their economic goals. Policymakers need to consider mechanisms to enhance the compliance of these vessels. For example, treatment methods other than using BWTS, such as using freshwater as ballast, may be good solutions for these vessels. Otherwise, a more careful cost allocation mechanism might be helpful to lower their compliance cost.

Table 3.8 Average proportions of compliance cost to the shipping cost for individual vessels

Strategy	The average proportion of compliance cost
Strategy 1.1	4.6%
Strategy 2.3	4.9%
Strategy 3.2	7.9%

3.4 Conclusion

This analysis evaluates the cost-effectiveness of the vessel- and barge-based BWTS under three policy scenarios. The analysis shows that the vessel-based system is more cost-effective under current regulation, and the barge-based system is cost-effective when some ports or all ports worldwide adopt a more stringent ballast water discharge regulation. Depending on the global traffic pattern and which ports/regions may require better protection from the stricter treatment of ballast water, barge-based BWTS could be used without updating otherwise BWM-compliant vessel-based BWTS.

Since barge-based BWTS is shown to be cost-effective in some situations, future studies can be done to examine the cost-sharing issue of barge-based BWTS. The systems are used by vessels but are purchased and installed by ports or private operators. Ports can consider charging ballast water treatment fees or increasing port dues according to the treated volume. Also, the strategy design and cost models can be applied to other regional regulatory scenarios. For example, with species invasion risk assessment models, hotspot ports can be identified and set as protection zones with higher regulatory standards.

Chapter 4

POTENTIAL IMPACTS OF BALLAST WATER REGULATIONS ON INTERNATIONAL TRADE, SHIPPING PATTERNS, AND THE GLOBAL ECONOMY: AN INTEGRATED TRANSPORTATION AND ECONOMIC MODELING ASSESSMENT[3]

4.1 Introduction

Vessels routinely intake and discharge ballast water, corresponding to carried cargo, to maintain their stability. This activity transports organisms contained in ballast water from one place to another. If the discharge occurs outside the organisms' native range, there is potential for the species to become established and invasive. More than half of all marine invasive species are attributed to transfers by global commercial shipping (Molnar et al., 2008, Saebi et al., 2019), with around 10,000 species estimated to have been transported in ballast water (Bax et al., 2003). The impacts of invasive species on the environment and economic activities have been long investigated and found to impose negative impacts on the economy, ecosystem and human health (Carlton, 2003, Chan et al., 2019, Lovell et al., 2006, Wan et al., 2016, Wan et al., 2018a, David et al., 2019).

Ballast water management (BWM) regulations attempt to reduce the risk of species' spread and associated negative impacts. The International Convention on the

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Control and Management of Ship's Ballast Water and Sediments (the BWM Convention) of the International Maritime Organization (IMO), for example, defines allowable concentrations for viable organisms and certain human health indicator microbes contained in discharged ballast water in the D-2 Standard. While most countries are parties to the BWM Convention, the U.S. is not. Instead, the U.S. independently regulates ballast water discharge according to the 2018 Vessel Incidental Discharge Act (VIDA). Section 151.1511 or 151.2030 of Title 33, Code of Federal Regulations (or successor regulations) establishes the U.S. ballast water discharge standard, which is currently the same as the BWM Convention. However, individual states of the U.S. can set independent standards. California's interim performance standards, in effect from January 2030, establish limits for the number of organisms for different functional groups, which are stricter than the BWM Convention[4]. California's final performance standard goal, in effect from January 2040, is to achieve zero detectable living organisms for all size classes. Current IMO standards are species concentration-based, instead of risk-based. Risks are not clearly mitigated by current standards, so there is a need for more stringent location-specific regulations at invasion hotspots (Verna and Harris, 2016, Saebi et al., 2019). To comply with the interim California performance standards, the California State Lands Commission funded a study to assess the feasibility of barge-based treatment methods (California State Lands Commission, 2018a).

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[4] California interim ballast water limits are as follows: no detectable living organisms greater than 50 micrometers in minimum dimension; less than 0.01 living organisms per milliliter less than 50 and more than 10 micrometers; less than 1000 bacteria and less than 10,000 viruses per 100 milliliters, and different standards for Escherichia coli and intestinal enterococci.

Compliance technology (i.e., type-approved ballast water treatment systems [BWTS]) are available to vessel operators to comply with both regulations and reduce species invasion risk. However, better systems may be necessary to achieve risk reduction targets. Procuring and installing BWTS on ships requires both capital and operating costs (King et al., 2009), and more advanced BWTS to comply with stricter regulations (if set) would cost more (Glosten et al., 2018a). Vessel operators may reduce shipping services or costs may be passed on to cargo owners and eventually to final consumers (Tseng et al., 2005, Schinas and Stefanakos, 2012), which may negatively impact the economic performance of particular sectors (Tseng et al., 2005). Herein, we assess the economic impacts of current international regulations and proposed location-specific alternatives including changes in international trade and transport (Estevadeordal et al., 2003, Hummels, 2007, Jacks et al., 2008). Shipping patterns serve as powerful tools in understanding environmental risk and analyzing policies, particularly those targeting marine bio-invasions and shipping emissions (Corbett et al., 2010, Wang et al., 2007, Johansson et al., 2017, Seebens et al., 2013). However, shipping patterns are dynamic, affected by economic policies (Halim et al., 2018b), climate change (Smith and Stephenson, 2013), and environmental regulations.

This work examines three aspects of impacts from current and future ballast water regulations: bilateral trade of specific commodities, overall impacts on national economies, and global shipping patterns by vessel type. This work can help inform risk-based assessments and allow comparisons of policies such as between current vessel-based treatment standards and additional measures to mitigate shipborne aquatic invasion risks. Our analysis informs evaluations of economic costs of

decreasing the risk of nonindigenous species spread in future policy contexts. Specific scenarios examined in this analysis are:

- Scenario 1 (Consistent BWM Regulation): This scenario is consistent with the current BWM regulation that all international and regional regulations require similar numeric standards of the BWM Convention.
- Scenario 2 (Stricter BWM Regulation): All ports in the U.S. adopt stricter BWM standards, following the regulation in California, while ports in all other countries apply the numeric standards of the BWM Convention.

We do not predict future policies but propose scenarios to explore the viability to drive policies forward. Choosing a U.S. based scenario adopting nationally the stringent standards of one state (California) is not without precedent. Many federal environmental policies since the adoption of the Clean Water Act and Clean Air Act have essentially learned from and expanded standards initiated by one U.S. state. Moreover, our research uses the U.S. as an example in shipping policy, partly because there is a precedent where international shipping adopted standards set by the U.S. One example is international double hull construction requirements for tank ships following U.S. enaction of the Oil Pollution Act of 1990. Lastly, insights from our analysis extend beyond investigation based on U.S. taking more stringent action (i.e., Singapore or Europe); this scenario design affords a major economy with hundreds of ports that trade with most of the major trading nations. We believe the study design is well suited to the economic-technology-environmental question of action to mitigate aquatic species invasion by ships. It is also important to note that our analysis does not evaluate or quantify the economic benefits of increased BWTS standards and corresponding decreased risk of nonindigenous species spread. The remainder of the

paper is organized as follows. Section 2 highlights the methods and data. Section 3 provides the analysis of results and discussion, and Section 4 concludes this work.

4.2 Methodology

This research employs an innovative approach by integrating a shipping cost model and a global economic model to examine the impacts of ballast water management regulations on international trade, shipping traffic, and the overall economy. Figure 4.1 gives an outline of the data, model, and outputs. The shipping cost model estimates changes in transport costs resulting from ballast regulation, which are employed as exogenous shocks to the marine transportation sector in the economic model to quantify changes in bilateral commodity trade and corresponding changes in national economies. Simulated changes in bilateral trade then serve as inputs for the shipping traffic accumulation model, which identifies potential changes in global shipping traffic. We include 20 countries[5] facing the highest compliance costs, most shipping voyages, and the largest trade flows. We analyze nation-specific data and results for these countries and include all other countries as the aggregate *rest of the world* region.

[5] Australia, China, Japan, South Korea, Singapore, Malaysia, Taiwan, the United States, Canada, Mexico, Columbia, Panama, Venezuela, Belgium, Germany, Spain, France, the United Kingdom, the Netherlands, and South Africa.

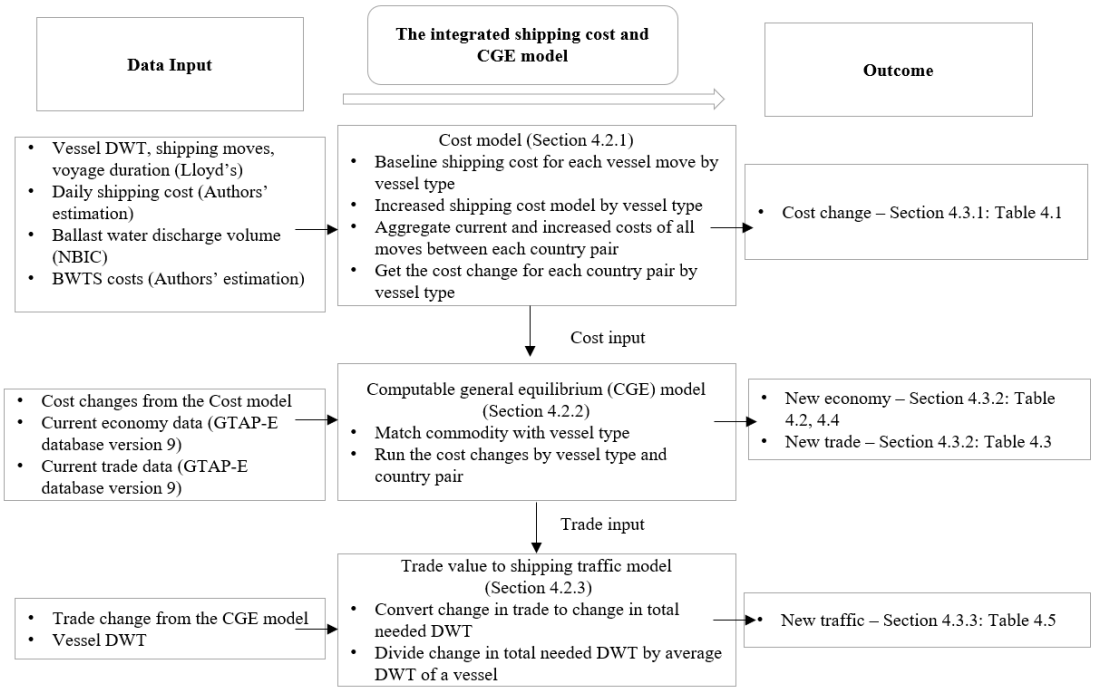


Figure 4.1 Outline of data, models, and outputs

4.2.1 Shipping cost model and data

The shipping cost model is composed of two parts: the current shipping cost model and the regulatory compliance cost model. We calculate the shipping cost and compliance cost separately for each vessel type and every voyage. We then aggregate all voyages in one year to get the annual total current shipping cost and total compliance cost for each pair of countries. From this, we calculate the percentage increases in international shipping costs (the first component in Figure 4.1), which are used as exogenous shocks in the economic model.

4.2.1.1 Baseline shipping cost for each vessel move

Shipping costs without ballast water management for each shipping voyage are the same over the two policy scenarios. The baseline shipping cost is comprised of

capital, operating, and daily fuel costs. The cost components differ by vessel type; hence, the models are built separately for the container, bulk, and tanker vessels. We estimate the total shipping costs for each vessel type with the daily shipping costs and voyage durations (See the descriptions in the Data section).

4.2.1.2 Increased shipping cost due to regulatory compliance

Baseline shipping costs increase across vessel types according to the compliance cost of each regulation. In this regard, it is estimated that type-approved BWTS can be used to meet the regulatory standards required by the BWM Convention (labeled as IMO-BWTS). IMO-BWTS can be applied to vessels or barges. On the other hand, the barge-based BWTS assessed by the California State Lands Commission is intended to meet California's interim stricter standards (labeled as stricter-BWTS) as described in footnote 1 on page 2 (Glosten et al., 2018a).

Because IMO-BWTS and barge-based BWTS generate different increases in shipping costs (i.e., the compliance costs), appropriate allocation of them to be vessel- or port-based can minimize the compliance cost. We identified the most economically efficient solutions for the world fleet in previous work (Wang and Corbett, 2020). That is, the fleet-wide most economically efficient pathway to comply with the Consistent Regulation scenario (Scenario 1) is to install vessel-based IMO-BWTS on every vessel; and the most economically efficient pathway to comply with the Stricter Regulation scenario (Scenario 2) is to use vessel-based IMO-BWTS at non-U.S. ports and use barge-based stricter-BWTS at U.S. ports. Then, with the following models, we compute the increased shipping costs due to regulatory compliance, which are composed of expenses associated with the BWTS capital, installation, operation, and ballast water treatment.

(1) **Regulatory compliance cost model under Consistent Regulation**

The compliance cost for each shipping voyage is obtained from Equation 1. Not all voyages calling at one port discharge ballast water, and we assume the discharge probability is 0.5 (Seebens et al., 2013). The capital and install costs are one-time costs used to calculate annual costs (lifetime of 30 years, a discount rate of 6%, and an annual inflation rate of 2.5%). Then we equally distribute annual costs to all voyages of that vessel because all the voyages use the onboard BWTS to treat discharged ballast water. The treatment cost for each voyage is obtained with the volume of discharged ballast water and unit treatment cost.

$$(C_{v-imo} + O_{v-imo})/N_v + T_{imo} * V_v \qquad \text{(Equation 1)}$$

Where

C_{v-imo}: annual capital cost and installation cost of vessel-based IMO-BWTS ($)

O_{v-imo}: annual operating cost for vessel-based IMO-BWTS ($)

N_v: the number of treatments of vessel *v* in one year; the capital, installation, and operating costs are assumed to be shared by all treatments of that vessel

T_{imo}: treatment cost of IMO-BWTS for each treatment tonnage ($/ton)

V_v: ballast water treatment volume of vessel *v* at that voyage (ton)

(2) Regulation compliance cost model under Inconsistent Regulation

Vessels often have different compliance costs because they call at different ports. We divide vessels into two groups: never call at U.S. ports, and may call at U.S. ports. Figure 4.2 shows the three kinds of voyages and corresponding equations used to calculate the compliance cost for each kind of voyage.

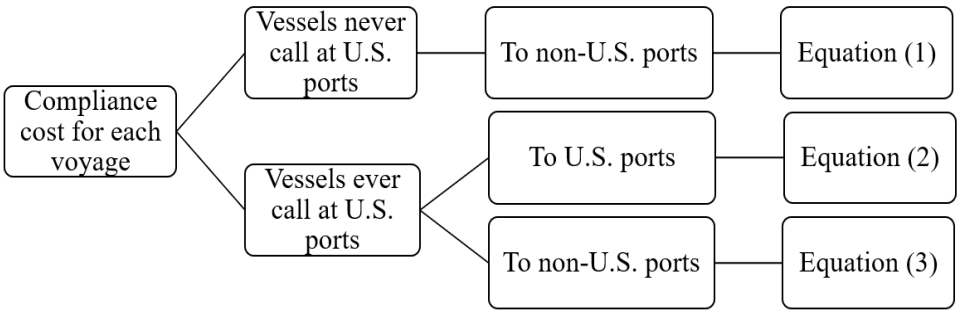


Figure 4.2 Three kinds of voyages determined by the vessel and voyage destination

If a vessel never calls at a U.S. port, it only needs to meet the IMO standard with the onboard IMO-BWTS, and the compliance cost is the same as Equation 1.

If a vessel ever calls at a U.S. port, and the destination port of its voyage is a U.S. port, the discharged ballast water must meet stricter regulation, and the compliance cost calculation for that voyage follows Equation 2. We assume the costs of all barge-based BWTS are shared by voyages to U.S. ports, and the shared cost for each voyage is determined by the ballast water discharge volume of that voyage. The treatment cost is obtained according to the volume of discharged ballast water and the higher unit treatment cost. In addition, a cost component accounting for tug cost is added because barge-based BWTS need tugs to be moved and fixed.

$$(C_{barge} + C_{p-us} + O_{p-us}) * P_{us} * V_v / V_{all\_US} + T_{us} * V_v + T_{tug} \quad \text{(Equation 2)}$$

Where

C_{barge}: annual capital cost and installation cost for one barge ($)

C_{p-us}: annual capital cost and installation cost for barge-based stricter-BWTS ($)

O_{p-us}: the sum of annual operating cost for one barge-based stricter-BWTS and one barge

P_{us}: the number of ports in the U.S., which need stricter-BWTS at port

V_{all_us}: the total volume of treated ballast water at all U.S. ports per year (ton)

T_{us}: treatment cost of stricter-BWTS for each treatment tonnage ($/ton)

T_{tug}: the cost to use a tug per treatment ($/treatment)

If the vessel ever calls at a U.S. port, but the destination port of that voyage is not a U.S. port, the compliance cost estimation for that voyage follows Equation 3. For that voyage, the vessel must meet the IMO-standard with the onboard BWTS. Accordingly, that voyage shares a part of the vessel-based IMO-BWTS costs with the other voyages using it for treatment.

$$(C_{v-imo} + O_{v-imo})/N_{v\_other} + T_{imo} * V_v \quad \text{(Equation 3)}$$

Where

N_{v_other}: the number of treatments at non-U.S. ports of vessel *v* in one year.

To verify the compliance cost model, we sum compliance costs of all voyages to get the compliance cost for the world fleet. Then we compare that with the fleet cost obtained from the fleet compliance cost model (Wang and Corbett, 2020) and get the same number.

(3) Data

Data used for the cost model include shipping movements, daily shipping costs, ballast water discharge volume, and costs of BWTS. We use the data purchased from Lloyd's List Intelligence that gives movements of vessels throughout the world prior to potential treatment. The data include Vessel ID, Origin/Destination port, Port ID, Origin/Destination country, Departure/Arrival time, along with vessel specifications (Vessel Type, Deadweight Tonnage (DWT), Year of build, and other descriptive data). Since the BWM Convention applies only to ships with international voyages, we exclude movements of ships that travel within a country. The final dataset includes 714,039 individual vessel moves.

The voyage durations are obtained from Lloyd's List Intelligence. Daily shipping costs are derived from the Guide to Deep-Draft Vessel Operating with a 2002 base year (US Army Corps of Engineers, 2002), following the literature (Corbett et al., 2009, Dumas and Whitehead, 2008, The EPA, 2012). To verify that these daily shipping costs reflect current costs, we run the recently established container vessel shipping cost model for vessels in sizes of 600, 1600, 2500, 4000, and 6000 TEU and get similar daily costs (Wang et al., 2020b). We also confirm that capital costs derived from the USACE publication are consistent with current costs using long-run analyses by the OECD (OECD and BRS Group, 2018). We believe this demonstrates that overcapacity in shipbuilding continues to impact market cycles and demand pricing, and partly because unit costs often decline over time for technology. If higher shipping cost baselines were used in the analysis, the relative effect of BTWS costs would be smaller. With these baseline shipping costs, we believe the relative effect of added ballast water treatment costs provides reasonable and conservative estimates for exogenous shocks to the global economic model.

We estimate ballast water discharge volume for each shipping voyage with a regression following Seebens et al. (2013), with ballast water discharge data published by the National Ballast Information Clearinghouse (National Ballast Information Clearinghouse, 2019, Seebens et al., 2013). Not all ships discharge ballast water when entering a port; the fraction of port arrivals without ballast water discharge is estimated to be between 42% and 88%, depending on vessel type (Seebens et al., 2013). Hence, we assume a ballast water discharge probability of 50% in this study. For vessels with missing DWT information, we use an average discharge volume to estimate ballast discharge volumes.

Several works estimate the cost of barge-based BWTS (Glosten et al., 2018a, COWI A/S, 2012, Maglić et al., 2015, King and Hagan, 2013), and we use cost estimates from Glosten et al. for California to achieve stricter-standard (Glosten et al., 2018a). Though a barge-based BWTS industry is not in place, the Glosten et al. (2018) report is the best estimate that can be obtained. The work of King and Hagan provides cost data for the IMO-standard BWTS (King et al., 2009). These two reports include various BWTS with different cost estimates for different vessels. This work does not aim to identify the best BWTS for each vessel; rather, we investigate the cost of the whole world fleet. Therefore, we use the average of the highest and lowest values from the literature to represent the best estimates. The lower cost values are within 0.75 times the average and higher cost values are within 1.5 times the average.

4.2.2 Economic model and data

This work uses a computable general equilibrium (CGE) modeling framework known as GTAP (Global Trade and Analysis Project), specifically an extension of the GTAP-Energy/Environment (GTAP-E) model by Nong and Siriwardana (2017). The GTAP-E model is widely used and has been employed to examine the impacts of various policies on international trade (for example, see Baier and Bergstrand (2009); Bekkers et al. (2016); Countryman et al. (2016)). CGE models include interactions between producers, consumers, investors, households, and governments. Though CGE models require more calibration data and behavioral assumptions than sector-specific economic models, CGE models are useful when relationships between sectors or countries are important or when policies imposed on one sector have economy-wide impacts, which are all likely to be true when considering policies targeting transportation and shipping sectors. A brief description of the model and specific

changes made for this analysis is given here; more details on the model structure can be found in Nong and Siriwardana (2017).

Economic agents in the model include households, government, industries, and investors. Households and governments are the final consumers in each country; they buy goods and services supplied by domestic and international industries. Households maximize utility subject to their budget constraints. A household receives income by supplying labor, and the government receives tax revenue (sales tax, business taxes, import and export taxes, and investment taxes). Industries provide outputs for final consumers and goods used in the production process of other sectors. The production process in each sector uses goods produced domestically and from international markets, labor, capital, and other resources. In addition, national economies are connected by bilateral trade for each commodity in the model.

The model includes transportation services, such as water, air, road, and rail, which are used to facilitate trade between sectors and countries. Industries use transportation services to move products to other sectors in domestic and international markets. For example, agricultural industries in China may use road and rail transport services to transport agricultural goods to customers in India, while air and/or water transport services are used to move products to customers in the U.S. or Canada. Agricultural industries in China also use transportation services to move products to other industries and final customers in their domestic market.

In this model, changes in transport costs affect consumer and industry purchasing power, thereby affecting trade volumes between sectors and countries. That is, demands for commodities will change when commodity prices change. For example, if transportation costs from China to the U.S. fall and other conditions held

constant, U.S. customers will substitute away from relatively higher-priced suppliers and purchase cheaper products from China. All agents are connected; therefore, changes in transport costs associated with ballast water treatment lead to changes in global trade patterns.

We use the GTAP-E database version 9, which represents the world economy in 2011 (Aguiar et al., 2016) in tandem with the modified GTAP-E model. The global database includes production, consumption, investment, import, and export values6. We aggregate 134 regions into 21 regions as discussed in Section 2.1 and aggregate 57 sectors/commodities into 17 main sector/commodity groups, which are mapped with 8 vessel types as described in Table C1 in Appendix C.1.

