Invasive Species and Ballast Water From the United States

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Abstract

This paper analyzes the consequences of the US Ballast Water Management Act (2012) on Invasive Alien Species (IAS). Our findings show the inefficiency of this policy that led to the discharge of IAS in neighboring countries before its full implementation (2012-2015). However, in the subsequent period (2015-2017), this policy successfully contributed to a reduction in the entry of new invasive species into the ports of US partners. The mechanism is based on the rapid adoption of ballast water system treatments by ships that generate a positive external effect on countries that trade with the US. Ships with treatment systems were first assigned to the lanes that connect the US and its main partners, explaining the reduction of IAS there.

1 Introduction

Marine Invasive Alien Species (hereafter IAS) represent by definition a critical threat to biodiversity[1] and have a significant effect on human health, fishing, aqua-

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[1]The International Union for Conservation of Nature (IUCN) defined IAS as: "an alien species which becomes established in natural or semi-natural ecosystems or habitat" and which "is an agent of change that threatens native biological diversity."

culture, tourism and marine infrastructures (Bax et al., 2003).

Ballast water is one of the main culprits of marine IAS (Kim et al., 2022). Once the cargo has been unloaded, the ships must carry an equivalent weight of water in their ballast to ensure stability until the next load. Thousands of organisms such as bacteria, algae and plankton, but also small fish and invertebrates are then transported over long distances and then discharged into different ecosystems (Seebens et al., 2017; Molnar et al., 2008). As a result, several policies have been implemented to regulate this worldwide exchange of water.

The purpose of this study is to assess the impact of the earliest and most ambitious policy, the US Ballast Water Management Act, enacted in 2012 and implemented throughout the US maritime zone. To comply with the law, the ships had two options, called ”D1” and ”D2”. They could replace their ballast water with seawater (which in theory does not contain IAS) before discharging at US ports (D1), or install a Ballast Water Treatment System (BWTS) that removes IAS directly from the ballast water (D2). Investing in BWTS has a significant cost (depending on the size of the ship and the price of fuel) but saves time; compared with discharging water, the ship does not need to be immobilized for several hours. However, this technology was not available before 2015, which allowed us to break down the effects involved. This analysis is interesting beyond the American case, because these two possibilities are still active all over the world and may have distinct effects that are yet unknown. What are these effects?

The regulation of water discharge (D1) exhibits characteristics of a ”beggar thy neighbour” policy; it may be beneficial for the United States, but discharges may occur close to the coasts of neighboring countries, leading to the spread of aquatic invasive species (AIS) in these areas. On the contrary, BWTS (set by the D2 regulation) is a “green” technology with positive externalities. As the US is a major importing country, ships often return to their point of origin with ballast tanks full of water; then with the use of ballast water treatment, this policy may lead to a reduction in invasive species in the rest of the world.

To address these questions, we compile daily data on the location and quantity of ballast water discharges from ships arriving at US ports between 2006 and 2019 from the US Gard Coast (Gerhard and Gunsch, 2018). We find evidence of negative consequences for American neighbors. The requirement to discharge water into the middle of the ocean is leading ships to increase their discharges into areas neighboring the United States.

We then track ships that have installed BWTS using a global database of ship movements from port to port to determine on which shipping routes these systems were first installed. Such an analysis of shipowners’ investment and strategy is important in order to understand in which partner ports this policy has generated positive environmental benefits. Using a staggered difference-in-difference analysis of BWTS adoption by ships, we find that the policy has led to an increasing adoption of BWTS in the main partners of the US. The reason is certainly economical, shipowners amortize the fixed costs of installation by using these vessels intensively on the most frequent connections with the US where water should be cleaned.

Finally, we analyze the impact of this law on IAS, and find that it has had a beneficial effect to reduce invasive species, both in the USA and in partner ports.

With regard to the literature, there is no paper that analyzes the effect of the Ballast Water Management Act on invasive species. Numerous biological and engineering research articles highlight how samples of water with IAS treated with different systems (chemical treatment methods, such as electro-chlorination or physical treatment with filter and UV radiation) are successfully cleaned (Bradie et al., 2018; Hess-Erga et al., 2019; Lakshmi et al., 2021), but none of these articles analyze the consequences of a policy regulation.

Furthermore, we tackle this issue in a very unique way, by bringing together a number of different databases on ships' journeys, on the ballast water treatment installed, and on the invasive alien species in each port at a global level. In contrast, there is an abundant literature that has, for a very long time, emphasized the role of maritime trade and ballast water in the spread of invasive species (Bax et al., 2003; Pimentel et al., 2005; Molnar et al., 2008; Cuthbert et al., 2021). For example, analyzing the strong increase in invasive species in the recent period, Seebens et al. (2017) concludes that "past efforts to mitigate invasions have not been effective enough to keep up with increasing globalization", which clearly motivates our research to analyze which policy is the most successful in reducing IAS.

Finally, there is a growing literature in international economics that analyzes maritime trade costs and ports network, such as Behrens et al. (2006), Behrens and Picard (2011), Xu and Itoh (2018), Ducruet et al. (2024), Brancaccio et al. (2020), and Ganapati et al. (2024). Given that the Ballast Water Act represents an increase in trade costs, our analysis may be seen to be related to this literature. Finally, our analysis of the environmental impact of vessel regulation is related to studies analyzing how emission control areas have led ships to change their route, causing positive environmental externalities (Klotz and Berazneva, 2021; Candau and Lafferrere, 2025; Hansen