4.2.3 Trade to shipping traffic

The next step is to estimate changes in shipping traffic for the container, bulk, and tanker vessels with the results of the economic model (the lowest part in Figure 4.1). Accordingly, we estimate changes in shipping voyages for different vessel types with the DWT of vessels engaged in trade and allocated to a route (Equation 4), which are determined by the simulated changes in total trade from the economic model (Equation 5). The total DWTs in the equations represent the demand for total DWT of the working world fleet of each vessel type.

$$\text{Change in shipping voyages} = \frac{\text{change in total allocated DWT}}{\text{vessels' average DWT}} \qquad \text{(Equation 4)}$$

$$\text{Value/weight ratio} = \frac{\text{current total trade value}}{\text{current total cargo volume}} = \frac{\text{change in trade value}}{\text{change in cargo volume}}$$

$$= \frac{\text{current total trade value}}{\text{current allocated DWT} * \alpha} = \frac{\text{change in trade value}}{\text{change in total allocated DWT} * \alpha} \qquad \text{(Equation 5)}$$

6 The database is measured in U.S. dollars. Exchange rates do not play any role in this modeling.

First, value/weight ratios are estimated for different commodities between different countries (Halim et al., 2018b, Halim et al., 2018a) to serve as a bridge to link the status quo and changes due to regulatory compliance for the same commodity between the same country pair. Second, we assume the utilization of a shipping route is constant, i.e., the cargo volume carried by a vessel is assumed to be constant with the proportion of its DWT.

4.3 Results and discussion

We present findings for changes in shipping costs, followed by the economic impacts on trade and national economies, and changes in global shipping traffic as a result of BWM regulations defined by Scenarios 1 and 2. Transportation industries account for small contributions to the global economy in terms of monetary values, which leads to modest aggregate economic effects. However, we find substantial impacts on certain commodities, countries, and shipping routes.

4.3.1 Changes in shipping costs

Changes in shipping costs for container vessels, bulk vessels, and tankers are provided in Tables C2-C7 in Appendix C.2. The average compliance cost (per vessel) of these three vessels accounts for 1.5% of the current shipping cost under Scenario 1, and 2% under Scenario 2. These percentages become 4.6% and 4.9% when all vessel types are included (Wang and Corbett, 2020). The current shipping cost is composed of operating cost (14%), periodic maintenance (4%), voyage cost (40%), and capital cost (42%) (Stopford, 2009). The average ballast water management compliance cost is lower than the periodic maintenance cost.

Shipping costs for voyages between most countries in both scenarios do not change substantially; however, the costs for routes between some country pairs change

greatly. Therefore, we report the pairs of countries with large cost changes, i.e., larger than 10% for at least one vessel type, in Table 4.1. Overall, Scenario 2, which provides better protection from species invasion, leads to the largest increases in shipping costs across vessel types.

Table 4.1 Changes in shipping costs in 2011 for three vessel types traveling between countries

Pair of countries	Container: Scenario 1		Container: Scenario 2		Bulk: Scenario 1		Bulk: Scenario 2		Tanker: Scenario 1		Tanker: Scenario 2	
	%	$ Thousand	%	$ Thousand	%	$ Thousand	%	$ Thousand	%	$ Thousand	%	$ Thousand
CAN/USA	2	800	15	7,800	3	4,000	36	46,000	2	1,600	14	16,000
COL/USA	1	150	8	1,300	2	560	15	5,100	1	890	9	8,900
MEX/USA	1	750	11	7,700	3	2,200	27	21,000	2	3,600	16	39,000
PAN/USA	1	1,800	6	13,000	2	3,100	16	25,000	1	2,300	8	19,000
VEN/USA	1	73	11	750	2	500	11	500	1	1,800	8	19,000
ESP/MEX	11	5	11	5	1	3	1	3	1	10	1	11
MEX/VEN	23	3	23	3	1	22	5	27	1	34	2	41
AUS/USA	7	2	53	11	1	210	4	1250	1	18	2	133
BEL/AUS	-	-	-	-	22	3	23	4	-	-	-	-
VEN/AUS	-	-	-	-	25	5	25	5	-	-	-	-
BEL/GBR	-	-	-	-	10	1,200	11	1,300	4	1,990	4	2080
DEU/VEN	-	-	-	-	19	2	19	2	-	-	-	-
NLD/VEN	-	-	-	-	23	3	24	3	-	-	-	-
DEU/USA	1	50	3	520	1	65	9	720	1	8	14	76
PAN/MYS	-	-	-	-	1	4	1	5	23	2	24	2
CHN/PAN	1	540	1	680	1	1100	1	1230	22	4	23	4
ESP/SGP	-	-	-	-	1	7	1	7	14	300	14	300
KOR/VEN	-	-	-	-	-	-	-	-	15	2	15	2
ZAF/VEN	-	-	-	-	1	9	1	9	15	5	16	5

Note: Scenario 1 corresponds to Consistent IMO BWM Regulation and Scenario 2 represents the U.S. Stricter BWM Regulation. Percentages rounded to integral for reader comparison; percentages less than 1% are round to 1%. Dollars rounded to thousand. The routes shown have at least a 10% change in cost for one of the ship types. No traffic may between the routes for certain vessel types, shown with -. Countries are shown in three-digits Code: https://unstats.un.org/unsd/tradekb/knowledgebase/country-code.
Source: Authors' calculations

The high percentage changes are a result of high compliance costs or relatively low baseline shipping costs. For example, the percentage change in container vessel shipping from Belgium to Australia in Table 4.1 is as high as 22%, but its absolute cost change is only $3,000. In contrast, the percentage change for a container vessel voyage from Belgium to the UK is less than half of the aforementioned value (10%), but the absolute cost change is $1.2 million. This is because of the relatively high baseline shipping cost from Belgium to the UK and the lower baseline shipping cost from Belgium to Australia. The baseline shipping cost from Belgium to the UK is higher than that of Belgium to Australia, even though the distance is shorter because there are a greater number of voyages that occur. The country-to-country shipping cost is aggregated over all shipping voyages between a country pair.

Table 4.1 indicates more country pairs have large changes in shipping costs for bulk vessels and tankers. The average changes in shipping costs of tankers are 3.4% and 3.9% under Scenario 1 and 2, respectively. The changes are 1.8% and 2.4% for bulk vessels, and 1.3% and 1.7% for container vessels. This reveals that ballast water discharge regulations fall more heavily on bulk vessels and tankers, and this is true for both Consistent IMO Regulation (Scenario 1) and Stricter Regulation (Scenario 2). This is attributed to several possible reasons: First, bulk vessels and tankers have fewer annual voyages per vessel on average (9 and 13 voyages), compared to container vessels (18 voyages), so the cost of vessel-based BWTS is shared among fewer voyages, causing higher cost changes[7]. Second, bulk vessels and tankers discharge more ballast water in total (389 and 280 million tons) compared to container

[7] The data are from authors' calculations.

vessels (108 million tons), so bulk vessels and tankers have higher treatment costs under both scenarios.

Changes in shipping costs under the two scenarios are similar in the magnitude for country pairs other than the U.S., indicating that regionally stricter ballast water regulation and better protection from aquatic invasion has minimal impact on non-U.S. routes. Relatively small differences that arise for some country pairs can be explained with the cost models. Taking a country pair, A-B for example, the shipping cost calculation only includes the voyages from A to B of all vessels. However, some vessels undertake many voyages and travel to other countries besides B. If all the destinations are non-U.S. countries, then the costs are identical in Scenarios 1 and 2. This is because the vessel only needs to meet the IMO standard with its onboard BWTS, and the increased compliance cost refers to the cost of the BWTS that does not change across the two regulatory scenarios. If the vessel travels to U.S. ports besides B, then shipping costs increase more under Scenario 2. This is because, under Scenario 2, the vessel must use port-based BWTS to treat ballast water at U.S. ports to achieve the stricter standards and use vessel-based BWTS at other ports. In this way, the compliance cost includes some of the port-based cost and its onboard BWTS. However, under Scenario 1, the compliance cost only refers to the cost of its vessel-based BWTS, which is lower than the cost incurred under Scenario 2.

4.3.2 Impacts on International Trade and National Economies

The impacts of increased costs from BWM in Scenarios 1 and 2 cause relatively minor changes to aggregate trade levels across countries; however, noteworthy decreases in bilateral trade of certain commodities between trade partners occurs. In Scenario 1, when all countries follow the international standard to the BWM

Convention, the induced costs are relatively small, as fully described previously, leading to corresponding minor impacts on overall trade between all countries. Columns (1) and (5) in Table 4.2 show that imports and exports for most countries decline by less than 0.1%. Stricter standards outlined in Scenario 2 lead to larger changes in trade than Scenario 1 and trade between the U.S. and its primary trading partners are affected the most. Columns (3) and (4) in Table 4.2 show that exports from Australia, the U.S., and Canada decline by 0.14% ($380 million), 0.31% ($5.7 billion), and 0.25% ($1.2 billion), respectively. In addition, imports into several countries also decrease by 0.27% ($700 million) for Australia, 0.33% ($8.8 billion) for the U.S., 0.4% ($1.9 billion) for Canada, 0.24% ($770 million) for Mexico, and 0.34% ($180 million) for Venezuela.

Although aggregate, country-level, changes in trade are minor, there are noteworthy disruptions in bilateral trade of several commodities resulting from increased BWM regulatory compliance costs. Table 4.3 provides changes in bilateral commodity trade shipped by container, bulk, and tanker vessels. In general, changes in bilateral exports of commodities are highly and negatively correlated with changes in shipping costs of vessels, as expected. For example, in Scenario 1, the shipping cost of container vessels from China to Venezuela increases by 8.83% (Table C2 in Appendix C.2), and exports of commodities transported by container vessels for this route decrease by -1 to -2.6% (Table 4.3). By contrast, shipping costs of container vessels from Mexico to China only increase by 0.13% in Scenario 1 (Table C2), leading to a 0.1% change in exports transported by container vessels for this route (Table 4.3).

Table 4.2 Changes in real aggregate imports and exports by country

Countries	Exports				Imports			
	Scenario 1		Scenario 2		Scenario 1		Scenario 2	
	% change (1)	Real change ($ million) (2)	% change (3)	Real change ($ million) (4)	% change (5)	Real change ($ million) (6)	% change (7)	Real change ($ million) (8)
Australia	-0.04	-110	-0.14	-380	-0.08	-220	-0.27	-700
China	-0.06	-1,200	-0.05	-950	-0.1	-1,700	-0.08	-1,300
Japan	-0.03	-300	-0.01	-130	-0.05	-510	-0.02	-210
South Korea	-0.02	-150	0	8	-0.04	-250	-0.01	-42
Singapore	-0.02	-59	0	-6	-0.02	-45	0.02	58
Malaysia	-0.03	-80	-0.02	-42	-0.07	-140	-0.05	-100
Taiwan	-0.03	-120	-0.02	-90	-0.06	-170	-0.04	-120
USA	-0.03	-580	-0.31	-5,700	-0.04	-990	-0.33	-8,800
Canada	-0.05	-250	-0.25	-1,200	-0.08	-400	-0.4	-1,900
Mexico	-0.02	-88	-0.06	-200	-0.07	-220	-0.24	-770
Colombia	-0.02	-10	-0.04	-20	-0.06	-34	-0.19	-110
Panama	-0.05	-9	-0.13	-22	-0.05	-18	-0.11	-37
Venezuela	-0.03	-25	-0.06	-45	-0.14	-71	-0.34	-180
Belgium	0.01	43	0.03	140	0.01	47	0.04	160
Germany	0	-30	0.01	160	0	6	0.02	320
Spain	-0.01	-23	0	7	-0.01	-49	0	-8
France	0.01	81	0.03	210	0.01	76	0.03	220
UK	-0.04	-290	-0.01	-80	-0.05	-420	-0.02	-170
Netherlands	0	-17	0.02	74	-0.01	-39	0.02	65
South Africa	-0.01	-15	0	-5	-0.03	-31	-0.01	-16
Rest of World	-0.03	-2,400	-0.04	-2,900	-0.06	-4,300	-0.08	-5,700
The whole world	-0.03	-5,600	-0.06	-11,000	-0.05	-9,500	-0.1	-19,000

Note: Scenario 1 corresponds to the Consistent IMO BWM Regulation and Scenario 2 represents the U.S. Stricter BWM Regulation. Export values are measured at FOB (free on board) prices, which include the costs of delivering goods to the ports. Import values are measured in CIF (cost insurance and freight) prices, which include transportation costs and insurance fees to having goods to the port of destinations. Percentages rounded to two decimals, and dollars rounded to millions, for reader comparison; smaller numbers do not imply precision.

Table 4.3 Changes in exports by commodity between countries.

Vessel types	Commodities	Australia to USA				China to Venezuela				USA to Canada				USA to Mexico			
		Scenario 1		Scenario 2		Scenario 1		Scenario 2		Scenario 1		Scenario 2		Scenario 1		Scenario 2	
		(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Bulk	Crop products	0.2	0	2.7	0.3	0	0	-0.4	0	-1	-3.4	-2.9	-9.4	-0.2	-0.5	-1.7	-4.9
Bulk	Wheat and grains	0.3	0	5.7	0	0.4	0	0.1	0	-0.8	-3.1	-1.8	-6.8	-0.3	-14	-0.8	-32.3
Bulk	Coal	0.4	0	5.3	0.2	0.3	0	-0.2	0	-1.8	-8.1	-3.7	-16.6	-1.4	-2.4	-2.3	-4.1
Container	Forestry and foods	-1.6	-16.5	-21.1	-220.9	-2.3	-0.4	-2.5	-0.4	-0.2	-21.1	-0.6	-63.8	-0.3	-19.7	-0.6	-42.9
Container	Textiles	-2.7	-6.7	-33.9	-83.4	-2.6	-22.1	-2.9	-24.7	-0.3	-44.3	-1	-142.4	-0.2	-18.1	-0.5	-56.2
Container	Metal & chemicals	-1.3	-46.1	-18.8	-686.9	-2.6	-27.3	-2.8	-29.5	-0.3	-160.3	-0.8	-502.6	-0.1	-47.9	-0.4	-207.8
Container	Machine & equip.	-0.7	-21.5	-12.1	-368.2	-1	-36.9	-1.1	-42.6	-0.1	-57.2	-0.5	-284.6	0	-12.7	-0.3	-119.1
Tanker	Oil products	0.1	0.1	0.9	0.8	-0.1	0	-0.2	0	0.2	22.8	-0.5	-59.5	-0.2	-47	-0.8	-164
Tanker	Gas	1.3	0.2	3.9	0.5	0.5	0	-0.6	0	-0.5	-12.1	-1.4	-31.1	-0.7	-12.8	-2.3	-44.2
Tanker	Crude oil	0.2	0.4	1.1	2.4	0.4	0	-0.2	0	-0.5	-1.8	-2.4	-8	-3	0	-6.5	0

Vessel types	Commodities	Canada to USA				Spain to Mexico				Colombia to China				Colombia to USA			
Bulk	Crop products	0	0.1	-1.6	-7.4	0.2	0	-0.3	0	0.1	0	1.9	0	-0.7	-12.8	-6.3	-119.3
Bulk	Wheat and grains	-0.4	-5.2	-6.2	-82.5	0.8	0	1	0	0.1	0	0.6	0	-0.1	0	2.3	0
Bulk	Coal	-0.8	-1.5	-14.4	-28.1	0.5	0	0.4	0	0.3	0.5	0.8	1.3	-0.3	-2.1	-2	-16.4
Container	Forestry and foods	0	-1	0.2	17.8	-2	-4.2	-2.1	-4.4	0.1	0	0.4	0	-0.2	-0.9	-1	-5.4
Container	Textiles	-0.3	-60.4	-3	-662.8	-2.7	-17.9	-2.7	-17.5	0.1	0	0.6	0.2	-0.1	-0.6	-0.8	-3.3
Container	Metal & chemicals	-0.2	-126.9	-1.8	-1220	-2.8	-29.4	-2.8	-29.1	0.3	1.7	0.7	4.1	0	-1.2	0	0.1
Container	Machine & equip.	-0.1	-34.3	-0.7	-251.7	-1	-13.9	-0.9	-13.1	0	0	0.6	0	-0.1	-0.3	-0.3	-1
Tanker	Oil products	-0.3	-31.7	-2.5	-316.3	0.2	0.1	0.5	0.3	0.2	0	0.7	0	-0.1	-0.5	-0.8	-8
Tanker	Gas	0.1	7.7	1.6	180.8	2	0	2.8	0	0.1	0	3.2	0	0.4	0	5.5	0
Tanker	Crude oil	0	-19.6	0	4.7	-0.2	0	-1.7	0	0.2	1.3	1.3	10.8	-0.1	-15.2	-1	-103.6

Vessel types	Commodities	Mexico to China				USA				Venezuela				Spain			
Bulk	Crop products	-0.3	0	1.4	0	-0.6	-3.2	-7	-38.5	-1.3	0	-0.3	0	0.1	0	1.8	0
Bulk	Wheat and grains	0.1	0	0.8	0	-0.5	-0.1	-3.4	-0.6	-0.7	-0.5	-0.5	-0.4	0	0	0.7	0
Bulk	Coal	-0.9	0	-0.5	0	0.6	0	7.8	0	0.3	0	0.6	0	0.2	0	0.8	0
Container	Forestry and foods	0.1	0.2	0.5	0.9	-0.1	-8.6	-0.8	-67.6	-7.6	-4.9	-7.5	-4.8	0	0.5	0.3	0
Container	Textiles	0.1	0.2	0.6	1.1	0	-2.3	0.1	16.3	-10.9	-7.6	-10.7	-7.5	0	0.2	0.4	0
Container	Metal & chemicals	0.1	4	0.5	16.7	-0.1	-17.5	-0.7	-213.5	-4.4	-40	-4.1	-37.6	0.1	1.6	0.5	0.2
Container	Machine & equip.	0.1	1.4	0.7	11	0	15.4	0.1	95.7	-3.1	-13.8	-2.7	-12	0.1	1.8	0.6	0.1
Tanker	Oil products	0.2	0	0.9	0.1	-0.2	-9.9	-2	-113.7	0	0	0.5	0	0.1	0	0.9	0
Tanker	Gas	-0.5	0	3.4	0	-0.5	-0.1	1.3	0.1	0.1	0	3.4	0	-0.5	0	3.5	0
Tanker	Crude oil	0	0.1	3.1	26.7	-0.3	-65.2	-2.3	-614.5	0.6	0	3.4	0	0.3	90.6	3.2	7.2

Vessel types	Commodities	Venezuela to China				USA				Belgium				Germany			
Bulk	Crop products	0.1	0	0.8	0	-0.4	0	-0.3	0	-0.2	0	0.2	0	0	0	0.5	0
Bulk	Wheat and grains	0.1	0	0.6	0	0.2	0	6.4	0	0	0	0.4	0	-0.1	0	0.4	0
Bulk	Coal	0.3	0	0.7	0	-0.6	-0.1	-0.8	-0.2	-0.1	0	0.3	0	-0.4	-0.1	-0.1	0
Container	Forestry and foods	0	0	0.4	0	-0.2	-0.1	-1.3	-0.6	0	0	0.2	0	-0.1	0	0.2	0
Container	Textiles	-0.1	0	0.5	0.1	-0.1	0	1.2	0.1	-0.2	0	0.4	0	-0.2	0	0.3	0
Container	Metal & chemicals	0	-0.3	0.4	4.9	-0.7	-7.9	-5.4	-66.1	-0.1	-0.3	0.4	1.2	-0.1	-0.2	0.4	0.9
Container	Machine & equip.	-0.2	0	0.6	0	-0.5	-0.4	-3.2	-2.2	-0.2	0	0.5	0	-0.2	0	0.5	0
Tanker	Oil products	0.1	7.1	0.5	26.7	-0.1	-2.8	-0.6	-34.2	0.1	0.1	0.6	0.4	0	0	0.5	0.5
Tanker	Gas	-0.5	0	1.4	0	-0.2	0	3.7	0	-1.1	0	1.1	0	-0.5	0	1.4	0
Tanker	Crude oil	0	1.9	1	52.8	-0.2	-43.6	-1	-272.4	0.2	2.5	1.3	13.1	0.3	3	1.3	12.6

Note: (a) indicates percentage change, (b) indicates value change ($ million). Numbers rounded to one decimal. Scenario 1 corresponds to the Consistent IMO BWM Regulation and Scenario 2 represents the U.S. Stricter BWM Regulation. Results include both absolute value changes greater than $10 million and percentage changes greater than 1% for at least one vessel type.

Source: Authors' simulations

Results for Scenario 1 in Table 4.3 indicate that if all international and regional regulations require similar standards to the BWM Convention, there will be negligible impacts on most bilateral trade in the international market. For example, exports of forestry and food products, and metal and chemicals commodities from Australia to the U.S. only decrease by 1.6% ($16.5 million) and 1.3% ($46.1 million), respectively. In Scenario 2, when all ports in the U.S. apply stricter BWM regulation, economic impacts are higher and spread across more commodities and countries (Table 4.3). For example, exports of textiles, metal, and chemicals, and machines and equipment from China to Venezuela decline by 2.6% ($22.1 million), 2.6% ($27.3 million), and 1% ($36.9 million) in Scenario 1, respectively. These exports fall by 2.9% ($24.7 million), 2.8% ($29.5 million), and 1.1% ($42.6 million) in Scenario 2, respectively. This is because higher transportation costs between the U.S. and all other countries in Scenario 2 cause trade diversion resulting from changes in relative shipping costs. Exports from some countries to the U.S. decrease substantially in Scenario 2. Specifically, exports from Australia to the U.S. decline at relatively high rates. For example, exports of the other agricultural commodities product category decrease by 21.1% ($220.9 million), textiles by 33.9% ($83.4 million), metal and chemicals by 18.8% ($686.9 million), and machine and equipment by 12.1% ($368.2 million). Trade diversion is illustrated when exports of metal and chemicals from Australia to the U.S. decrease, as previously described, yet increase to China (+0.14% or +$80 million), Japan (+0.37% or +$62 million), and South Korea (+0.5% or +$62 million) (Table C8 in Appendix C.3). In this regard, stricter regulation applied to all U.S. ports adversely affects exports to the U.S., as expected. Trade diversion also affects

domestic and foreign production. For example, the impacts on Australian sectors' performance are relatively higher in Scenario 2 (Table C9 in Appendix C.4).

There are mixes of both positive and negative changes because of the substitution effects when global transport costs increase. That is, countries will divert purchases from higher-cost suppliers with lower-cost sources. Also, there are sectoral level substitution effects in each country where low-cost inputs are used in place of relatively higher cost commodity inputs. For example, sectors can substitute between coal, petroleum products, natural gas, and crude oil when prices of any commodities increase relative to the others. Table C9 also shows that the production levels of sectors in the U.S. are more negatively affected in Scenario 2. This is because U.S. sectors face higher costs for imported commodities, thereby increasing production costs. Some sectors, however, experience additional gains because industrial, private, and public sectors substitute lower-cost inputs to replace higher-cost commodity inputs. For example, the crop product and crude oil sectors increase output levels by 0.51% and 0.17% in Scenario 2, respectively, compared to 0.03% and 0.01% in Scenario 1. In this instance, crude oil can be substitutable for coal, petroleum products, and natural gas, while crop products are used as substitutes for other agricultural products.

Results indicate macroeconomic effects, including changes in the real gross domestic product (GDP), real private consumption, and the consumer price index, decline by less than 0.05% in all countries for Scenarios 1 and 2. As discussed previously, we expect nominal impacts at the global scale given the relatively small increases in international ballast water treatment costs, and more importantly, because water transport only accounts for relatively minor contributions to total GDP in all

countries. For example, water transport contributes 0.2% of GDP in the U.S. and 0.5% of world GDP in total. Stricter BWM regulation applied to all U.S. ports in Scenario 2 negatively affects U.S. economic welfare[8] and negatively affects the economic welfare of other countries by a lesser degree; in both cases, the welfare impacts are nominal. Economic welfare in the U.S. decreases by $1.5 billion (-0.01%) in Scenario 1 and $15 billion (-0.11%) in Scenario 2 (Table 4.4). Welfare losses are less than 0.2% for all countries considered, and Australia, Canada, and Mexico experience higher economic welfare reductions in Scenario 2 resulting from higher transport costs.

Table 4.4 Changes in economic welfare across countries.

	Scenario 1		Scenario 2	
	% change	Absolute change ($ million)	% change	Absolute change ($ million)
Australia	-0.03	-300	-0.09	-1,100
China	-0.03	-1,600	-0.02	-1,100
Japan	-0.01	-660	0.00	-200
South Korea	-0.03	-270	-0.02	-180
Singapore	0.00	-11	0.02	40
Malaysia	-0.06	-140	-0.06	-140
Taiwan	-0.04	-170	-0.03	-130
USA	-0.01	-1,500	-0.11	-15,000
Canada	-0.04	-600	-0.18	-2,800
Mexico	-0.02	-250	-0.11	-1,100
Colombia	-0.02	-49	-0.06	-170
Panama	-0.06	-18	-0.11	-34
Venezuela	-0.05	-140	-0.11	-310
Belgium	0.01	39	0.03	150
Germany	0.00	-160	0.00	110
Spain	-0.01	-77	0.00	3
France	0.00	37	0.01	220
UK	-0.03	-590	-0.01	-200
Netherlands	-0.01	-84	0.00	-21
South Africa	-0.01	-43	-0.01	-26

[8] We measure economic welfare in terms of equivalent variation, a money-metric measure of economic well-being associated with changes in prices.

Note: Economic welfare is measured by equivalent variation. Scenario 1 corresponds to the Consistent IMO BWM Regulation and Scenario 2 represents the U.S. Stricter BWM Regulation. Percentages rounded to two decimals, and dollars rounded to millions, for reader comparison; smaller numbers do not imply precision.
Source: Authors' simulations.

4.3.3 Changes in shipping traffic

In general, changes in shipping traffic resulting from ballast water regulation are small, and the shipping pattern is robust to ballast water regulation. Table 4.5 reports the routes that have at least 10 shipping voyages changed for one of the ship types. For container vessels, the shipping voyages decline by 21 voyages (of 3640 voyages) at most under both policy scenarios, and most of the percentage changes in voyages are less than 1%. The percentage changes in container vessel traffic from South Korea to China and Canada to the U.S. are the same (0.2%), but the absolute voyage change from South Korea to China is much higher (8133 voyages). This is due to the high current voyage numbers from South Korea to China. Stricter U.S. BWM regulation, Scenario 2, has the biggest impact, from a percentage change perspective, on the shipping routes for container vessels from Canada and Venezuela to the U.S.

The changes in bulk vessel traffic are almost the same under both scenarios between Asian countries, while bulk vessel traffic decreases more in Scenario 2 for North American routes, such as Canada to the U.S. (voyages decrease by 5 to 91 trips), Mexico to the U.S. (voyages decrease by 4 to 52 trips), and the U.S. to Canada (voyages decrease by 20 to 45 trips).

Some routes experience larger decreases for tanker traffic under both policy scenarios, such as Malaysia to Singapore, Singapore to Malaysia, and Netherlands to the UK. Scenario 2 brings a much larger traffic change than Scenario 1 for the routes from Mexico to the U.S., (voyages decrease by 4 to 40 trip) and the U.S. to Mexico

(voyages decrease by 1 to 16 trips). The stricter ballast water treatment standards in the U.S. under Scenario 2 will reduce the species invasion risk to the U.S., and decreased shipping traffic will further decrease species introduction risk by limiting the number of voyages. However, one exception to this is for voyages from the U.S. to Columbia, where the decline in tanker traffic is smaller when the U.S. adopts stricter regulation in Scenario 2.

Table 4.5 Country pairs with largest changes in shipping traffic

Country pair	Container vessel					Bulk vessel					Tanker				
	Current Voyage number	Scenario 1		Scenario 2		Current Voyage number	Scenario 1		Scenario 2		Current Voyage number	Scenario 1		Scenario 2	
		Number reduced	%	Number reduced	%		Number reduced	%	Number reduced	%		Number reduced	%	Number reduced	%
KOR/CHN	8,123	14	0.2	15	0.2	1,368	11	0.8	11	0.8	3,259	13	0.4	13	0.4
JPN/CHN	5,206	14	0.3	17	0.3	872	3	0.3	3	0.3	1,300	2	0.2	2	0.2
TWN/CHN	6,366	10	0.2	11	0.2	903	9	1.0	9	1.0	1,230	6	0.5	6	0.5
CHN/JPN	6,077	19	0.3	19	0.3	926	8	0.9	10	1.1	1,200	12	1.0	10	0.8
KOR/JPN	4,456	15	0.3	16	0.4	1,031	16	1.5	17	1.6	3,671	12	0.3	10	0.2
SGP/MYS	3,640	21	0.6	22	0.6	533	8	1.5	8	1.5	5,729	29	0.5	26	0.5
CAN/USA	625	1	0.2	10	1.6	1,535	5	0.3	91	5.9	778	0	0	5	0.6
CHN/TWN	4,664	8	0.2	7	0.2	956	8	0.8	10	1.1	1,374	17	1.2	17	1.2
CHN/KOR	7,537	3	0	3	0	2,102	18	0.8	22	1.1	3,797	14	0.4	11	0.3
USA/CAN	801	2	0.2	5	0.6	1,565	20	1.3	45	2.9	840	0	0	0	0
CHN/AUS	292	0	0	1	0.3	3,747	6	0.2	24	0.6	40	0	0	0	0
JPN/AUS	-	-	-	-	-	1,758	3	0.2	12	0.7	77	0	0	0	0
MEX/USA	700	0	0	1	0.1	757	4	0.5	52	6.9	1,738	4	0.2	40	2.3
MYS/SGP	5,000	7	0.1	7	0.1	570	4	0.7	4	0.7	5,946	50	0.8	51	0.9
NLD/GBR	3,287	4	0.1	4	0.1	988	0	0	1	0.1	5,103	36	0.7	43	0.8
USA/COL	271	1	0.4	2	0.7	122	0	0	1	0.8	438	19	4.3	3	0.7
USA/MEX	381	1	0.3	3	0.8	612	2	0.3	5	0.8	1,773	1	0.1	16	0.9

Note: Scenario 1 corresponds to the Consistent IMO BWM Regulation and Scenario 2 represents the U.S. Stricter BWM Regulation. The routes shown have at least 10 shipping voyages in traffic change for one of the ship types. No container vessel traffic exists from Japan to Australia. Percentages rounded to one decimal. Countries are shown in International Organization for Standardization (ISO) codes: https://unstats.un.org/unsd/tradekb/knowledgebase/country-code.
Source: Authors' simulations

4.3.4 Comparison with studies on environmental policies

The environmental policies for BWM examined in this study target increased costs for marine transport. Spillover effects are then spread throughout the economy. Since the marine transport sector only accounts for small contributions to individual country GDP, and comprise 0.5% of world GDP, BWM policies we investigate have minor economic impacts at aggregate levels for trade, output, and national economic welfare for each country in this study. Other environmental or climate-related policies, such as carbon taxes, emissions trading schemes (ETS), and energy taxes, are found to impose higher costs on national economies than the costs we estimate for BWM scenarios. For example, Adams et al. estimated that an international ETS to decrease global emission levels by 5% in 2050 relative to 2000 levels would decrease real GDP of Australia by 1.1% by 2030 relative to the base case scenario, while real household consumption and imports would decline by 1.5% and 2%, respectively (Adams et al., 2014). Using different assumptions and emission quotas of an ETS to achieve the 2030 target of 28% below the 2005 level in Australia, Nong et al. found a decline of 1.6% of Australian real GDP by 2030 relative to the baseline when examining the impacts of such ETS in Australia. Real exports and imports for Australia would also fall by 2.77% and 2.94%, respectively (Nong and Siriwardana, 2017). Carbon tax studies in South Africa find real GDP decreases by 1-1.59% under different carbon tax rates from $9.15 to $30 per ton of carbon dioxide equivalent (CO_2e) (Alton et al., 2014, Nong, 2020). An international carbon tax study of $50 per ton of CO_2e also indicates that real GDP would decline by 0.94–1.28% for the United States, 0.66–1.54% for China, 0.34–0.57% for India, 0.44–0.55% for Brazil, and 0.12% for the European Union (Nong and Simshauser, 2020).

Energy tax scenarios impose much larger economic costs than explored in our analysis and find larger unfavorable impacts. Tax rates of 5–15% on energy, for example, simulate a decrease of 0.27–1.13% in Chinese GDP (Peng et al., 2019). Energy taxes associated with renewable energy development and proper revenue recycling mechanisms equal to a 7% tax rate would the decrease real GDP of Spain by 0.08–0.1% (Freire-González and Puig-Ventosa, 2019). Nong et al. also found that substantial increases in energy taxes of 50% for coal and 33% for petroleum products would reduce real GDP of Vietnam by 1.05% and 2.23%, respectively, with private consumption declines ranging from 0.34 to 1.06% (Nong et al., 2019).

It is worth noting that the impacts of a carbon tax, ETS, or energy tax vary across countries, depending on several key factors. Economic effects depend on the magnitudes of the costs imposed, the market structures and market shares of energy/emission-intensive sectors and expenditure shares for energy commodities, details of revenue recycling mechanisms, and on the extent of sector coverage in each country and potential policy. These environmental or climate change policies in the literature focus on reduced greenhouse gas emission levels and apply to most (if not all) sectors in the economy, while BWM regulations impose direct costs on the marine transport sector.

Both the costs imposed and the economic impacts of BWM regulations are also small relative to other transport costs studies. For example, Bekkers et al. (2018) found that melting Arctic sea ice enabling the Northern Sea Route with transportation cost reductions between Northern Europe and East Asia by 20–30% for all goods transported by sea would affect bilateral real exports from China by -0.51% to 11.98%, and Japan by -0.49% to 16.23%. Real GDP is also affected differently from -

0.1% to 0.4% across countries (Bekkers et al., 2018). On the same topic, but also accounting for the additional new route of the Northwest Passage connecting Northeast Asia and the U.S. east coast, Countryman et al. (2016) found major impacts on the trade of different countries resulting from decreased shipping costs given shorter shipping distances through the Arctic. They found that transportation costs between China, Japan, South Korea, Taiwan and the U.S. east coast would decrease by 6.8–11.2% for all sea transport, while transport costs for routes between Europe and Northeast Asian countries would decrease even further. For example, shipping costs between East Asian nations and Germany would decrease by 19.9–39.4%. As a result, U.S. exports were simulated to increase by 13.5% to China, 13.5% to Japan, and 5% to South Korea. Real GDP changes across countries vary from -0.5% to 1% and are notably higher than the GDP effects of BWM because the costs changes are of larger magnitudes and affect all goods transported by sea between these regions (Countryman et al., 2016).

This policy review shows that the costs imposed by the aforementioned policies are relatively much higher than those derived from examining BWM policies in the present study. Accordingly, results from other environmental policy studies are substantially higher at aggregate and sectoral levels than the economic effects of alternate BWM policy scenarios investigated in this work. However, it is important to note that while the costs and resulting economic impacts of BWM are minor across countries at aggregate levels, potential environmental benefits from BWM may be more widespread across countries and sectors and merit investigation in future work. Further research to explore the benefits of improved environmental quality relative to the costs that we estimate is warranted.

4.4 Conclusion and implications

This study provides a noteworthy contribution to exploring the viability to drive ballast water management policies forward, as well as to integrated economic modeling research. We investigate the impacts of international ballast water policy on transport costs, international trade, national economies, and global shipping patterns. Our findings are consistent with fundamental trade theory and show that the costs of environmental action through BWM in the shipping industry have small economic consequences at aggregate levels but vary in magnitude for bilateral trade of specific commodities between certain countries.

Specifically, our work provides three key findings: 1) current BWM regulation that is uniform across countries (Scenario 1) has nominal negative economic impacts across countries; 2) the proposed scenario of stricter BWM regulation imposed for transport to/from U.S. ports (Scenario 2) has minor effects on trade and national economies at aggregate levels, but causes noteworthy trade reductions of certain commodities between some countries; 3) BWM policies under uniform and stricter standards lead to modest changes in global shipping patterns.

Findings suggest that international ballast water treatment regulation, even when the U.S. applies stricter standards, has minor effects on the global economy when considering changes in international trade, economic welfare, and shipping patterns, yet increased environmental quality can be achieved. However, it is important to consider both aggregate and bilateral trade effects when imposing increased transport costs to achieve invasive species risk reduction through BWM since considerable sector, and country-specific effects are masked when assessing economic effects at aggregate levels across countries.

Results show that changes in shipping costs vary across vessel types, as well as between trade partners because of different trade volumes and values. We find that shipping costs between the U.S. and its trade partners only change slightly in Scenario 1 and are higher for some routes in Scenario 2 due to stricter regulation at U.S. ports. Such cost changes yield relatively small adverse impacts on the global economy for both scenarios due to small shares of the marine transportation sector in the overall economy in each country. However, the trade impacts for certain commodities between countries shipped by different vessel types are highly affected due to relatively high increased shipping costs of vessels for certain shipping routes, including trade between Australia and the U.S., for example. Due to modest changes in total trade values/volumes, there are also only minor changes in shipping voyages on a global scale.

Both uniform and stricter BWM standards negatively affect global economic welfare by small rates, driven by the small share of total global GDP (0.5%) attributed to the marine transport sector. Stricter regulation increases the transportation costs for commodities originating from any trade partner to the U.S. market. However, the U.S. is a large trade partner of many countries around the world, and the costs of BWM are shared across voyages for each vessel type. As a result, the overall marine transport services costs in all countries increase at higher rates in Scenario 2 relative to the increases in Scenario 1 – when all countries apply an international BWM standard regulation. Since the costs of commodities exported to the U.S. market increase, trade is diverted as exporters find other countries for their export products. One key example of trade diversion can be seen for Australian producers of forest products and foods, textiles, metal and chemicals, and machine and equipment, which increased

exports to all other countries at the expense of the U.S. in Scenario 2 when shipping to the U.S. becomes substantially more expensive for this route under stricter BWM regulation. However, trade effects from these cost signals may result in perturbations to the volume of trade (as per GTAP output) or to other shifts in shipping patterns or fleet operations not modeled here

Economic welfare losses are small for all countries when compared to the size of each national economy. U.S. economic welfare losses are the highest, though nominal, totaling -$1,500 in Scenario 1 and -$14,800 in Scenario 2. Other key exporters to the U.S. including Australia, Canada, and Mexico face decreased economic welfare by lesser magnitudes than the U.S. Results confirm that stricter BWM standards applied to U.S. ports affect U.S. producers the most, followed by key U.S. trading partners. While our work focuses on the economic costs of BWM regulation, research to investigate the benefits of increased environmental quality due to stricter BWM standards is warranted for further study to provide decision-makers with an evaluation of the net benefits of BWM and the cost-effectiveness thresholds of potential policy measures.

Chapter 5

SCIENCE-BASED GEOPOLITICAL SHIFT IN SHIPBORNE BIOLOGICAL INVASION MANAGEMENT

5.1 Introduction

This work presents an integrated analysis to move ballast water management policies forward with a risk-policy-economic-technology nexus. Risk reductions at connecting ports are the key to break down the inter-cluster connection and may need stricter regulations. Decision makers require an assessment of cost-effective risk-mitigaing strategies to offset projected surge in unmitigated risk of biological invasions where future shipping may increase substantially. The International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM Convention) aims to prevent, minimize and ultimately eliminate the risk of introducing harmful aquatic organisms and pathogens (HAOP) transferred in ships' ballast waters and sediments.

Two performance standards are set in the D-2 standards of the BWM Convention for "viable organisms" and three performance standards are set for "indicator microbes" in order to protect human health from pathogens. However, these standards are dilution-based, instead of risk-based, so risks may not be clearly mitigated by current standards. Also, such a regulation at the international level is consistent for all the ports, but species invasion risks vary at different locations. The uniform standards cannot meet the higher protection need at certain ports. Therefore, besides the uniform international ballast water management regulation, regional

stricter regulatory standards are necessary to achieve better protection for certain ports.

The D-2 standard is likely only happen with a Ballast Water Treatment System (BWTS) onboard. One BWTS to achieve IMO standards (IMO-BWTS) cost $640,000 to $ 1 million, depending on its capacity and treatment method (can be mechanical, physical or chemical method) (King et al., 2009). California State Lands Commission funded a study to assess the feasibility of purpose-used barge-based treatment systems (called "Stricter-BWTS") to achieve its interim standards can cost even more, which can be $4 to $10 billion (Glosten et al., 2018a). The high costs of compliance technologies motivate the cost-effectiveness analysis of compliance strategies.

Current invasion risk assessment methods based on ship trajectories (Sardain et al., 2019, Seebens et al., 2013, Drake and Lodge, 2004), implicitly assume the next calling port depends only on conditions during ballast uptake at the current port. However, many ships do not discharge entire ballast water in their first port of call (McGee et al., 2006). Ignoring the dependence on multiple past voyages of any destination port neglects carryover of species due to partial ballast water discharge introduced from prior ports (Xu et al., 2016, Saebi et al., 2020). Higher-order-network (HON) analysis can better assess risks among ports and reveal port clusters sharing risk (Xu et al., 2016, Saebi et al., 2020, Sardain et al., 2019). Probabilistic risk-based simulation based on actual vessel movements more accurately achieves reliable and informative clustering results (Xu et al., 2016), and can inform port- or country-level invasion risk assessment and subsequent policymaking. This work identifies both intra- and inter-cluster invasion pathways by using a higher-order species flow network and cluster analysis, and identifies ports linking several clusters; regulating

the connecting ports or high-risk port clusters may disproportionately control species invasion.

We then discuss possible ways for global shipping governance innovation for ship-borne biological invasion management based on risk assessment and cost-effectiveness.

5.2 Ballast water treatment efficacy and species invasion risk

Last section illustrates the potential for more stringent BWM standards from the perspective of regulations, and this section further proves that from the perspective of the port invasion risk assessment. We show this from two aspects: (1) stricter ballast water treatment can reduce the order of port risks, and (2) change the global risk cluster pattern.

5.2.1 Current invasion risk assessment overview and the necessity of HON risk

The risk assessment is based on Species Flow Higher-Order-Network (SF-HON) to consider the more practical species introduction pathway. NIS spread as a result of shipping activity depends on multiple environmental and geographical factors, as well as the complex interactions in the global shipping network. Several studies in the literature attempt to provide an accurate model for NIS risk (Saebi et al., 2019, Seebens et al., 2013, Keller et al., 2011). Recent studies have shown that the NIS spread through the global shipping network is not a simple first-order Markov process (Drake and Lodge, 2004, Saebi et al., 2019). Many ships do not discharge their entire ballast water in their first port of call. As a result, the remaining ballast water discharged by the ship at the next stops poses the risk of NIS transfer from the original port to the next stops. For example, if a vessel goes from Port A to Port B, and

to Port C. The NIS risk not only happens between A-B and B-C (first-order) but also between A-C (higher-order) (Xu et al., 2016). To account for higher-order patterns of NIS spread, we use a model recently developed by Saebi et al. (Saebi et al., 2019). The HON model can do better aquatic species invasion predictions, proved with the largest available datasets of invasive species for Europe and the United States. This model integrates the data of ship trajectories, environmental similarity, and biogeographical data of the ports. Below we briefly explain the risk calculation process and the data source.

5.2.2 Port risk assessment model

(1) Pairwise first-order network (FON) risks

The first step is to calculate the pairwise first-order risk for each route. The pairwise NIS risk spread model consists of three main components. The NIS risk spread for a ship v traveling from port i to port j is the product of these three components:

$$\mathrm{P}(\text{NIS spread})_{ij}^{v} = P(\text{nonindigenous})_{ij} \times \mathrm{P}(\text{intro})_{ij}^{v} \times \mathrm{P}(\text{establish})_{ij}$$

Probability of being *nonindigenous*. This probability is 0 if both source and target ports belong to the same or neighboring ecoregions, and 1 otherwise. Neighboring ecosystems are likely to share more species that are considered non-indigenous (Abell et al., 2008).

Probability of introduction *through ballast water*. This probability calculates the introduction risk for all ships traveling from port i to port j. For each ship v traveling during the time $\Delta t_{ij}{}^{v}$ we have:

$$\mathrm{P}(\text{intro})_{ij}^{v} = \rho^{v}(1 - e^{-\lambda D_{ij}{}^{v}})e^{-\mu \Delta t_{ij}{}^{v}}$$

Where $D_{ij}{}^{v}$ is the amount of ballast water discharged at a port, and estimated with a random forest model ($R^2_{testing}$ = 0.77). ρ^{v} is used to consider different ballast water treatment efficacies. 1-ρ^{v} is the efficacy of BWM for the route. ρ^{v} is 1 when there is no treatment/efficacy. Treatment efficacies of different BWM standards are estimated by the reduction in species concentration, described in the Data section. λ is the species introduction potential per volume of discharge.

Probability of establishment. This probability is calculated based on the model originally proposed by Seebens et al. (Seebens et al., 2013). For every pair of ports (i,j) this probability uses the temperature difference ΔT_{ij} and the salinity difference ΔS_{ij} between port i and port j as follows:

$$\mathrm{P(establish)}_{ij} = \alpha e^{-\frac{1}{2}\left[\left(\frac{\Delta T_{ij}}{\delta T}\right)^2+\left(\frac{\Delta S_{ij}}{\delta S}\right)^2\right]}$$

Where δT and δS are the standard deviation in temperature and salinity.

For the first-order risk between every pair of ports, we aggregate the NIS risk over all voyages from port i to port j:

$$\mathrm{P(NIS\ spread)}_{ij} = 1 - \Pi_{r,v}(1 - \mathrm{P(NIS\ spread)}_{ij}^{v})$$

where the product is taken over all routes r such that a ship v travels from port i to j.

(2) Pairwise higher-order risks

For the higher-order risk between every pair of ports, we calculate the probability of NIS spread for each potential higher-order path using the same formula above. We then feed these paths along with their probabilities to the HON algorithm (Xu et al., 2016) to obtain the higher-order network of species flow. We then build the physical adjacency matrix in which each edge weight (NIS spread risk) is calculated by averaging over all HON edges that correspond to that pair of ports. Finally, we normalize the edge weights by dividing all the edge weights by the maximum value in

the network (For each ballast water treatment scenario, we normalize risks using the maximum risk in the scenario with no treatment for better comparison, instead of using the maximum value for each scenario).

(3) The cumulative risk for each port

In order to calculate the cumulative NIS risk for each port *k*, we aggregate the NIS spread risk over all incoming ports:

$$\mathrm{P(NIS\ spread)}_k = 1 - \Pi_i(1 - \mathrm{P(NIS\ spread)}_{ik})$$

(4) Data

We use the ship movement data from Lloyd's List Intelligence (LLI, New York, NY, USA), which contains the ship travel information including port ID, sail date, and arrival date, along with ship meta-data (from which we used ship size, ship gross weight-tonnage, and type of the cargo carried by ship). The data cover May 2018-April 2019 with 1,425,157 individual voyages. The LLI port dataset includes 4257 ports. The discharge volume of ballast water is estimated with data from National Ballast Information Clearinghouse (NBIC).

In order to calculate the probability of establishment, we use the Global Ports Database (Keller et al., 2011) and the World Ocean Atlas (Locarnini et al., 2013, Zweng et al., 2013) and use a similar approach as suggested by Keller et al. (Keller et al., 2011). The temperature and salinity for 6695 ports were obtained. We did not include the ports for which the environmental data were not available through these sources (such as Panama Canal, Dover Strait, Dardanelles, etc). 3006 of the 4257 ports included in LLI have complete environmental data and we generate risks for 3006 ports. These 3006 ports are the research scope of this work. We calculated the

probability of species being non-indigenous using the ecoregion data from Marine Ecoregion of the World (MEOW) (Spalding et al., 2007).

The ballast water treatment efficacy is obtained with species concentration from the literature and the numeric standards in the regulations. We reviewed seven papers using experimental methods to examine the efficacy of BWTS, which either include the concentration reduction percentage or the species concentration in untreated and treated ballast water (Cohen and Dobbs, 2015, Reusser et al., 2013, Minton et al., 2005, Briski et al., 2015, Briski et al., 2014, Briski et al., 2013, Herwig et al., 2006). Table D1 in Appendix D.1 shows the reviewed data. These papers are focused on different organism classes and BWTS treatment methods. While most of the experiments show that the BWTS cannot meet the IMO standards, and the average percentage reduction is 77.61%. If we use the obtained organism concentrations in untreated water and the IMO standards (assuming BWTS can meet the IMO standards), the average organism percentage reduction should be 99.15%. If BWTS can meet the stricter standards, the efficacy is 99.94%.

5.2.3 Invasion risks for ports with different ballast water treatment efficacies

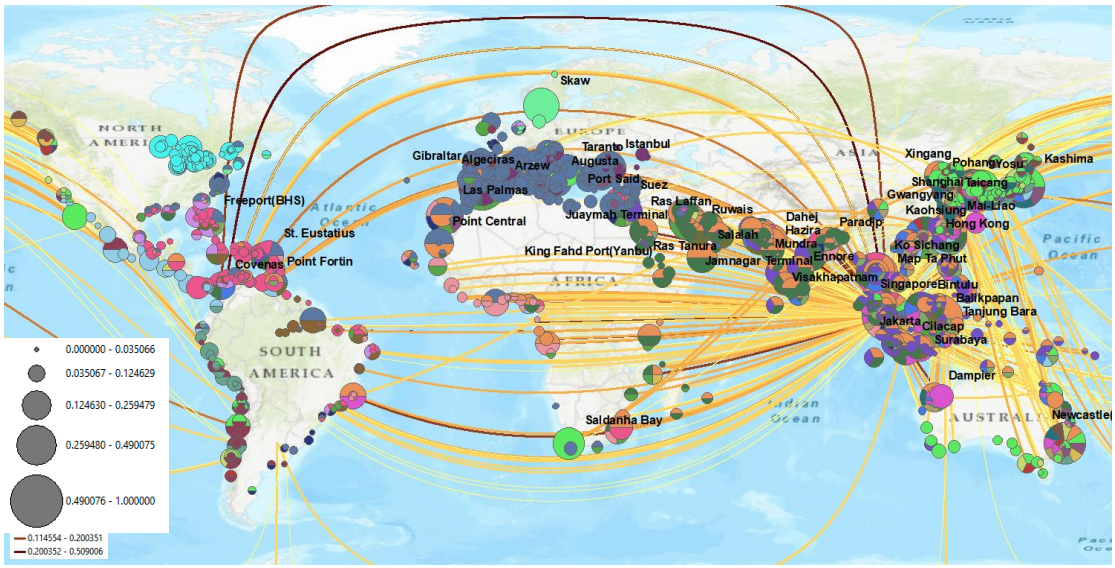
We obtain invasion risks for all ports under different treatment efficacies with the HON risk assessment model. See Table D2 in Appendix D.2. Port risks decrease by 75% when the treatment efficacy of BWTS is 77.61%. If BWTS can meet the IMO standards, the risks decrease by 94% when the treatment efficacy is 99.15% under the current IMO regulation. Risks decrease by 95% with the treatment efficacy is 99.94% when all ports adopt stricter ballast water management standards.

We further compare port risks estimated by the HON risk assessment model with other models based on FON, using shipping traffic to represent invasion risk, or

not considering the impact of ecoregions. See Table D3 in Appendix D.3. The shipping traffic in 2012-2013 is used. It shows that Duluth has the highest risk HON, which is 1; but only a smaller FON risk, which is 0.5. If not considering ecoregion, the HON and FON risks are 0.82 and 0.52. However, the risks are only 0.06 and 0.08 if we use shipping traffic to estimate the risks. Even though the shipping traffic and ballast water discharge events to Duluth are very small, Duluth has very high invasion risk considering environmental parameters and ecoregion. The situation is different for Gibraltar and Singapore. They have very high risks in all risk assessment models, no matter whether the model considers shipping traffic, environmental conditions, and ecoregion impacts or not.

5.2.4 Invasion risk cluster analysis with different treatment efficacies

Cluster analysis provides a large-scale view of species spread and identify the groups of ports within which ports are more connected (Saebi et al., 2019). Ports within the same cluster are more likely to have mutual species spread. This work uses *Infomap* network clustering method with a recursive random-walk algorithm (Rosvall and Bergstrom, 2008), which is the most similar to the species flow pattern.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Taranto
Istanbul
Augusta
Port Said
Suez
Las Palmas
Ras Laffan
Ruwais
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Freeport(BHS)
St. Eustatius
Covenas
Point Fortin
King Fahd Port(Yanbu)
Ras Tanura
Salalah
Jamnagar Terminal
Dahej
Hazira
Mundra
Ennore
Visakhapatnam
Paradip
Xingang
PohangYosu
Kashima
Shanghai
Taicang
Gwangyang
Kaohsiung
Mai Liao
Hong Kong
Ko Sichang
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Balikpapan
Tanjung Bara
Jakarta
Cilacap
Surabaya
Dampier
Saldanha Bay
Newcastle
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0.035067 - 0.124629
0.124630 - 0.259479
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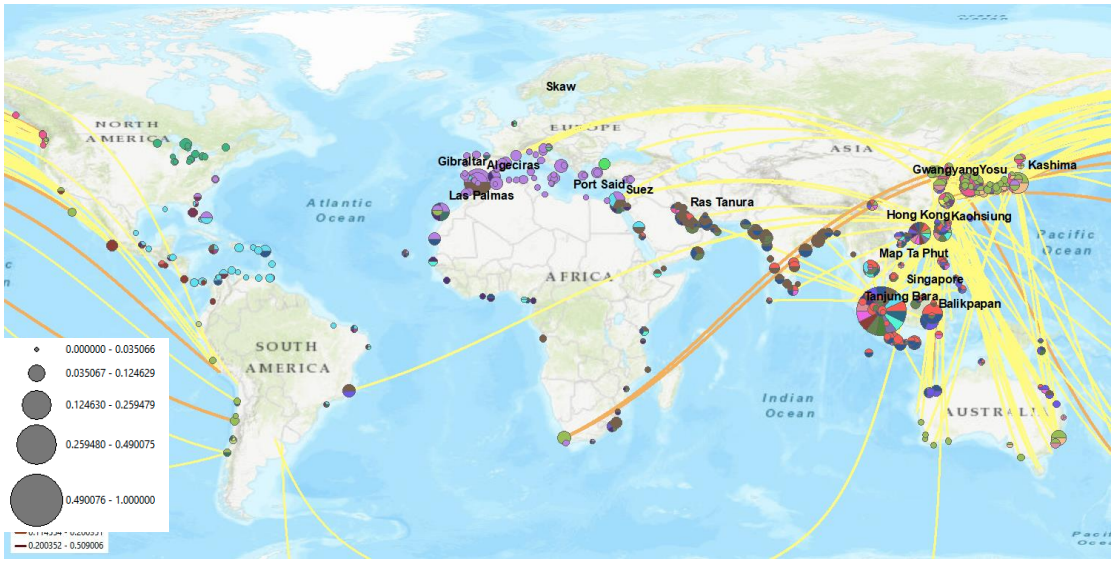
(a)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Singapore
Tanjung Bara
Balikpapan
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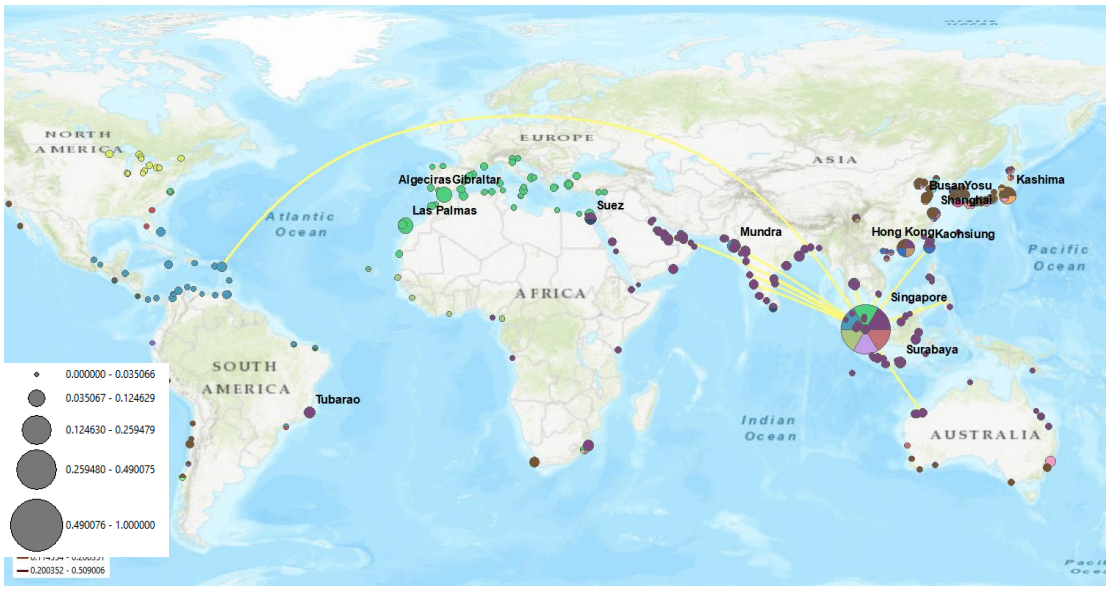
(b)

(c)



(d)

Figure 5.1 Main introduction pathways through ballast discharge and invasion clusters (a) no ballast water treatment (b) treatment with current available BWTS (c) treatment to achieve IMO standards (d) treatment to achieve California's standards. High-risk connections are displayed darker, while low-risk connections are displayed lighter.

The coloring of the ports indicates the port cluster. Ports which belong to multiple clusters through the higher-order patterns are shown as pie charts with multiple colors. The pie chart size indicates the relative NIS spread risk for the port. We visualize the top 30 clusters for visibility.

Each color in the circles represents a different cluster, and the ports in the same cluster have higher invasion risks between each other. Figure 5.1(a) shows that the clusters are overlapping and globally connected, and ports located distantly can fall into the same cluster. This shows the demand for global ballast water management strategies. Also, the plots show many high-risk ports belong to different clusters, forming strong inter-cluster connections. For example, Singapore has the highest invasion risks under four treatment scenarios. It connects 92 clusters in Figure 5.1(a). This further shows the demand for local ballast water management strategies, aiming at high-risk port linking different clusters.

Figures 5.1(b), 5.1(c), and 5.1(d) show that the sizes of clusters become smaller, meaning that ballast water treatment lowers the ports' risks. Also, ballast water treatment can change the cluster patterns. Clusters become less and less overlapping and connected. The globally applied IMO regulation can reduce the risk among ports regardless of their geographical proximity. The stricter regulation on the ports connecting one or more clusters may break down the interconnection of the clusters and reduce the global invasion risk by reducing inter-cluster species introduction. For example, Singapore, remaining the port with the highest risk, belong to 28, 13, and 6 clusters in Figures 5.1(b), (c), and (d), respectively. See Table 5.1.

Table 5.1 the number of clusters linked by each high-risk port

Port	No treatment	Experimental	IMO standards	Stricter standards
Singapore	92	28	13	6

Gwangyang	17	7	6	4
Hong Kong	24	15	11	5
Kashima	17	6	4	3
Gibraltar	8	4	1	1
Las Palmas	14	5	1	1
Yosu	16	7	5	3
Algeciras	14	8	3	2
Shanghai	19	13	9	6
Mundra	12	5	4	3
Suez	20	8	3	2

Table 5.2 the network statistics for each treatment scenario

	No treatment	Experimental	IMO standards	Stricter standards
Number of HON nodes	14674	7790	5057	4366
Number of HON edges	139000	116000	100000	95000
Number of clusters	278	148	108	97

The number of HON nodes and HON edges become fewer under ballast treatment. They are also positively correlated with higher-order patterns. The number of HON nodes is always greater than the number of physical ports, and the additional notes result in higher-order introduction pathways (Saebi et al., 2019). The higher this number, the more higher-order patterns exist. Saebi et al. show that number of higher-order patterns is positively correlated with risk. As a result, nodes with higher-order patterns are more vulnerable to species spread (Saebi et al., 2019). This indicates that ballast water treatment can reduce the higher-order pathways of species transfer via ballast water discharge.

Also, we observe that the number of clusters drops for stricter policies. This is expected since more strict ballast treatment policies result in a lower number of higher-order nodes. These nodes are treated as separate nodes in the clustering algorithm and then mapped back to their physical ports (For example, p2|p0 belongs to

cluster 1 and p2|p1 belongs to cluster 2, while they both represent the physical node "p2"). Therefore, fewer high-order nodes automatically result in fewer unique clusters.

Note that, using the higher-order approach, each physical port can belong to several clusters, because its corresponding higher-order nodes belong to different clusters. For example, $p_2|p_0,p_1$ belongs to cluster 1 and $p_2|p_1$ belongs to cluster 2, while they both represent the physical node p_2. Currently, 37% of ports belong to two clusters and more and species may spread easier within these clusters due to these ports as linkages. The percentage of ports belonging to two clusters and more becomes 13% under the IMO regulation and becomes 10% under stricter regulations.

Table 5.3 the percentage of ports connecting more than one clusters

Treatment	Percentage of ports belong two clusters and more	Percentage of ports belong three clusters and more	Percentage of ports belong four clusters and more	Percentage of ports belong five clusters and more
R0	37	28	22	19
R1	24	16	12	10
R2	13	8	5	4
R3	10	5	4	2

5.3 Cost-effectiveness methods to achieve stricter regulation

Since regional stricter BWM regulations may be needed to achieve better protection from species invasion. High-risk ports are identified in Section 3. This section examines the most cost-effective BWM technologies under different policy scenarios: current IMO regulation, and regional stricter regulation. We use the interim standards of California to represent the stricter standards since it is the only standard proposed besides IMO standards and technological analysis is done to achieve such

standards (Glosten et al., 2018a, California State Lands Commission, 2018b, Wang and Corbett, 2020).

5.3.1 Technological strategy alternatives to comply with the regulations

This work considers vessel- and port-based BWTS methods. Currently, the BWM Convention requires all vessels to have vessel-based BWTS installed onboard by 2024. Port-based BWTS is also another alternative. Port-based BWTS has shown with the benefits because they can accommodate larger and heavier BWTS, use different treatment methods, and are safer for the workers (Maglić et al., 2015, Cohen and Foster, 2000, Pereira et al., 2010, King and Hagan, 2013). The port-based method also avoids the costs in retrofitting vessel-based IMO-BWTS with Stricter-BWTS (COWI A/S, 2012, Rivas-Hermann et al., 2015). Therefore, port-based stricter-BWTS is a potential alternative, especially for future stricter regulation at certain ports.

5.3.2 Policy scenarios and fleet regulatory cost models

This work includes two general policy scenarios: the current IMO regulation and the regional stricter regulation. For each of them, we vary the number of high-risk ports to follow the IMO or stricter regulation. 4257 ports are included in LLI, so 4257 different policy cases are included in each general policy scenario. The ports with the highest risks are obtained by ranking all ports related to international shipping by their HON invasion risks. Since we generate risks for 3073 of 4257 ports, the rest ports are then ranked by the number of vessel arrivals.

Under the IMO regulation, the selected ports follow the IMO standards, and the other ports are not regulated by any policy. When the selected port number is 4257 ports, it represents the policy case that every port/vessel needs to meet IMO standards.

This is the case of current international ballast water management practice. Two compliance strategies are available: (1) all the regulated ports install port-based BWTS, and (2) all vessels calling at the selected ports install vessel-based BWTS.

Under the regional stricter regulation, the selected ports will follow California's standards, and the other ports follow IMO standards. Again, 4257 policy cases are included. This work considers two different assumptions. When we assume no BWTS has been installed onboard before, four alternative compliance strategies are available9: (1) the selected ports install stricter-BWTS at ports and other ports install IMO-BWTS at ports, (2) the selected ports install stricter-BWTS at ports and all vessels install IMO-BWTS onboard, (3) the vessels may call at the selected ports install stricter-BWTS onboard and other vessels install IMO-BWTS onboard, and (4) the vessels may call at the selected ports install stricter-BWTS onboard and the rest ports install IMO-BWTS at ports. When we assume that all vessels have installed BWTS onboard before, only two strategy alternatives are left: (1) the selected ports install port-based BWTS at the port, and (2) the vessels that call at the selected high-risk ports install vessel-based BWTS (other vessels have already have IMO-BWTS onboard).

For each of the 4257 policy cases, we compare fleet compliance costs of different compliance strategies with the established model in previous work (Wang and Corbett, 2020). We update the model from two aspects. (1) We estimate the ballast water discharge volume and probability for each voyage with a random forest model, which provides better estimation than the linear regression method. (2) We

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[9] Other combinations of vessel- and port-based BWTS strategies obviously more expensive are not included in the cost analysis.

adjust the number of barges needed at each port. The model in Wang and Corbett (2020) assumes one barge is used at each port. However, the top-ranked ports are often with more vessel calls, so one BWTS and barge may not provide enough treatment capacity. To avoid possible underestimation of the p-based cost, we adjust the number and barge needed at each port according to the port treatment volume per day (treatment demand) and average BWTS treatment capacity. This is considered in terms of the BW discharge rate, i.e. 30,000MT discharged in 24 hours is similar to 15,000 MT discharged in 12 hours (Glosten et al., 2018b). We choose one day as a unit, then the number needed = volume per day/BWTS capacity/24h (the BWTS capacity is about 2000 ton/h). We also consider the possible vessel arrival peak because vessel arrivals at each port may not be constant within each hour, we checked the vessel arrival profile10 and found the arrival peak is about 3 times as the average arrival number. We assume the vessel arrival number is proportionate to the treated BW volume.

[10] https://www.myshiptracking.com/ports

5.3.3 Cost-effectiveness analysis results

5.3.3.1 Vessel-based BWTS is the less costly way to comply with current IMO standards

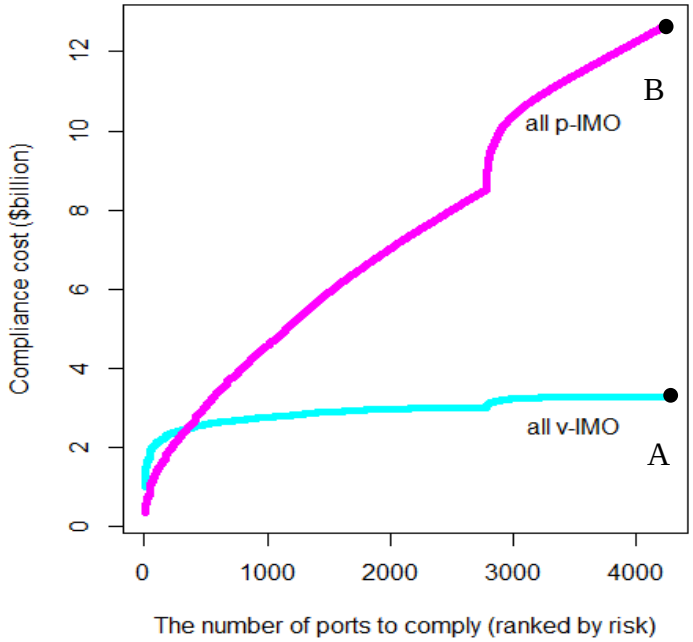

Figure 5.2 first x ports follow IMO regulation, other ports not regulated

Figure 5.2 shows the fleet total costs when the first x ports comply with the BWM Convention and the rest ports are not regulated. The x-axis is the number of ports regulated. This work ranks all the 4257 ports (including straits; domestic voyages removed) by risk (followed by vessel arrivals). The first port is Singapore and the second one is Gwangyang. When x is 2, it means the top two ports are regulated by the BWM Convention and other 4255 ports are not regulated. The y-axis is the fleet total compliance cost. The two lines are discrete and composed of costs at each port number from 1 to 4257. The purple line shows the costs of the port-based treatment method, that all regulated ports need to have BWTS at the port. The blue line represents the costs of the vessel-based treatment method, that all vessels are required

to install BWTS onboard. The current BWM Convention of the IMO requires every vessel to install a BWTS onboard, which is the case of Point A in Figure 5.2. At Point A, all 43,215 vessels install BWTS onboard and the fleet cost is $3.3 billion. Point B shows the port-based method is used at all ports to meet IMO standards, and the total cost is as high as $13 billion. Therefore, Figure 5.2 shows that the vessel-based method is the best way to comply with the current IMO regulation. Though a port-based BWTS can be shared by many vessels, the very high cost of port-based BWTS makes the total cost higher than vessel-based BWTS.

Port-based is not always more expensive. The intersection is where the port number is 350 and the fleet number is 36,004. At the intersection, the cost of vessel-based BWTS is the same as port-based BWTS. When the first 350 ports with higher invasion risks are regulated under IMO regulation, the port-based method costs less; when the number of regulated ports increases to more than 83, the vessel-based method becomes less expensive. This is because these ports tend to be large ports with many arrived vessels. Even though each port-based BWTS costs much more than vessel-based BWTS, a large number of vessels makes the vessel-based method more expensive. This means port-based can be less costly when the number of ports regulated is small, but such a case may not be enough to effectively protect water from species invasion risks.

5.3.3.2 Port-based treatment feasibility for potential future regulatory standards

This section shows the cost comparisons of different regulatory compliance strategies to achieve potential stricter standards. In this case, the work varies the number of ‘selected’ ports with higher risks doing better protection and the rest ports comply with IMO standards. Since the compliance costs are calculated under two

different assumptions, the results are shown respectively in Figure 5.3 and Figure 5.4. In general, we have strong results that the strict BWM regulation is not likely to be cost-effective if they are vessel-based. That is, if we want to do stricter BWM, we need the port-based treatment at high-risk ports.

Figure 5.3 shows the results when no vessel has ever installed IMO-BWTS. The x-axis is the number of ports regulated by potential stricter standards. The ports represented by the numbers are the same as Figure 5.2: the first port is Singapore and the second one is Gwangyang. When x is 2, it means the top two ports are regulated by potential stricter standards and the other 4255 ports are regulated by current IMO standards. This case includes four alternative compliance strategies. The blue and black lines are always higher than the purple and green lines. The blue and black lines represent the methods to use vessel-based BWTS at selected high-risk ports, and the green and purple lines are the methods installing port-based BWTS at selected high-risk ports. Therefore, using port-based BWTS at high-risk ports is the less costly method.

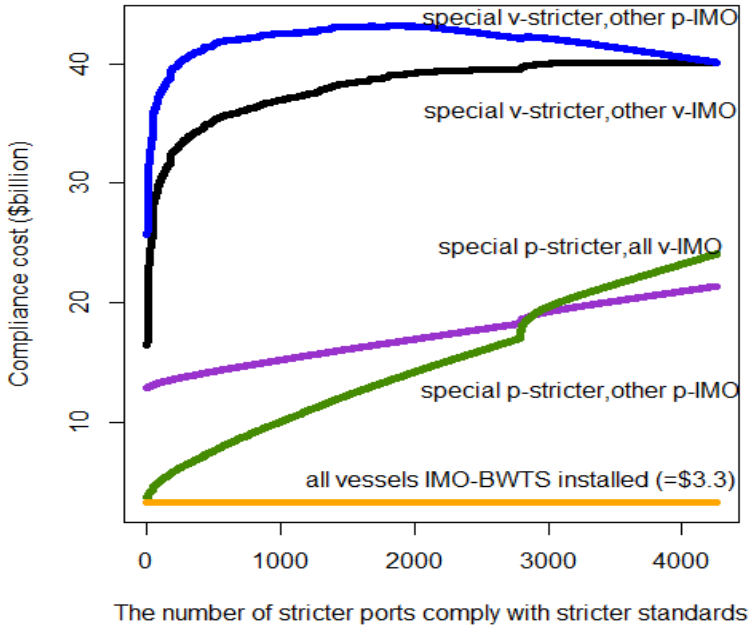

Figure 5.3 first x ports comply with stricter standards and other ports follow IMO regulation (no vessels have installed BWTS before)

The purple and green lines intersect when the selected port number is 2882 and the total cost is $19 billion. Remember these two compliance strategies both include port-based BWTS at the selected high-risk ports, and the difference is the method selection at ports regulated to IMO standards. The green line means using the vessel-based method at these ports, and the purple line means using port-based BWTS at these ports. When the number of selected high-risk ports regulated by stricter standards is fewer than 2882, the green line is lower, meaning that the less costly strategy is the vessel-based method at the other lower-risk ports. When the number of selected ports is more than 2882, the port-based method at all ports is less costly. The ultimate compliance strategy selection depends on the decision on how many ports regulated by stricter standards, but the port-based method is always the best for the high-risk ports to achieve better protection from species invasion.

Figure 5.4 shows the compliance costs when all vessels have installed IMO-BWTS onboard that the regional stricter regulation is based on the current BWM Convention. In this case, when vessels call at lower-risk ports, they can use installed BWTS to achieve the standards. Therefore, two compliance alternatives are left: the vessel-based or the port-based method at the selected high-risk ports. When x is 1, the green line means that vessels use the port-based BWTS when they call at Singapore and use their previously installed onboard BWTS when they call at the other ports. The black line is the vessel-based method, meaning that the 15041 vessels calling at Singapore (generated from the 2018-2019 shipping traffic dataset by the author) need to retrofit their current IMO-BWTS with stricter-BWTS. These vessels use the new stricter-BWTS at all ports and the vessels never calling at Singapore can use the IMO-BWTS at the rest ports. The black line is always higher than the green line, meaning the port-based method is always less costly than the vessel-based method, no matter how many ports are selected to do the stricter regulation. This is because many vessels call at high-risk ports, making the centralized port-based method less costly.

The yellow line is constant as $3.3 billion, which is fleet compliance cost under the current BWM Convention. Figure 5.3 and Figure 5.4 show that all compliance strategies to achieve regional stricter regulations cost more than the current IMO regulation. The distance between the green line (or the purple line in Figure 5.3) and the yellow line represents the increased cost to do regional stricter ballast water management. Decision-makers can decide the number of ports regulated by the stricter regulation with cost constraints.

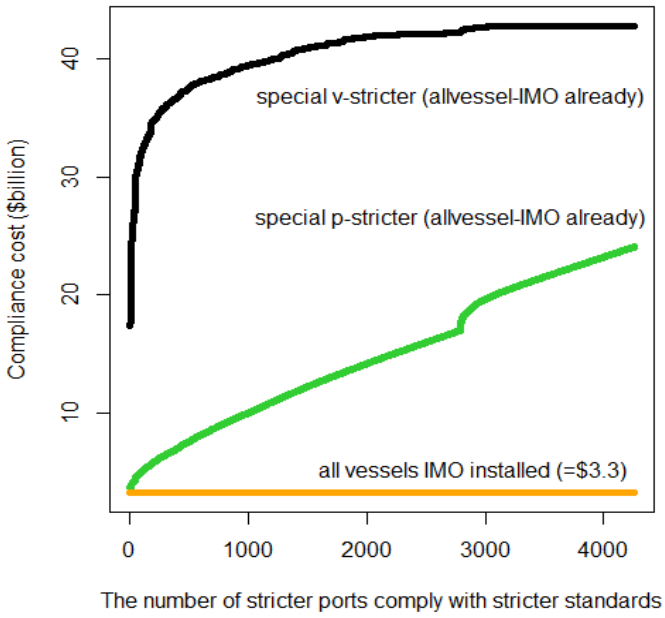

Figure 5.4 First x ports comply with stricter standards and other ports follow IMO regulation (all vessels have installed IMO-BWTS)

5.3.4 Robustness analysis

We further examine the robustness of the least costly compliance technologies. We consider possible impacts of the possible change of annual shipping traffic, and 'selected' ports hoping to achieve stricter regulations. The number of international shipping voyages in 2012 -2013 is 1.3million (it is 1.4 million in 2018-2019). Figure D1 to Figure D3 in the appendix D.4 show similar shapes to Figure 5.2 to Figure 5.4. We rank the ports by the shipping traffic and when we modify the risk assessment model by excluding the ecoregion effect, the rest figures in Appendix D.4 also show similar shapes. These two changes change the ports selected to perform IMO or stricter regulations. Therefore, our results are robust to the ports. When a certain port or region needs a stricter regulation, the port-based method is still the least costly.

5.4 Discussion and policy implications

While port-based technologies to achieve stricter standards become more cost-effective for ports at greater risk of invasions, we confirm that vessel-based methods are more cost-effective to meet the standards set forth in the current BWM Convention.

The results have implications for policymakers. A mixed strategy – representing current IMO BWM policy plus potential stricter action – indicates that cost-effective port-based implementation of stricter standards could be taken by high-risk ports either cooperatively or unilaterally. More stringent environmental regulations being proposed and ratified and individual States adopting nationally stringent standards are not without precedent in the industry (Wang et al., 2020a). Also, the BWM Convention explicitly acknowledges that a party of the BWM may propose more stringent amendments individually or jointly with other Parties, consistent with international law (Article 2.3). Regulation C-1 addresses the regulations on such "additional measures" and such additional measures may include a stricter discharge or a no-discharge area (Firestone and Corbett, 2005), while currently, no provisions for special areas are under the BWM Convention. Other than the BWM Convention, certain areas may decide to take action to regulate foreign-flag ships to address a particular concern regionally (Johnson, 2004). The Port and Coastal States can protect their jurisdictional waters under the United Nations Convention for the Law of the Sea (UNCLOS) or domestic laws. Therefore, the next level of policymaking either could be for special areas designated by the IMO or by voluntary port applications.

The advantages of the IMO regulations include broader cooperation, more efficient global management, and possible cost allocation mechanisms. However, the

BWM Convention depends upon fleet-regulation where IMO is the authority (through flag-state and port-state control) in regulating vessels, not ports. IMO convention cannot require port-based ballast water treatment methods. This suggests a science-based geopolitical shift in international environmental protection for shipborne invasive species. Cooperation among nations to reduce shipborne invasive species risk may for special areas designated by the IMO, by State or multi-state authorities independent from the IMO, or by voluntary port applications. The key question is how nations come together.

The work identifies possible international agreement structures that most likely to work and identifies nations that are most likely to partner for shared benefits:
(1) single port regulation. These ports will be cluster central ports, key risk partners in cluster risk, and ports connecting two or more clusters. For example, Port of Singapore connects 13 different clusters even under current IMO regulation, which makes it exposed to more biological invasions from ports in different clusters. It also forms a highway for species invasion among different clusters. The stricter regulation on the high-risk connection ports, like Singapore, not only improves biological safety at the port but also breaks down the interconnection of clusters and has a disproportionately positive role in reducing invasion risks globally.
(2) multilateral agreement version A. Ports belong to the same cluster are more likely to become invasive to each other, so ballast water management for intra-cluster is very important. For example, the ports in the Mediterranean Sea can work together to set stricter regulations to manage the biological invasion. Refer to Data Availability for the highest risk ports identified by “group” and country information for ports;

(3) multilateral agreement version B. The agreement will include all economically feasible ports. Nations most likely to partner are identified in the cost-effectiveness analysis part; and

(4) sets of bilateral agreements. The nations will be partners based on combinations of trade connectivity, independent risk rank, shared or common risk, or other characteristics. Policymakers can use the results of port clusters to figure out which country to cooperate with. Refer to Data Availability for port-port bilateral risks.

Our work also informs regional regulations. For example, the Vessel Incidental Discharge Act of 2018 of the United States, stipulates that if proved appropriately, the Great Lakes basin can do different standards from the national one. Figure 1(c) shows that the Great Lakes area, falling in the same cluster, have significantly higher invasions risk than other U.S. coastal areas even under the perfect implementation of the IMO BWM Convention. This information informs a stricter ballast water regulation towards the Great Lakes area.

Our work reveals that port-based BWTS is less costly than vessel-based BWTS at certain ports to help comply with stricter ballast water management standards. California State Lands Commission funded a study on the feasibility of the port-based methods to achieve stricter regulation in California's ports, and we show a broader cost-effective application of such methods globally. The results will stimulate technology innovation to move forward policymaking in global ballast water management. Also, the new strategy does not contradict to current BWM Convention, since vessels do not need retrofit installed vessel-based treatment methods and will not be "grandfathered" at the expense of better protection from biological invasions.

Furthermore, such implications are robust to the rank of ports and the 'selected' ports regulated to current IMO or future stricter regulations. For example, in the case study of all U.S. ports doing stricter regulations, the port-based method remains the least costly way (Wang and Corbett, 2020). More generally, the least costly strategies remain the same when we modify the risk assessment model by excluding the ecoregion effect, when we vary shipping traffic with data of 2012 (i.e. the numbers of vessels, ports, the number of needed BWTS, and ballast water discharge profile). See the cost-effectiveness analysis under different model and data scenarios in Supporting Information.

Risk results in our "no-treatment case" compare well with other research. We confirm with our Higher-Order-Network that invasion hotspots include East Asia and the Middle East. We identify high-risk ports to include Singapore, Hong Kong, Kaohsiung and Port Said, consistent with earlier work by Seebens et al. (Seebens et al., 2013); however, our HON approach demonstrates the cluster effects determining different sets of high-risk ports. Moreover, we confirm that Northeast Asia being the most significant NIS source for most regions, consistent with Sardain et al. (Sardain et al., 2019). Importantly, our results under mitigation scenarios (e.g., Table 1) indicate that shipborne invasion risk can be reduced by a factor of 300 to 3000 by implementing stricter ballast treatment for high-risk ports, which may offset potential 3- to 20-fold risk increase due to global shipping traffic growth predicted by Sardain et al. Taken together, the no-action and with-stricter-action scenarios may provide critical decision support, especially given the cost-effectiveness findings of feasible action by ports.

Vector-based management, which manages the entire assemblages of biological invasions associated, avoid the requirements of extensive data on the invasion history and biological traits of target species in species-specific risk assessment (Chan et al., 2013, Ruiz and Carlton, 2003). The risk model does not consider invasion history and stepping-stone effects, while the stepping-stone effects can be reduced by the vector-based ballast management because the use of BWTS can reduce the species concentration to certain limits no matter how species accumulated before.

Conversion of relative risk to a measure of absolute risk might improve the risk analysis and prediction model but would necessitate the inclusion of species-specific information for each port (node) in the network. This could be conceived through the adoption of the Jaccard Similarity Index (JSI) (Jaccard, 1901, Jaccard, 1912, Azaele et al., 2009). Implementing Jaccard type algorithms into the risk model, therefore, require significantly expanded Environmental DNA (eDNA) sampling. Our findings may support the need for integrated science to inform risk-based modeling and direct expanded biological data for eDNA and species similarity indexing to areas and ports with higher relative risks.

Chapter 6

CONCLUSION

6.1 Four Papers and the Connection

This dissertation is composed of four independent but connected articles, aiming to propose cost-effective ways to inform next step policymaking to reduce pollutions from international-going ships.

The first essay examines the potential global shipping pattern to the trans-Arctic shipping routes under climate change and ice retreat since global shipping pattern can reveal the vessel-borne pollution introduction pattern. The potential diversion pattern of global shipping traffic to the Arctic will inform further pollution risk introduction pattern. The work is also motivated by inconsistent conclusions on the economic feasibility of trans-Arctic routes in the literature. The work also reveals the potential environmental impacts of trans-Arctic diversions, including GHG emissions and ice cover. We identify the shipping routes between which vessels can reduce the most GHG emissions, informing ship operators to assign their vessels operating between those routes to the trans-Arctic routes to reduce GHG emissions and help achieve the 2050 GHG emission abatement goal of the shipping industry to reduce GHG emission by 50% compared to 2008. Another contribution of this paper to the dissertation and species invasion management is the distance and shipping costs established. The shipping traffic, shipping distance and cost data are the basis of economic analysis and cost-effectiveness analysis in the other three papers.

The second essay starts to study ballast water management to reduce species invasion. This essay focuses on technological policy and aims to find cost-effectiveness technological solutions to achieve ballast water regulatory standards. The work is not about different vessel-based ballast water treatment systems with different treatment methods, such as mechanical, chemical and physical methods. Instead, the work considers these traditional vessel-based treatments methods as well as central port-based alternatives. Even though one port-based BWTS costs more than one vessel-based BWTS, the same port-based BWTS is used by many vessels. This motivates the work to design several treatment strategies with different combinations of vessel- and port-based methods and analyze the cost-effective strategies. Another progress made in this paper is to consider potential future regulations. The work not only includes current IMO BWM Convention, but also proposes two new regulatory scenarios. The work chooses the U.S. as a case study to examine the economic feasibility of port-based method when U.S. ports adopt stricter regulations, i.e. the interim goal of California. The contribution of this work to the dissertation is that it starts to move the policy forward to better management ballast discharge and establishes a regulatory compliance model, which is used in the next two chapters.

The third essay continues the work of the second essay. The second essay identifies the least costly technological strategies to comply with ballast management regulations, and this work examines the impacts of the increased shipping cost on the national economy, international trade, and the shipping pattern to better inform the trade-off between species invasion management and possible negative impacts. The second establishes the basic regulatory cost model for the world fleet, and this essay modifies the model to be voyage-specific. Together with the shipping cost model

established in the first paper, this work calculates the increased shipping cost due to regulations, as input to a CGE model to study economic impacts. This work also includes the same two policy scenarios in the second one. The contribution of this work in the dissertation is further balancing environmental management and negative economic impacts. By comparing impacts of ballast water management with impacts of other environmental regulations, we know the economic feasibility of ballast water management. Since costs of species invasions are much higher than possible ballast management cost, the relatively small negative impacts revealed support ballast water management and even stricter species standards.

The fourth essay is the synthesized analysis of this dissertation. It further moves ballast management policies forward by combining a risk-based method with a technical economic analysis to inform possible geopolitical shift in international environmental protection for shipborne invasive species. This work expands from policy and technology study to species risk assessment and network analysis. The risk assessment model better quantifies the efficacy of ballast regulations and the cluster analysis helps find inter- and intra- cluster species introduction pathways. Also, this work extends the cost-effectiveness analysis to all ports and all countries. Port-based is less costly for high-risk ports and nations to achieve stricter regulations, but the IMO is the place to regulate vessels. This work designs a new regulatory framework and policy approach to international ballast management policies. Nations most likely to partner for shared benefits are identified and given, forming a tool for policymakers to refer to as a decision-making supporting tool. The work contributes to the dissertation with a science-based policymaking analysis and designs new regulatory framework for international ballast management beyond the IMO.

6.2 Summary of Findings

The first essay finds some trans-Arctic routes are economically feasible, but the diversion potential of trans-Arctic routes may be overestimated. The sample in this work contains 522,691 shipping moves. Results show that a mere 83 moves would reduce distance and 45 would save sailing time through the Arctic; however, 20 moves would reduce shipping cost. Though few diversions may happen, we find that 20 economically feasible trans-Arctic diversions reduce GHG emissions. Their average fuel consumption reduction through the Arctic is 264 metric tons (MT) (reduced by 26%); the range is 125-328 MT. The average CO2e emission is 767 MT (reduced by 24%); the range is 359-954 MT. Most of these voyages are between North America and East Asia. Ship operators may consider making a diversion to achieve the GHG abatement goal.

The second essay reveals economic feasibility of port-based BWTS methods. The results show that the required numeric standards matter a lot. If a single global standard is a weak standard, then adopting vessel-based compliant technology is less costly than centralized barge-based compliance. Specifically, if some region or all regions adopt standards different from current global standards (i.e., stricter), barge-based systems can be less costly than retrofitting world fleets. The findings reveal the potential role of barge-based treatment measure. The increased $0.7 billion compliance cost for the U.S. to achieve stricter ballast water regulation per year may inform the relevant policymakers.

The third essay investigates the impacts of international ballast water policy on transport costs, international trade, national economies and global shipping patterns. Findings are consistent with fundamental trade theory and show that the costs of environmental action through BWM in the shipping industry have small economic

consequences at aggregate levels but vary in magnitude for bilateral trade of specific commodities between certain countries. Specifically, the work provides three key findings: 1) current BWM regulation that is uniform across countries (Scenario 1) has nominal negative economic impacts across countries; 2) the proposed scenario of stricter BWM regulation imposed for transport to/from U.S. ports (Scenario 2) has minor effects on trade and national economies at aggregate levels, but causes noteworthy trade reductions of certain commodities between some countries; 3) BWM policies under uniform and stricter standards lead to modest changes in global shipping patterns. Findings suggest that international ballast water treatment regulation, even when the U.S. applies stricter standards, has minor effects on the global economy when considering changes in international trade, economic welfare, and shipping patterns, yet increased environmental quality can be achieved. However, it is important to consider both aggregate and bilateral trade effects when imposing increased transport costs to achieve invasive species risk reduction through BWM since considerable sector, and country-specific effects are masked when assessing economic effects at aggregate levels across countries.

The fourth essay shows that the stricter regulations not only can reduce the risks of ports, but also can change the cluster pattern and reduce the species invasion risks among different clusters. Results show that vessel-based BWTS is less costly to comply with current IMO standards, and port-based treatment method is more economically feasible for potential future regulatory standards. Rivas-Hermann et al. suggest that port-based systems have the highest potential for eco-efficient value creation and regulations need to be approved to stimulate port-based BWTS (Rivas-Hermann et al., 2015), our work reveals that port-based BWTS can only be less costly

at regional ports to help compliance with stricter ballast water management standards. Such implications are robust to the rank of ports and the 'selected' ports regulated to current IMO or future stricter regulations. For example, in the case study of all U.S. ports, the port-based method is also the least costly way to achieve stricter regulation. The selected compliance technologies are robust to the change of shipping traffic and 'selected' ports hoping to achieve stricter regulations. This paper also shows how policy could be made going forward. Results suggest that the next level of policymaking either must be for special areas designated by IMO, or by voluntary port applications. The IMO is not the right place to cost-effectively regulate ballast water discharge more because no provisions for special areas under the BWM Convention. Other than these policy approaches, the work informs new regulatory frameworks for ballast management with an instrumental approach to international law and proposes possible international agreement structures most likely to work including common international agreement like the IMO, or bilateral and multilateral agreements. The work also identifies nations most likely to partner for shared benefits, as a tool for policymakers.

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Appendix

APPENDIX OF CHAPTER 2

A.1 The GIS-based UMTM models

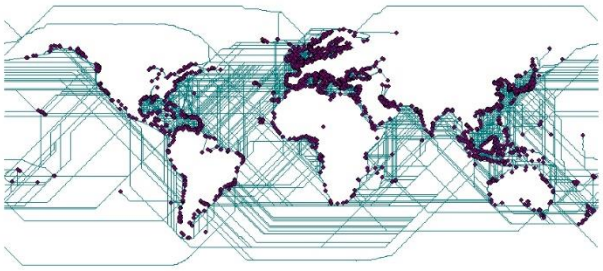


Figure A1 UMTM model when the Arctic is navigable

Figure A2 UMTM model when the Arctic is unnavigable

A.2 Shipping cost model for conventional routes

The methods and data used in this work and literature to estimate the shipping cost model for conventional routes are summarized in Table A1.

Capital Cost

Capital cost can be covered in profit account or in cashflow (Stopford, 2009). This study uses profit account with depreciation and interest and uses matching service to calculate interest. Capital cost per year is expressed by this equation: $P/N +$

$i(1+i)\text{^}n/[(1+i)\text{^}n-1]*(P-P_0)$. P is ship price, N is operation period in year, P_0 is down payment, n is financing maturity, and i is yearly interest rate.

Table A1 compares the ship price estimations in selected literature. They use different methods to do the estimation and get different results. This work does not use their estimates directly. Instead, we use the regression method of Cullinane and Khanna (Cullinane and Khanna, 1999), because they provide stronger basis and vary capital cost according to vessel size. However, their estimation is about 120 percent to 130 percent of newbuilding price in recent Shipping Intelligence Network Database (2017) because their data are from year of 1996. This article does a new regression with 262 container vessels from year 2014 to 2016 with data from World Fleet Register (2017), and get the vessel price: $\ln(P)= 0.6919*\ln(NTEU)+11.965$, with r^2 of 0.9132.

This work sets salvage value as 0, which is a compromised outcome considering different situations: some vessels are be sold as a second-hand vessel, some are be recycled, and others generate a cost to be deposited. This article sets the operation period as 20 years, down payment as 30 percent of the built price, financing maturity as 15 years, and annual interest rate as 0.1.

Operating Cost

Operating cost is, as confidential information of shipping companies, is composed of maintenance fees, crew cost, stores and consumables cost, insurance premium, and general management cost. This work sets operation cost as 3.5% of vessel price. Verifications are from three aspects. Firstly, the daily total operating cost for a 3643 TEU vessel calculated by this method is $6266 per day, similar with other articles, such as $6100 per day, estimated with data of Drewry Shipping Consultant

Ltd. by Liu and Kronbak (Liu and Kronbak, 2010). Furuichi and Otsuka (Furuichi and Otsuka, 2015) get $5500 per day, without stores and consumables cost or management cost, which is around $1000. Secondly, the figure is consistent with market report. According to OpCost Online (2015) of Moore Stephens, the operating costs for a 3600 TEU vessel in 2014 is $7238 daily. Thirdly, the generated operating cost is about one-third of capital cost, and Stopford claims that capital cost takes account of 42 percent of total cost and operating costs takes account of 14 percent of total cost (Stopford, 2009). Due to these three arguments, the estimation of operating cost with 3.5 percent of ship price is reasonable.

Fuel Cost

Fuel cost is determined by fuel oil consumption and fuel price. This work does not include diesel oil and lubricating oil cost because they only account for 2% of total daily fuel consumption (Verny and Grigentin, 2009). Table A1 summarizes the main engine fuel consumption and fuel price in literature. However, this work does not use their data directly, but estimate the Main engine daily consumption rate by considering the power-to-speed relationships between design speed and average service speed with the updated data: $FO = Installed\ power * (s_1/s_2)^3 * SFOC * 24 / 1000000$. *SFOC* is specific fuel oil consumption, s_1 is sailing speed, and s_2 is designed speed. Sailing and designed speeds are from Third IMO GHG Study 2014. This estimation considers slow steaming practice in shipping industry, resulting in reduced fuel consumption (Furuichi and Otsuka, 2015, Corbett et al., 2009, Notteboom and Cariou, 2009). It does not include draft, weather or fouling effects when estimating the instantaneous power, which are considered in the Third IMO GHG Study 2014, because these typically are second-order or third-order cost effects.

As to designed power estimation, this work adopts regression method used by Cullinane and Khanna and Solakivi, Kiiski et al. (Cullinane and Khanna, 1999, Solakivi et al., 2017): ln (*Installed power*) = 2.3374 + 0.967 ln (*NTEU*), r^2 = 0.94. It can be verified by comparison with the average consumption from Third IMO GHG Study 2014 (International Maritime Organization, 2015), shown in Figure A1. The dots are estimated power with this regression equation for container vessels with various sizes. Its trend line is showed by the dash line with r^2 of 0.95, and 95 percent confidence interval is showed. The grey straight line can represent the perfect of estimation. The difference between the dash line and the grey straight line is small, representing the reasonable estimation.

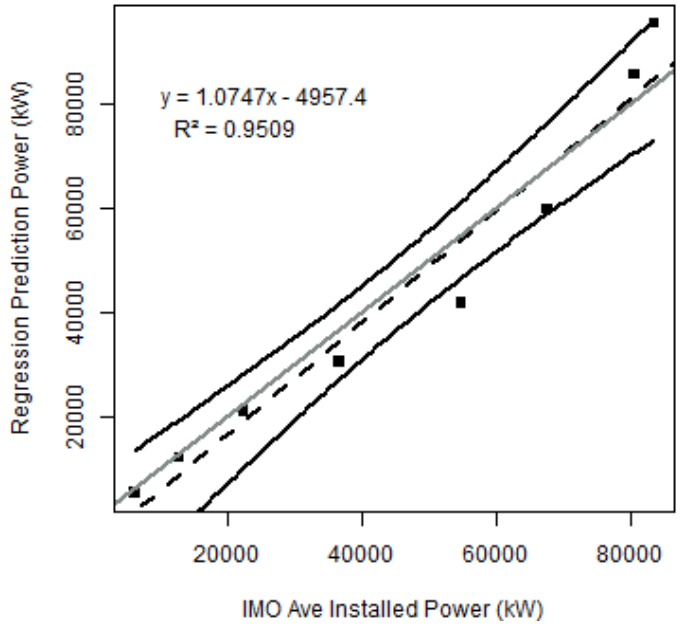


Figure A3 Installed power estimation reliability

The values of *SFOC* differ with the ages of main engines, obtained from the Third IMO GHG Study 2014. In the report, main engine *SFOC* is 180 g/kWh for engines built after year of 2001, 190 g/kWh for engines built in 1984-2000, and 210 g/kWh for engines built before 1983. Daily consumptions estimated with this method

differ in literature, because the data used are from different years and this work considers speed effect.

Articles set fuel price with default values, with scenarios or with average price in a period, shown in Table A1. This work uses IFO 380 and the average price of $386/MT in year of 2014 to 2017 from Bunker Index (2017).

Canal Fee

We firstly determined whether the vessels go through the Panama or Suez Canal. Panama Canal offers Panamax locks and neo-Panamax locks for vessels with different dimensions (Panama Canal Authority, 2018). For simplification, the Panamax locks toll system is applicable to vessels smaller than 5100 TEUs, and neo-Panamax locks toll system is applicable to vessels larger than 5100 TEUs. Suez Canal fee is determined by ship type, ship size and vessel ballast condition, calculated based on Special Drawing Rights (*SDRs*) per Suez Canal Net Tonnage (*SCNT*) and can be obtained from Suez Canal website (Suez Canal Authority, 2018). *SCNT* is calculated with regression method (Chen et al., 2018): $SCNT = 10.356 * TEU - 2279.3$, R^2 is 0.9851. *USD/SDR* ratio is 1: 0.7074 (International Monetary Fund, Oct 11, 2017). The ballast-laden ratio is set to 90%, with a comparison of 60% in sensitivity analysis. The method in this work to estimate Suez Canal Tolls works quite well because the estimates are close to the Suez Canal Pricing Forecast 2005 – 2025 report (R.K. Johns & Associates Inc., 2015). For example, the Suez Canal Toll for a 6258-TEU container vessel with 90% utilization is $58/TEU with the regression method, and the number is $60/TEU in the report. The difference may be caused by the fluctuation of *USD/SDR*.

Table A1 Shipping cost estimations for conventional routes

Article	Ship price (million)	Operating cost (per day)	Daily fuel consumption (MT/day)	Fuel price (/MT)
This work	$53 for 4500 TEU	3.5%*initial capital cost/365	Installed power * SFOC *24 / 1000000* (s_1/s_2) ^3	Four years (2014-2017) average price of IFO 380 ($386)
(Cullinane and Khanna, 1999)	$72 for 4500 TEU Regression based on 153 vessels	3.5%*initial capital cost/365	Installed power * SFOC * Utilization *24	-
(Solakivi et al., 2017)	-	-	-	Five years average of IFO 180 ($599); five years average of IFO 380 ($629)
(Furuichi and Otsuka, 2015)	$47 for 4000 TEU $67 for 6000 TEU Market transaction prices	$5500	-	$300, $500, $900
(Lasserre, 2014a)	$90 for 4500 TEU No explanation	$10443	100	IFO 380: $602
(Somanathan et al., 2009)	$50 no size specified From a General Manager	Insurance: $1165	83	$500
(Liu and Kronbak, 2010)	$60 for 4300 TEU Market report	$6100	98	$350, $700, $900
(Verny and Grigentin, 2009)	-	-	125	IFO 380: $420
(Guy, 2006)	-	-	170	$500
(Notteboom and Vernimmen, 2009)	-	-	90	-

A.3 Shipping cost model for trans-Arctic routes

The methods and data used in this work and literature to estimate the shipping cost model for trans-Arctic routes are summarized in Table A2.

Capital Cost Premium

Articles adopt vessels with different ice-classes to do estimation. Solakivi et al. (2017) estimate capital cost with regression method, and other articles use the capital cost for vessels sailing through conventional routes with a coefficient to represent the increased capital cost through the Arctic.

As to vessel ice-class assumption, Furuichi and Otsuka (Furuichi and Otsuka, 2015), Liu and Kronbak (Liu and Kronbak, 2010) and Somanathan et al. (Somanathan et al., 2009) do not distinguish different ice classes in detail. Solakivi et al. (Solakivi et al., 2017) put IA and IAS into one group, and put IB, IC and conventional vessels into another group with no explicit reason given. Pruyn ((Pruyn, 2016) classifies vessels into four groups, according to whether they are ice strengthened and whether they are with inspection and pilotage. Other articles choose different ice classes based on different ice class rules, such as 1B, PC7 to PC2 and DAS (Liu and Kronbak, 2010, Mulherin et al., 1996, Kamesaki et al., 1999, Kitagawa et al., 2001, Srinath, 2010, Chernova and Volkov, 2010).

Most of them calculate the capital cost of Arctic routes as 10 percent to 40 percent more than that of conventional routes (Lasserre, 2014b). CSCM does not classify vessels into different ice classes. All vessels sailing through Arctic are ice-classed, and their capital costs are 20 percent more than those of ordinary vessels. A sensitivity analysis for the capital cost increase is done for 20 percent, 10 percent and no increase. The cost increases can represent different ice classes, and no increase can represent the situation when same ordinary vessels are used for Arctic sailing.

Operating Cost Premium

Polar Code requires higher level trained officers in the Arctic area for safety, and higher wages should be paid to these experienced seamen (Verny and Grigentin,

2009). Insurance fee includes protection and indemnity insurance (P&I), and hull and machinery insurance (H&M). H&M provides insurance to the ship itself, and P&I provides cover to shipowners, operators, and charterers for third-party liabilities encountered in the commercial operation of vessels. These insurance fee will go up due to higher risks in the Arctic region.

Solakivi et al.(Solakivi et al., 2017) do not consider the effects of ice class on operating cost, and use ordinary vessel operating cost from Drewry Shipping Consultants Ltd. 2012. Other articles estimate each operating cost component seperately. They get the different costs of $6700, $7300, $8900, $9400 and $13000, when conducting estimations for a 4000 TEU ice class container vessel. These estimations are 3 percent to 47 percent higher that operating cost in conventional routes.

This work uses a 20 percent higher operating cost to do Arctic shipping cost estimation, with a sensitivity analysis of 20 percent, 10 percent, and no increase.

Fuel Cost Adjustment

Fuel consumption rate in the Arctic is higher because heavier ship weight needs more power (Furuichi and Otsuka, 2015, Notteboom and Vernimmen, 2009), and speed is slower (Lasserre, 2014a). CSCM uses an SFOC which increase by 20% compared to conventional routes, with a sensitivity analysis of 20%, 10%, and no change. With the method described in Section 2.2, the speed in the trans-Arctic routes is 90% of conventional routes. Then we did the sensitivity analysis of 90%, 80%, and no change.

Most articles use IFO 380 to estimate fuel price, by using single year's market price index (Somanathan et al., 2009, Verny and Grigentin, 2009, Lasserre, 2014a),

average of several years' price (Solakivi et al., 2017), or different scenarios based on real prices (Furuichi and Otsuka, 2015, Liu and Kronbak, 2010). However, IFO 380 may be not well-suited for very cold weather in the Arctic due to freezing points (Lasserre, 2014a). Naval Distillate and P50 can be used in the Arctic because the much lower freezing point, and are more expensive than IFO 380. The price is about 30 percent more than IFO 380.

Ice-breaker Fee

Additional costs in the Arctic region include ice-breaker fee and pilot fee. The pilot fee only occurs to some vessels (Furuichi and Otsuka, 2015) as an alternative of an experienced master, so this work includes it in operating cost (Somanathan et al., 2009).

Polar Code at IMO requires safe transit through Arctic and shipping companies consider safety as an import aspect (Shyu and Ding, 2016), so this work assumes that all Arctic navigations need ice-breaker escort to improve the safety. Table A2 shows the estimations in the literature. The ice-breaker tariff for vessels in different ice classes are available (The Northen Sea Route Administration, 2014). Based on the NSR tariff table, this article sets the ice-breaker fee as $5/GT, plus a sensitivity analysis of $5/GT, $10/GT and $15/GT.

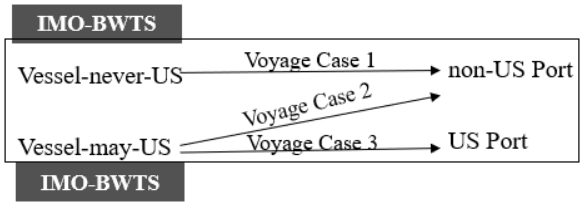
Table A2 Shipping cost estimation for trans-Arctic routes

Article	Capital cost	Operating cost (per day)	Voyage cost	Additional cost (icebreaker)
This work	20% higher (0, 10%, 20% sensitivity analysis)	20% higher (0, 10%, 20% sensitivity analysis)	SFOC 20% higher (0, 10%, 20% sensitivity analysis) Speed 10% slower (0, 10%, 20% sensitivity analysis) Fuel price: 30% higher	$5/GT (0, $5, $10 Sensitivity analysis) Calculated with the tariff from the Northern Sea Route Administration (NSR) website
(Liu and Kronbak, 2010)	20% higher	$8925 46% higher	Daily consumption rate: 91 days: 98 MT/day 182 days: 93 MT/day 274 days: 87 MT/day Based on all-year round NSR/Suez Canal round shipping move	$4 million per shipping move if using icebreaker
(Lasserre, 2014a)	20% higher	$13,432 28% higher	Daily consumption rate 78.76 MT/day Based on all-year round Northwest Passage /Suez Canal loop	$288,800 per shipping move if using icebreaker
(Notteboom and Vernimmen, 2009)			No change	
(Furuichi and Otsuka, 2015)	10% higher	$6689	Fuel consumption 10% higher	$5/GT
(Somanathan et al., 2009)	30% higher	H&M: 50% higher P&I: 50% higher Crew: 20% higher	Daily consumption rate 50% higher	
(Solakivi et al., 2017)	IA and IAS class vessels are 8% higher than other vessels	No change	Constant SFOC; Daily consumption rate is regression function of TEU and ice class; 10% higher fuel cost	Depend on Ice Class
(Verny and Grigentin, 2009)		$9369		

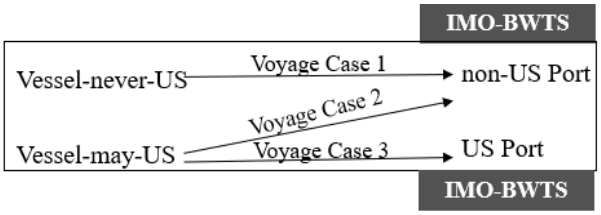
Appendix B

APPENDIX OF CHAPTER 3

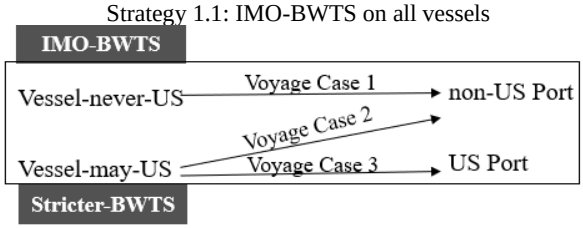
B.1 Compliance strategy design



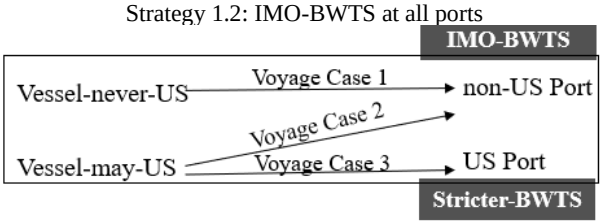
Strategy 1.1: IMO-BWTS on all vessels



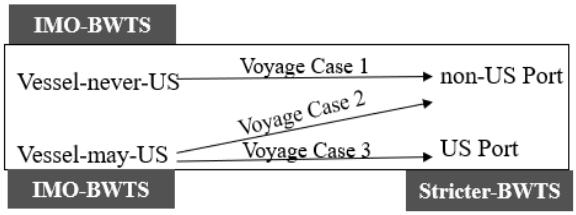
Strategy 1.2: IMO-BWTS at all ports



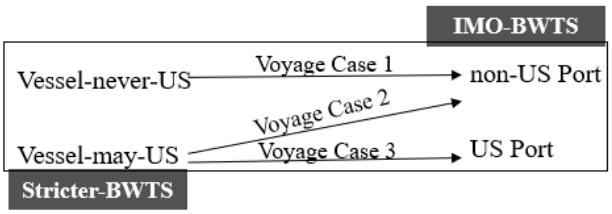
Strategy 2.1: Stricter-BWTS on Vessel-may-US,
IMO-BWTS on Vessel-never-US



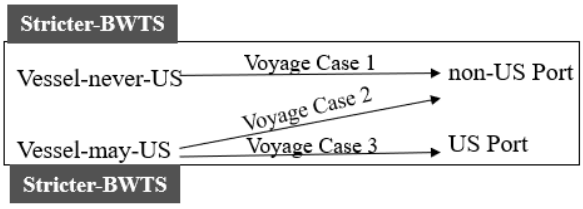
Strategy 2.2: Stricter-BWTS at US Ports,
IMO-BWTS at non-US Ports



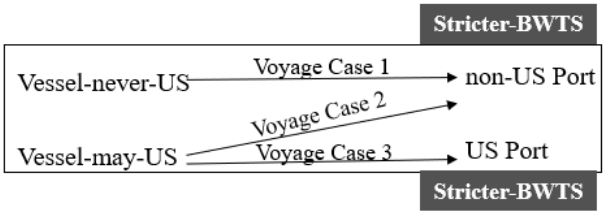
Strategy 2.3: Stricter-BWTS at US Ports,
IMO-BWTS on All vessels



Strategy 2.4: Stricter-BWTS on Vessel-may-US,
IMO-BWTS at non-US Ports



Strategy 3.1: Stricter-BWTS on all vessels



Strategy 3.2: Stricter-BWTS on all ports

Figure B1 Illustration of compliance strategies

B.2 Ballast water discharge volume estimation

The regression formula: $log10(Discharge_{volume}) = a + b * log10(DWT)$

Table B1 shows the regression relationship of ballast water discharge volume and DWT.

Vessel Type	a (Intercept)	Standard error	b (coefficient)	Standard error
Bulk-Dry	-0.5445	0.323	0.8783	0.07
General-Cargo	-0.5968	0.164	0.80865	0.043
Other	2.18543	0.273	0.16062	0.072
Ro-Ro-Cargo	2.39503	0.253	0.05436	0.063
Chemical	0.716941	0.799	0.56166	0.176
Liquified-Gas	-0.4236	0.581	0.77677	0.145
Passenger	-1.3222	0.361	0.98214	0.093
Refrigerated-Cargo	-0.4484	0.304	0.74458	0.081
Container	-0.006	0.176	0.632	0.039
Oil	-0.697	0.406	0.861	0.036

Appendix C

APPENDIX OF CHAPTER 4

C.1 Map of commodity types with vessel types

Table C1 GTAP commodity mapping to vessel types

GTAP Commodities	Aggregated commodities	Vessel types	Group number
OCR (Crops nec)	Crop products	Bulk	1
WHT (Wheat)	Wheat & grains	Bulk	2
GRO (Cereal grains nec)	Wheat & grains	Bulk	2
SGR (Sugar)	Forestry and foods	Con/Bulk	3
PDR (Paddy rice)	Forestry and foods	Container	3
OSD (Oil seeds)	Forestry and foods	Container	3
C_B (Sugar cane, sugar beet)	Forestry and foods	Container	3
PFB (Plant-based fibers)	Forestry and foods	Container	3
WOL (Wool, silk-worm cocoons)	Forestry and foods	Container	3
FRS (Forestry)	Forestry and foods	Container	3
PCR (Processed rice)	Forestry and foods	Container	3
OFD (Food products nec)	Forestry and foods	Container	3
B_T (Beverages and tobacco products)	Forestry and foods	Container	3
CTL (cattle, sheep and goats, horses)	Life animal	Livestock carrier	4
V_F (Vegetables, fruit, nuts)	Meats & vegetable	Refrigeration	5
FSH (Fishing)	Meats & vegetable	Refrigeration	5
CMT (Bovine meat products)	Meats & vegetable	Refrigeration	5
OMT (Meat products nec)	Meats & vegetable	Refrigeration	5
VOL (Vegetable oils and fats)	Meats & vegetable	Refrigeration	5
MIL (Dairy products)	Meats & vegetable	Refrigeration	5
OAP (Animal products nec)	Meats & vegetable	Refrigeration	5
RMK (Raw milk)	Meats & vegetable	Refrigeration	5
TEX (Textiles)	Textiles	Container	6
WAP (Wearing apparel)	Textiles	Container	6
LEA (Leather products)	Textiles	Container	6
LUM (Wood products)	Textiles	con/bulk	6
PPP (Paper products, publishing)	Textiles	Container	6
CRP (Chemical, rubber, plastic)	Metal & chemicals	con/bulk	7
OMN (Minerals nec)	Metal & chemicals	con/bulk	7
NMM (Mineral products nec)	Metal & chemicals	con/bulk	7

I_S (Ferrous metals)	Metal & chemicals	con/bulk	7
NFM (Metals nec)	Metal & chemicals	con/bulk	7
FMP (Metal products)	Metal & chemicals	con/bulk	7
ELE (Electronic equipment)	Machine & equipment	Container	8
OME (Machinery and equipment nec)	Machine & equipment	Container	8
OMF (Manufactures nec)	Machine & equipment	Container	8
OTN (Transport equipment nec)	Machine & equipment	General cargo	8
MVH (Motor vehicles and parts)	Motor vehicles	Vehicle	9
ELY (Electricity)	Electricity		10
COA (Coal)	Coal	Bulk	11
P_C (Petroleum, coal products)	Petroleum products	Tanker	12
OIL (Oil)	Crude oil	Tanker	13
GAS (Gas)	Natural gas	LG/pipeline	14
WTP (Water transport)	Water transport		15
OTP (Transport nec)	Other transport		16
ATP (Air transport)	Other transport		16
GDT (Gas manufacture, distribution)	Other Services		17
WTR (Water)	Other Services		17
CNS (Construction)	Other Services		17
TRD (Trade)	Other Services		17
CMN (Communication)	Other Services		17
OFI (Financial services nec)	Other Services		17
ISR (Insurance)	Other Services		17
OBS (Business services nec)	Other Services		17
ROS (Recreational and other services)	Other Services		17
OSG (Public Administration, etc.)	Other Services		17
DWE (Dwellings)	Other Services		17

Source: Commodity cargo and vessels matched and summarized by authors.

C.2 Percentage changes in shipping costs

Table C2 Percentage changes in shipping costs for container vessels from countries in rows to countries in columns

(Scenario 1)

% change	AUS	BEL	CAN	CHN	COL	DEU	ESP	FRA	GBR	JPN	KOR	MEX	MYS	NLD	PAN	SGP	TWN	USA	VEN	ZAF	ROW
Australia (AUS)				0.97						0.42	0.41		0.60			0.61	0.66	7.35			1.72
Belgium (BEL)			0.36		0.24	1.36	0.77	2.09	2.19					1.38	0.23			0.23			1.55
Canada (CAN)		0.32		0.38	0.77	0.29	0.31		0.35	0.16	0.18			0.42				1.58			0.64
China (CHN)	0.81		0.34		0.60		1.26		0.15	1.87	1.35	0.32	0.56		0.40	0.68	1.94	0.33	8.83		1.12
Colombia (COL)	7.35			0.16		0.19			0.23			0.70		0.22	1.74			0.88	1.35		0.98
Germany (DEU)		1.09	0.31				0.26	0.97	1.35			0.20		1.24	0.15			0.30		0.23	1.90
Spain (ESP)		0.77	0.28	0.05	0.23	0.49		2.00	0.60			11.35		0.71	0.22			0.27	0.71	0.47	0.76
France (FRA)		1.74	0.31		0.22	0.67	1.23		1.94			0.22		1.26		0.06		0.25			0.56
UK		1.72	0.34		0.22	1.07	0.98	1.88				0.24		2.10	0.21	0.32		0.33	1.05	0.25	0.63
Japan (JPN)				1.45							2.56	0.23			0.25	0.40	1.09	0.39			0.80
South Korea (KOR)			0.19	1.28	0.11					2.31		0.25	0.16		0.24	0.47	1.04	0.26		0.11	1.39
Mexico (MEX)				0.13	0.71					0.18	0.18				0.61		0.21	1.03	22.80		0.59
Malaysia (MAL)	0.53			0.53						0.35	0.35					2.72	0.51	0.24		0.37	0.39
Netherlands (NLD)		1.66	0.35			1.41	1.52	1.52	2.55						0.17			0.40			2.92
Panama (PAN)	8.11	0.26	0.30	0.26	1.91	0.20	0.24		0.22	0.23	0.23	0.53		0.24			0.19	0.83	1.88		0.63
Singapore (SGP)	0.71			0.43		0.14	0.07			0.24	0.26		3.10				0.65			0.38	0.44
Taiwan (TWN)	0.33		0.11	1.63						1.30	1.20		0.77		0.23	0.63		0.18			1.22
USA	0.51	0.29	2.08	0.31	0.87	0.22	0.24	0.21	0.30	0.36	0.17	1.05	0.06	0.27	0.87		0.14		1.12	0.57	0.73
Venezuela (VEN)				0.31	1.79							0.76			1.44			1.10			1.86
South Africa (ZAF)				0.31			0.53		0.26				0.30	0.40		0.30	0.16	0.81			0.61
Rest of world (ROW)	0.87	0.90	0.46	0.76	1.04	1.69	1.06	0.90	0.62	0.62	1.48	0.68	0.44	1.15	0.80	0.35	0.78	0.95	1.64	0.57	1.15

Note: Scenario 1 corresponds to the Consistent IMO BWTS Regulation.

Source: Authors' simulations

Table C3 Percentage changes in shipping costs for bulk vessels from countries in rows to countries in columns (Scenario 1)

% change	AUS	BEL	CAN	CHN	COL	DEU	ESP	FRA	GBR	JPN	KOR	MEX	MYS	NLD	PAN	SGP	TWN	USA	VEN	ZAF	ROW
Australia (AUS)		0.44	1.02	0.93		0.33	0.57		0.20	0.85	0.84	0.59	1.11	0.27	0.62	1.05	0.94	0.66		0.90	0.85
Belgium (BEL)	21.52		0.66			3.40	1.30	3.94	9.94			0.51		3.74				0.71			2.45
Canada (CAN)	0.69	0.89		0.67	1.13	0.64	0.75	0.85	0.80	0.90	0.75	1.38	0.50	0.49	0.95	0.37	0.63	3.09	1.32	0.73	0.76
China (CHN)	1.08		0.90		0.54				0.56	2.31	3.43	0.74	2.12	0.52	0.59	1.54	2.67	1.13	0.71	0.82	1.90
Colombia (COL)		0.69	0.75	0.67			0.65	0.58	0.61	0.36	0.68	1.95		0.52	3.57	0.31		1.64	1.86	0.57	1.32
Germany (DEU)		4.29	0.74				0.85	1.18	3.99					3.17				0.84	18.59		2.60
Spain (ESP)		3.35	0.91	0.10	0.76	2.59		2.24	3.15			0.78		2.86	0.71	0.25		0.78	0.91	0.48	1.36
France (FRA)		4.95	0.53		0.63	1.86	2.03		5.86			0.59		3.62	0.84	0.36		0.73	0.53		1.65
UK		2.44	0.77	0.28	0.66	1.99	2.31	3.42			1.02	0.61	0.33	3.82	0.63	0.28	0.24	0.72	0.70	0.60	0.86
Japan (JPN)	0.97		1.20	1.92	0.50						2.96	0.93	1.76	0.32	0.66	1.38	2.04	1.12		0.76	1.45
South Korea (KOR)	0.87		0.96	2.41	0.47					2.99		0.77	1.69		0.53	1.45	2.60	1.05		0.43	1.44
Mexico (MEX)	1.53		1.34	0.99	1.92				0.36	0.75	0.69				1.98		0.56	2.78	4.49		1.69
Malaysia (MAL)	1.44			1.53			0.41	0.50	0.32	0.71	1.60			0.39	0.43	4.98	2.03			0.87	1.46
Netherlands (NLD)		5.81	0.76	0.23	0.57	3.52	1.10	5.86	8.24							0.25		0.86	23.04		2.06
Panama (PAN)	0.64	0.81	1.05	0.61	5.90	0.68	0.85	0.25	0.85	0.63	0.58	2.26	0.53	0.82		0.41	0.49	2.04	0.93	0.45	1.60
Singapore (SGP)	1.35	0.62	0.34	1.26	0.30	0.51	0.34	0.31	0.35	1.14	1.17	0.37	3.63	0.37	0.41		1.60	0.41		0.63	0.81
Taiwan (TWN)	0.96		0.93	2.01						1.97	2.27	0.64	1.43		0.76	1.66		1.05		0.57	1.85
USA	0.80	0.78	4.54	0.74	1.72	0.56	0.66	0.61	0.72	0.96	0.81	2.99	0.52	0.66	1.93	0.36	0.88		1.13	0.50	0.76
Venezuela (VEN)	24.97	1.12	0.93	3.16	3.19	1.57	1.16	0.61	0.96			1.62		1.14	2.15	0.38		1.72		0.78	1.85
South Africa (ZAF)	0.92	1.59	0.55	0.52	0.49	0.50	0.58	0.57	0.47	0.41	0.42	0.65	0.74	0.38		0.66	0.43	0.59	0.66		0.88
Rest of world (ROW)	1.23	1.65	0.90	0.90	1.35	1.37	1.60	1.46	1.98	0.87	0.90	1.36	1.16	1.13	1.74	0.77	1.04	1.04	1.51	1.15	1.95

Note: Scenario 1 corresponds to the Consistent IMO BWTS Regulation.
Source: Authors' simulations

Table C4 Percentage changes in shipping costs for tanker vessels from countries in rows to countries in columns (Scenario 1)

% change	AUS	BEL	CAN	CHN	COL	DEU	ESP	FRA	GBR	JPN	KOR	MEX	MYS	NLD	PAN	SGP	TWN	USA	VEN	ZAF	ROW
Australia (AUS)				0.82						0.81	0.76		0.89		0.46	1.05	1.02	0.32		0.31	0.78
Belgium (BEL)			0.71			1.88	1.00	2.31	4.04			0.42		3.13				0.52			1.37
Canada (CAN)		0.57		0.47	1.03	0.60	1.05	0.63	0.84	0.69	0.66	1.03	0.35	0.74	0.71	0.43		1.48	0.89		0.93
China (CHN)	0.96		0.91							1.78	2.61		1.60		21.49	1.21	3.48	0.58	0.95	5.08	1.00
Colombia (COL)		0.69	0.43				0.39	0.51	0.40			1.52		0.55	2.92	0.18		0.91	2.19	0.20	1.54
Germany (DEU)		1.69						1.91	2.06					1.74	0.43			1.42			1.59
Spain (ESP)		1.69	0.74		0.30	1.10		1.93	1.46			0.64		1.40	0.74	14.36		0.57	0.57	0.41	1.31
France (FRA)		2.10	1.02			1.46	2.31		2.84					1.66		0.49		0.65	0.36		1.20
UK		2.40	0.66	0.09	0.23	1.62	1.27	2.07			0.14	0.45	0.13	2.37	0.49	0.12		0.51	0.54	0.40	0.91
Japan (JPN)	0.81		0.65	1.46							2.14	0.55	1.59		0.47	0.72	1.64	0.63			0.39
South Korea (KOR)	0.90		0.54	2.48	0.45					2.30		2.56	1.06		0.38	0.88	2.35	0.63	14.90		0.67
Mexico (MEX)		0.53		0.66	1.49		0.37	0.54	0.31		0.49			0.43	2.34	0.24	0.27	1.49	1.25		0.63
Malaysia (MAL)	0.65			1.43				0.29		0.76	0.87				0.33	4.46	1.85	0.80		0.86	1.44
Netherlands (NLD)		2.87	0.71			2.50	0.93	2.09	4.04						0.55			0.68		0.44	1.38
Panama (PAN)	0.45	0.36	0.88	0.36	3.73		0.37	0.40	0.57	0.42	0.53	2.08	23.41	0.37		0.69	0.61	1.02	1.65		1.60
Singapore (SGP)	0.97		0.62	1.06			0.30			0.75	0.80		4.25		2.55		1.18	0.36	0.25	0.75	0.73
Taiwan (TWN)	0.94		0.57	2.65						1.66	2.03		1.34		0.42	1.21		0.55			1.42
USA	0.56	0.51	1.60	0.42	1.07	0.34	0.53	0.53	0.58	0.55	0.61	2.16	0.22	0.55	1.24	0.40			0.93	0.34	0.78
Venezuela (VEN)		0.34	0.72	0.15	2.51	0.29	0.59	0.48	0.55			1.15		0.57	2.02	0.16	0.38	0.76			0.90
South Africa (ZAF)		0.29		0.78		0.13	0.72	0.39	0.39				0.50	0.90		0.74		0.46	15.27		1.23
Rest of world (ROW)	0.60	1.05	0.58	0.39	1.95	1.54	1.21	1.10	1.17	0.31	0.44	1.65	0.97	1.10	1.51	0.73	0.63	0.47	2.44	0.88	1.79

Note: Scenario 1 corresponds to the Consistent IMO BWTS Regulation.
Source: Authors' simulations

Table C5 Percentage changes in shipping costs for container vessels from countries in rows to countries in columns (Scenario 2)

% change	AUS	BEL	CAN	CHN	COL	DEU	ESP	FRA	GBR	JPN	KOR	MEX	MYS	NLD	PAN	SGP	TWN	USA	VEN	ZAF	ROW
Australia (AUS)				0.98						0.42	0.41		0.61			0.61	0.70	53.45			1.83
Belgium (BEL)			0.36		0.24	1.42	0.77	2.11	2.27					1.42	0.23			2.43			1.55
Canada (CAN)		0.37		0.48	0.89	0.29	0.31		0.37	0.18	0.22			0.42				15.40			0.74
China (CHN)	0.82		0.47		0.60		1.26		0.15	1.91	1.42	0.32	0.56		0.50	0.69	2.01	1.91	8.83		1.13
Colombia (COL)	8.28			0.16		0.19			0.24			0.82		0.23	1.84			7.59	1.46		1.05
Germany (DEU)		1.10	0.32				0.26	1.06	1.43			0.22		1.28	0.15			3.02		0.23	1.90
Spain (ESP)		0.78	0.29	0.05	0.25	0.50		2.01	0.60			11.35		0.71	0.22			2.89	0.71	0.47	0.77
France (FRA)		1.85	0.32		0.22	0.67	1.25		2.01			0.27		1.27		0.06		3.11			0.57
UK		1.82	0.37		0.22	1.12	0.98	1.96				0.25		2.14	0.21	0.32		3.38	1.07	0.25	0.63
Japan (JPN)				1.50							2.62	0.24			0.32	0.40	1.14	2.72			0.80
South Korea (KOR)			0.23	1.32	0.11					2.37		0.26	0.16		0.28	0.47	1.12	1.88		0.11	1.39
Mexico (MEX)				0.13	0.73					0.19	0.20				0.63		0.22	10.58	22.80		0.63
Malaysia (MAL)	0.53			0.54						0.35	0.35					2.74	0.52	1.36		0.38	0.39
Netherlands (NLD)		1.67	0.45			1.45	1.52	1.59	2.61						0.17			3.64			2.92
Panama (PAN)	9.26	0.27	0.31	0.30	1.99	0.20	0.24		0.22	0.29	0.27	0.57		0.24			0.21	5.74	1.93		0.67
Singapore (SGP)	0.71			0.44		0.14	0.07			0.24	0.27		3.11				0.66			0.39	0.45
Taiwan (TWN)	0.33		0.13	1.72						1.31	1.25		0.77		0.27	0.63		1.53			1.22
USA	0.61	0.35	2.50	0.49	1.04	0.25	0.27	0.26	0.36	0.49	0.21	1.27	0.07	0.34	1.05		0.18		1.40	0.88	0.97
Venezuela (VEN)				0.32	1.88							0.77			1.49			11.14			1.97
South Africa (ZAF)				0.31			0.53		0.26				0.30	0.40		0.30	0.16	2.05			0.62
Rest of world (ROW)	0.93	0.90	0.48	0.78	1.12	1.69	1.09	0.91	0.63	0.62	1.50	0.74	0.44	1.15	0.85	0.35	0.78	10.04	1.76	0.59	1.17

Note: Scenario 2 represents the U.S. Stricter BWTS Regulation.

Source: Authors' simulations

Table C6 Percentage changes in shipping costs for bulk vessels from countries in rows to countries in columns (Scenario 2)

% change	AUS	BEL	CAN	CHN	COL	DEU	ESP	FRA	GBR	JPN	KOR	MEX	MYS	NLD	PAN	SGP	TWN	USA	VEN	ZAF	ROW
Australia (AUS)		0.47	1.03	0.94		0.35	0.58		0.20	0.87	0.85	0.59	1.14	0.28	0.70	1.07	0.95	3.92		0.94	0.88
Belgium (BEL)	22.47		0.72			3.58	1.30	4.17	10.59			0.63		3.89				7.56			2.56
Canada (CAN)	0.71	0.97		0.72	1.27	0.67	0.80	0.89	0.82	0.97	0.78	1.52	0.52	0.52	1.02	0.38	0.64	35.61	1.47	0.73	0.81
China (CHN)	1.10		0.96		0.59				0.56	2.40	3.61	0.80	2.13	0.52	0.65	1.56	2.69	7.82	0.82	0.82	1.93
Colombia (COL)		0.73	1.01	0.78			0.66	0.60	0.63	0.38	0.71	2.17		0.53	3.92	0.31		14.85	1.97	0.57	1.42
Germany (DEU)		4.49	0.80				0.98	1.18	4.17					3.24				9.24	18.59		2.71
Spain (ESP)		3.43	0.95	0.10	0.79	2.65		2.29	3.23			0.90		2.98	0.74	0.26		9.09	0.96	0.50	1.43
France (FRA)		5.26	0.53		0.66	1.89	2.09		6.13			0.69		3.77	0.87	0.38		10.17	0.56		1.69
UK		2.61	0.81	0.29	0.68	2.02	2.42	3.55			1.02	0.67	0.34	3.95	0.66	0.29	0.24	8.87	0.73	0.61	0.89
Japan (JPN)	0.98		1.28	1.99	0.50						3.07	1.02	1.81	0.34	0.77	1.41	2.08	7.38		0.77	1.50
South Korea (KOR)	0.89		1.00	2.53	0.51					3.09		0.81	1.73		0.60	1.47	2.78	7.11		0.44	1.48
Mexico (MEX)	1.73		1.57	1.06	2.11				0.38	0.79	0.76				2.23		0.56	26.91	5.40		1.81
Malaysia (MAL)	1.49			1.53			0.41	0.50	0.35	0.74	1.64			0.39	0.50	5.09	2.04			0.90	1.47
Netherlands (NLD)		6.23	0.77	0.24	0.59	3.64	1.18	6.05	8.70							0.25		10.81	23.90		2.14
Panama (PAN)	0.69	0.86	1.13	0.68	6.51	0.72	0.89	0.27	0.88	0.73	0.64	2.48	0.56	0.87		0.42	0.54	16.16	1.00	0.46	1.74
Singapore (SGP)	1.39	0.63	0.35	1.29	0.30	0.51	0.35	0.32	0.37	1.18	1.21	0.38	3.70	0.38	0.47		1.64	3.48		0.64	0.83
Taiwan (TWN)	0.97		0.97	2.03						2.01	2.42	0.67	1.44		0.81	1.69		6.43		0.57	1.88
USA	0.93	0.87	7.65	0.89	2.23	0.63	0.75	0.71	0.85	1.27	0.95	4.05	0.58	0.74	2.20	0.40	1.09		1.40	0.57	0.93
Venezuela (VEN)	24.97	1.15	1.07	3.26	3.46	1.63	1.24	0.63	0.99			1.94		1.21	2.27	0.40		10.78		0.83	1.97
South Africa (ZAF)	0.96	1.75	0.58	0.53	0.49	0.52	0.60	0.57	0.48	0.41	0.42	0.70	0.76	0.40		0.67	0.43	4.01	0.66		0.91
Rest of world (ROW)	1.26	1.73	0.95	0.92	1.46	1.43	1.66	1.50	2.06	0.89	0.92	1.50	1.17	1.18	1.90	0.78	1.05	9.29	1.59	1.18	1.99

Note: Scenario 2 represents the U.S. Stricter BWTS Regulation.
Source: Authors' simulations

Table C7 Percentage changes in shipping costs for tanker vessels from countries in rows to countries in columns (Scenario 2)

% change	AUS	BEL	CAN	CHN	COL	DEU	ESP	FRA	GBR	JPN	KOR	MEX	MYS	NLD	PAN	SGP	TWN	USA	VEN	ZAF	ROW
Australia (AUS)				0.83						0.82	0.77		0.90		0.48	1.06	1.04	2.36		0.34	0.80
Belgium (BEL)			0.79			1.89	1.00	2.47	4.20			0.53		3.29				3.04			1.39
Canada (CAN)		0.64		0.55	1.21	0.62	1.13	0.74	0.93	0.80	0.75	1.47	0.35	0.80	0.88	0.51		14.41	1.00		1.05
China (CHN)	1.00		0.96							1.79	2.64		1.61		22.65	1.23	3.52	5.45	1.09	5.08	1.01
Colombia (COL)		0.73	0.58				0.43	0.54	0.45			1.96		0.61	3.34	0.20		9.11	2.61	0.20	1.78
Germany (DEU)		1.70						2.08	2.11					1.77	0.43			14.34			1.61
Spain (ESP)		1.73	0.77		0.32	1.19		1.97	1.50			0.71		1.45	0.81	14.36		5.60	0.63	0.42	1.36
France (FRA)		2.16	1.15			1.48	2.36		2.94					1.72		0.51		5.00	0.38		1.24
UK		2.49	0.74	0.09	0.23	1.67	1.30	2.12			0.14	0.54	0.13	2.48	0.55	0.12		4.71	0.60	0.43	0.95
Japan (JPN)	0.82		0.76	1.47							2.16	0.61	1.60		0.59	0.73	1.65	4.38			0.39
South Korea (KOR)	0.91		0.63	2.51	0.50					2.32		2.58	1.07		0.43	0.90	2.38	4.52	14.90		0.68
Mexico (MEX)		0.53		0.67	1.98		0.42	0.71	0.38		0.49			0.54	2.65	0.28	0.28	15.87	1.48		0.72
Malaysia (MAL)	0.67			1.44				0.29		0.77	0.88				0.36	4.50	1.86	8.14		0.89	1.45
Netherlands (NLD)		2.97	0.76			2.54	0.96	2.14	4.27						0.63			4.63		0.44	1.43
Panama (PAN)	0.51	0.45	1.09	0.40	4.27		0.44	0.45	0.63	0.49	0.58	2.50	24.16	0.40		0.77	0.71	8.11	1.93		1.85
Singapore (SGP)	0.97		0.71	1.08			0.30			0.77	0.82		4.28		2.58		1.19	3.91	0.26	0.76	0.75
Taiwan (TWN)	0.94		0.72	2.68						1.68	2.06		1.36		0.46	1.22		3.54			1.42
USA	0.70	0.61	2.24	0.52	1.40	0.36	0.61	0.64	0.69	0.66	0.68	3.27	0.25	0.65	1.58	0.48			1.28	0.38	1.00
Venezuela (VEN)		0.37	0.92	0.17	3.00	0.35	0.70	0.59	0.64			1.64		0.66	2.32	0.16	0.48	8.26			0.96
South Africa (ZAF)		0.29		0.78		0.13	0.74	0.39	0.41				0.50	0.96		0.76		3.18	16.20		1.26
Rest of world (ROW)	0.61	1.08	0.66	0.39	2.28	1.56	1.24	1.13	1.23	0.31	0.45	1.83	0.98	1.13	1.76	0.74	0.64	4.72	2.65	0.90	1.83

Note: Scenario 2 represents the U.S. Stricter BWTS Regulation.
Source: Authors' simulations

C.3 Changes in exports from Australia to key trade partners

Table C8 Changes in exports of selected commodities transported by container vessels from Australia to selected overseas countries.

Scenario 1

Commodity	China		Japan		South Korea		Malaysia		Taiwan		USA	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Forestry and foods	0.03	1.39	0.09	0.86	0.07	0.29	-0.02	-0.04	0.02	0.04	-1.58	-16.6
Textiles	-0.22	-1.5	0.37	2.6	0.17	0.2	0.02	0.04	0.13	0.2	-2.7	-6.6
Metal & chemicals	-0.28	-161	-0.04	-5.9	0.08	9.8	0.28	5.2	0.12	4.5	-1.26	-46.1
Machine & equipment	0.07	0.7	0.28	0.81	0.22	0.62	0.2	0.55	0.21	0.15	-0.71	-21.5
Commodity	Canada		Belgium		Germany		UK		South Africa			
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)		
Forestry and foods	0.19	0.53	0.12	0.3	0.11	0.38	0.09	0.5	0.13	0.04		
Textiles	0.34	0.06	0.25	0.01	0.22	0.12	0.21	0.21	0.23	0.1		
Metal & chemicals	0.36	3.8	0.24	2.2	0.27	2.6	0.18	2	0.25	2		
Machine & equipment	0.28	0.69	0.24	0.14	0.23	1.48	0.23	1.21	0.24	0.64		

Scenario 2

Commodity	China		Japan		South Korea		Malaysia		Taiwan		USA	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
Forestry and foods	0.36	16.3	0.41	3.9	0.37	1.6	0.25	0.7	0.34	0.8	-21.1	-220.9
Textiles	0.32	2.2	0.93	6.4	0.73	0.8	0.56	0.9	0.67	1	-33.9	-83.4
Metal & chemicals	0.14	80	0.37	62	0.5	62	0.79	14.5	0.61	24	-18.8	-687
Machine & equipment	0.74	7	0.96	2.8	0.9	2.5	0.9	2.5	0.91	0.7	-12.1	-368.3
Commodity	Canada		Belgium		Germany		UK		South Africa			
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)		
Forestry and foods	0.3	0.8	0.4	1	0.39	1.4	0.4	2.1	0.42	0.1		
Textiles	0.58	0.1	0.8	0	0.74	0.4	0.77	0.8	0.78	0.4		
Metal & chemicals	0.65	6.9	0.73	6.7	0.75	7.3	0.69	7.6	0.77	6.1		
Machine & equipment	0.8	2	0.88	0.5	0.86	5.5	0.88	4.7	0.88	2.4		

Note: (a) indicates percentage change, (b) indicates value change ($ million). Scenario 1 corresponds to the Consistent IMO BWTS Regulation and Scenario 2 represents the U.S. Stricter BWTS Regulation. Also, the minus sign indicates a loss and the opposite means a gain.
Source: Authors' simulations

C.4 Changes in output levels of selected sectors in Australia and the U.S.

Table C9 Percentage changes in output levels of selected sectors in Australia and the U.S. (%)

	Australia		USA	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Crop products	-0.02	-0.02	0.03	0.51
Wheat and grains	0.10	0.28	-0.03	-0.11
Forestry and foods	-0.02	-0.30	-0.01	-0.04
Life animal	0.02	0.07	-0.02	-0.14
Meats & vegetable	0.02	0.09	-0.02	-0.13
Textiles	0.02	-0.07	0.00	0.06
Metal & chemicals	-0.05	-0.09	0.01	-0.02
Machine & equipment	0.04	-0.28	0.00	-0.10
Motor vehicles	0.04	0.14	-0.01	-0.15
Electricity	-0.02	-0.04	0.00	-0.04
Coal	-0.01	0.15	-0.01	-0.05
Petroleum products	0.01	0.00	-0.01	-0.18
Natural gas	-0.01	0.31	-0.06	-0.12
Crude oil	0.05	0.19	0.01	0.17

Note: Scenario 1 corresponds to the Consistent IMO BWTS Regulation and Scenario 2 represents the U.S. Stricter BWTS Regulation.
Source: Authors' simulations

Appendix D

APPENDIX OF CHAPTER 5

D.1 Organism concentration used to determine the BWTS efficacy

Table D1 Organism concentrations used to determine the BWTS efficacy

Literature	Organism class	Untreated (average)	Treated (average)	Test Reduction	IMO standards	Reduction to IMO	Stricter standards	Reduction to stricter
Cohen and Dobbs, 2015	E.coli (cfu/100 ml)	550000	-	-	250	99.95%	126	99.98%
Herwig et al., 2006	E.coli (cfu/100 ml)	-	-	99.99%	250	-	126	-
Cohen and Dobbs, 2015	enterococci (cfu/100 ml)	5500	-	-	100	98.18%	33	99.40%
Reusser et al., 2013	>50 micrometer (individuals)	3512	-	-	10	99.72%	0	100.00%
Minton et al., 2005	>50 micrometer (individuals)	3000	-	-	10	99.67%	0	100.00%
Briski et al., 2015	>50 micrometer (individuals)	25599	5546	78.34%	10	99.96%	0	100.00%
Briski et al., 2014	>50 micrometer (individuals)	470500	402000	14.56%	10	100.00%	0	100.00%
Briski et al., 2013	>50 micrometer (individuals)	75886	91%	91.00%	10	99.99%	0	100.00%
Herwig et al., 2006	>50 micrometer (individuals)	-	-	96.00%	10	-	0	-
Briski et al., 2015	10~50 micrometer (individuals)	703	88	87.48%	10	98.58%	0.01	100.00%
Briski et al., 2014	10~50 micrometer (individuals)	310	126.5	59.13%	10	96.77%	0.01	100.00%
Briski et al., 2013	10~50 micrometer (individuals)	766	64%	64.00%	10	98.69%	0.01	100.00%

Herwig et al., 2006	10~50 micrometer (individuals)	-	-	99.00%	10	-	0.01	-
Minimum				14.56%		96.77%		99.40%
Average				76.61%		99.15%		99.94%
Maximum				99.99%		100.00%		100.00%

D.2 Port risk estimation under different treatment efficacies

Table D2 Port risks drop with stricter regulations and higher treatment efficacies

Port	No treatment	Experimental	IMO standards	Stricter standards
Singapore	1	1	1	1
Gwangyang	1	0.609305	0.162845	0.166095
Hong Kong	0.999584	0.762114	0.275175	0.271473
Kashima	0.99896	0.692003	0.235595	0.181805
Gibraltar	0.996513	0.718757	0.266968	0.222441
Las Palmas	0.992409	0.650209	0.139284	0.132091
Yosu	0.989933	0.612591	0.163714	0.180471
Algeciras	0.989921	0.631378	0.209397	0.142676
Shanghai	0.980005	0.544887	0.138866	0.116137
Mundra	0.973133	0.544293	0.161287	0.155915
Suez	0.971653	0.523248	0.153561	0.106619
Surabaya	0.967221	0.476517	0.122058	0.071237
Tubarao	0.962495	0.509811	0.149974	0.146521
Kaohsiung	0.962341	0.523357	0.152571	0.147772
Pohang	0.950923	0.366846	0.088347	0.075016
Ko Sichang	0.949908	0.496614	0.14643	0.143085
Port Said	0.93977	0.37109	0.093902	0.091383
Rizhao	0.937915	0.465147	0.133018	0.129821
Paradip	0.936859	0.466047	0.13368	0.130484
Richards Bay	0.935602	0.462063	0.131954	0.128776
Saldanha Bay	0.934059	0.445365	0.124222	0.121114
Fujairah	0.932939	0.460375	0.131614	0.128452
Jamnagar Terminal	0.924045	0.443435	0.124948	0.121878
St. Eustatius	0.923715	0.440794	0.123747	0.120687
Newcastle(AUS)	0.922454	0.424216	0.117587	0.114624
Busan	0.920665	0.399961	0.084586	0.064583
Balikpapan	0.911061	0.424586	0.118065	0.113277
Dahej	0.906253	0.409523	0.111855	0.108974
Jakarta	0.901008	0.370368	0.083677	0.081348

Ras Laffan	0.899198	0.404265	0.096951	0.09436

Note: ports shown are ranked by the HON risk without treatment

D.3 Port risk estimation using different models (top 30 ports)

Table D3 Port risk estimated with different models

Port	FON traffic	HON traffic	FON risk noEco	HON risk noEco	FON risk sameEco	HON risk sameEco
Duluth	0.0882	0.0639	0.5266	0.8227	0.5264	1.0000
Gibraltar	0.9528	0.9641	0.9859	0.9992	0.9858	0.9997
Singapore	0.9634	0.9736	0.9949	0.9972	0.9949	0.9997
Tarifa	0.7894	0.7719	1.0000	0.9160	1.0000	0.9784
Cape Finisterre	0.9886	0.9932	0.8358	0.9299	0.8356	0.8207
Suez	0.4552	0.3852	0.7203	0.6635	0.7201	0.7341
Kaohsiung	0.7591	0.7875	0.6916	0.7554	0.6914	0.7160
Visakhapatnam	0.0997	0.0677	0.6237	0.6150	0.6235	0.6877
Paradip	0.0563	0.0355	0.5809	0.6202	0.5807	0.6694
Thursday Is.	0.0738	0.0693	0.5862	0.5095	0.5861	0.6582
Taranto	0.1659	0.1528	0.2159	0.4717	0.2158	0.6571
Nanticoke	0.0358	0.0213	0.3841	0.4728	0.3839	0.6522
Tubarao	0.0626	0.0418	0.3656	0.5076	0.3655	0.6381
Superior	0.0230	0.0127	0.3633	0.4328	0.3631	0.6198
Hay Point	0.0698	0.0528	0.4898	0.5478	0.4896	0.5991
Busan	0.8195	0.8520	0.5703	0.4883	0.5701	0.5883
Taichung	0.3425	0.3276	0.5352	0.7598	0.5350	0.5763
Kashima	0.1747	0.1559	0.3920	0.4458	0.3918	0.5626
Detroit	0.0659	0.0430	0.4533	0.3963	0.4531	0.5617
Laem Chabang	0.4176	0.3938	0.5271	0.5731	0.5269	0.5556
Richards Bay	0.1220	0.0811	0.4114	0.5049	0.4112	0.5108
Haldia	0.1079	0.0693	0.8112	0.6614	0.8111	0.4912
Istanbul	1.0000	0.9546	0.9091	0.5098	0.9090	0.4857
Mormugao	0.0368	0.0210	0.1485	0.4112	0.1484	0.4820
Port Hedland	0.0595	0.0527	0.5106	0.3868	0.5104	0.4745
Tarragona	0.1739	0.1345	0.4181	0.4156	0.4179	0.4571
Pohang	0.2001	0.1546	0.4245	0.4102	0.4243	0.4446
Gwangyang	0.2956	0.2694	0.4703	0.3955	0.4701	0.4300

Ennore	0.0107	0.0059	0.1819	0.4313	0.1818	0.4213
Chennai	0.0958	0.0800	0.3843	0.4125	0.3841	0.4195

Note: ports shown are ranked by the HON risk considering ecoregion impacts

D.4 Cost-effectiveness results under other risk assessment

(1) 2012-2013 shipping traffic data, ranked by risk

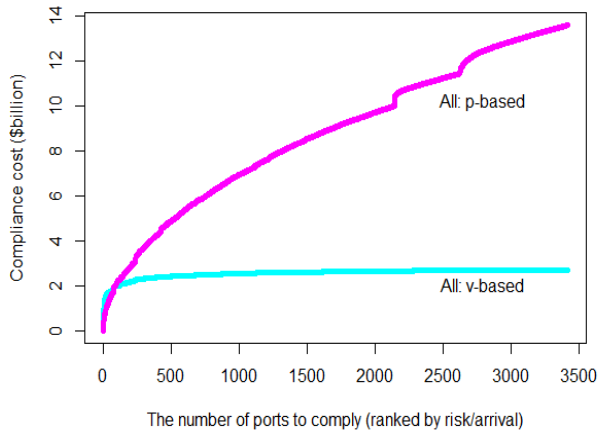


Figure D1 first x ports follow IMO regulation, other ports not regulated (2012-2013 traffic)

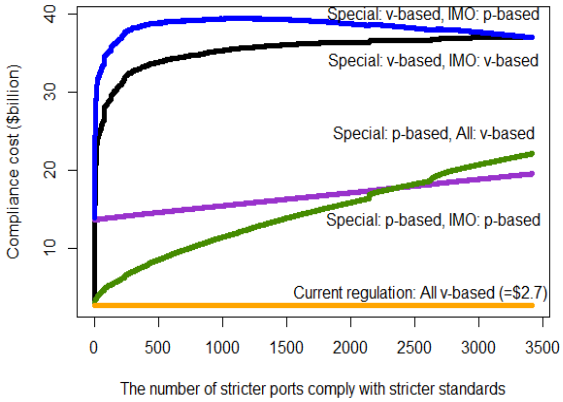


Figure D2 first x ports comply with stricter standards and other ports follow IMO regulation

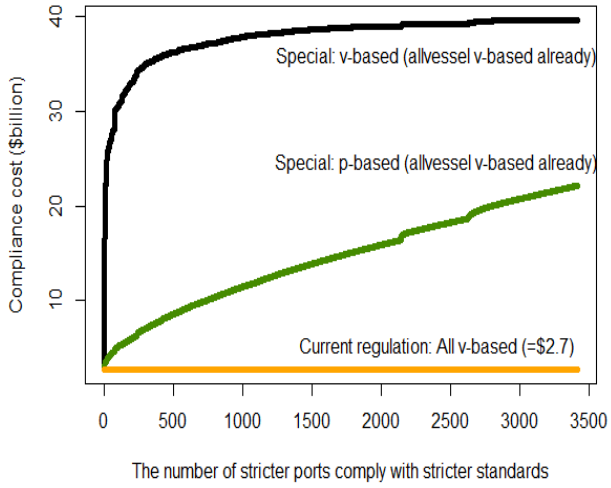


Figure D3 first x ports comply with stricter standards and other ports follow IMO regulation (all vessels have installed IMO-BWTS) (2012-2013 traffic)

(2) 2012-2013 shipping traffic data, ranked by vessel arrivals

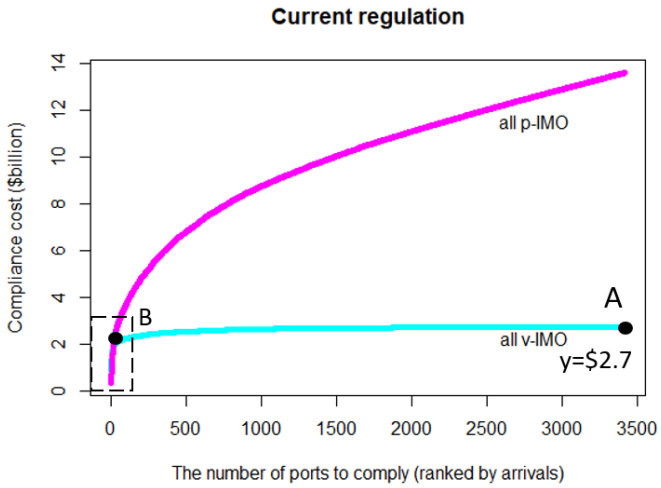


Figure D4 first x ports follow IMO regulation, other ports not regulated (ranked by ports' arrival traffic)

Note: Point A is the fleet cost under current IMO regulation calculated with 2012-2013 shipping traffic data. Point B is the intersection of two lines.

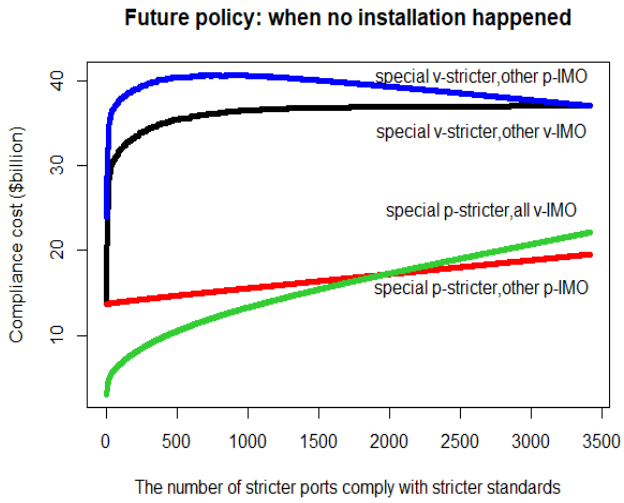


Figure D5 first x ports comply with stricter standards and other ports follow IMO regulation (no vessels have installed BWTS before) (ranked by ports' arrival traffic)

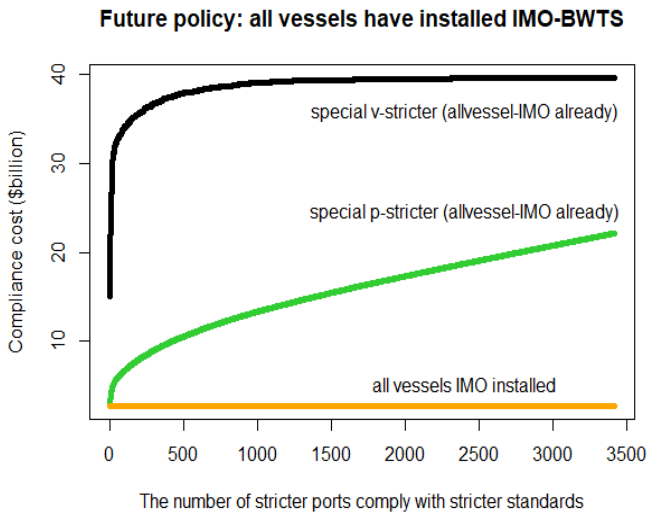


Figure D6 first x ports comply with stricter standards and other ports follow IMO regulation (all vessels have installed IMO-BWTS) (ranked by ports' arrival traffic)

(3) 2012-2013 shipping traffic data, not including ecoregion impact

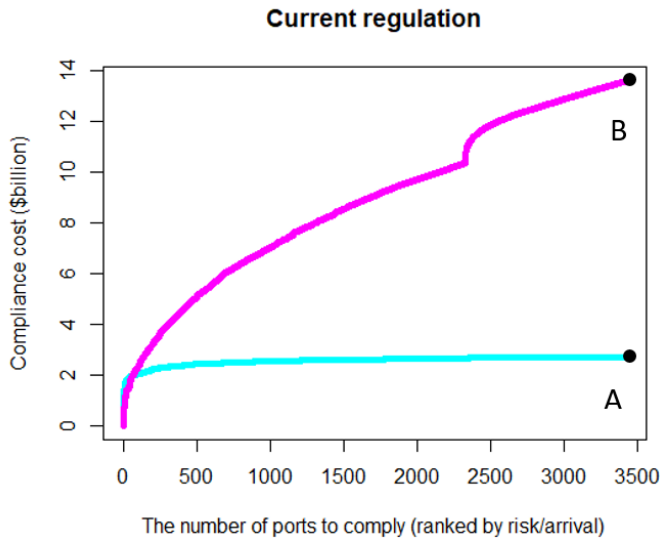


Figure D7 first x ports follow IMO regulation, other ports not regulated (excluding ecoregion effect)

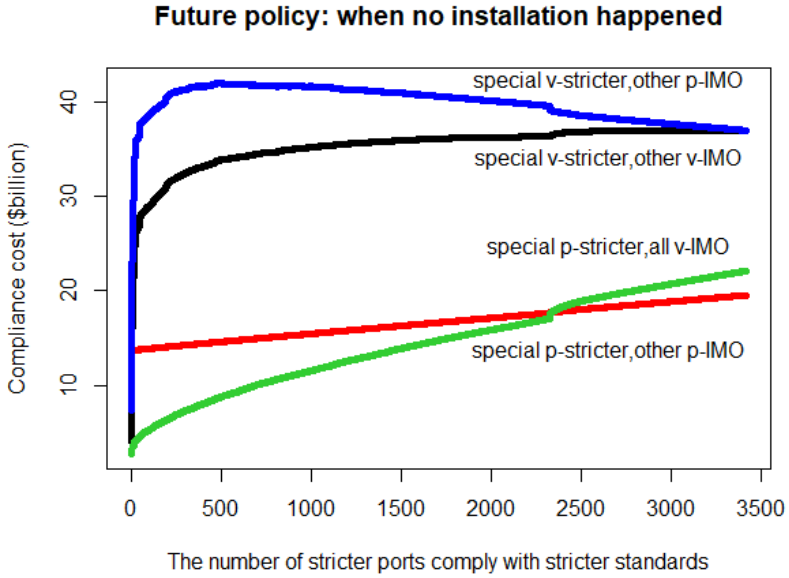


Figure D8 first x ports comply with stricter standards and other ports follow IMO regulation (no vessels have installed BWTS before) (excluding ecoregion effect)

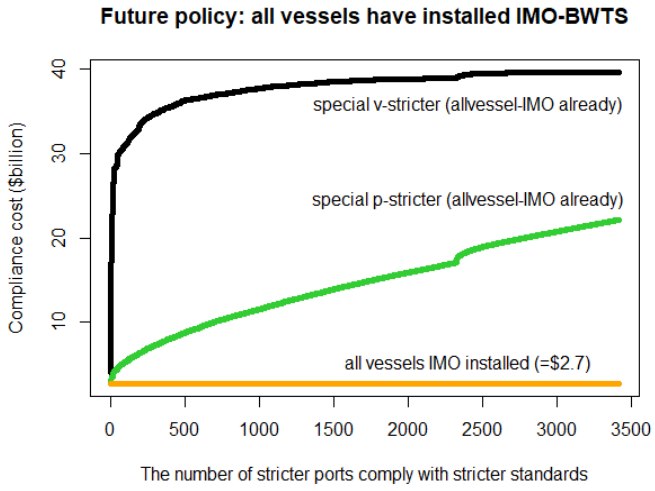


Figure D9 first x ports comply with stricter standards and other ports follow IMO regulation (all vessels have installed IMO-BWTS) (excluding ecoregion effect)

Appendix E

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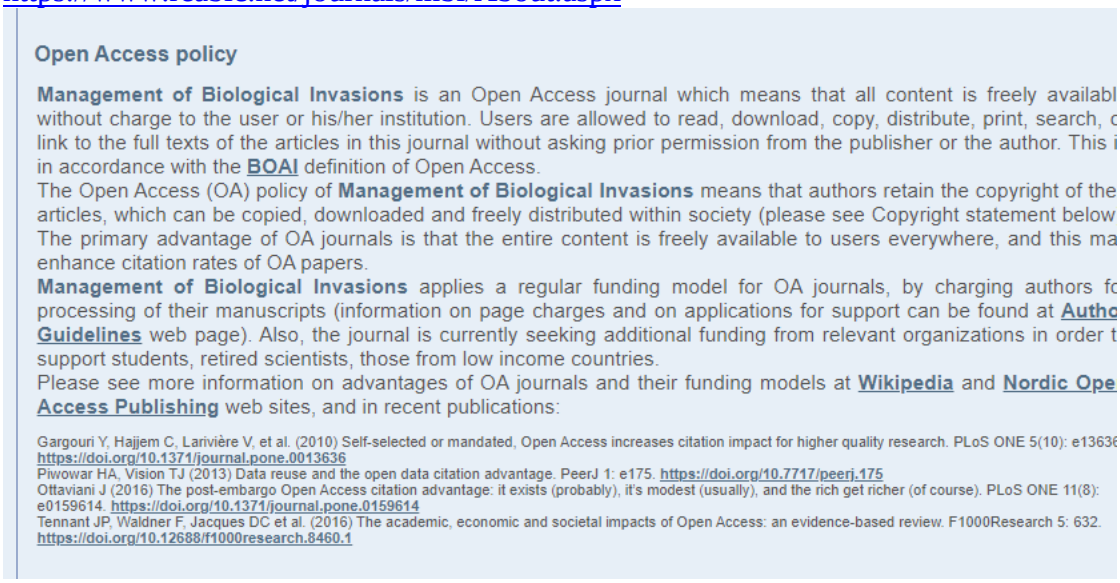

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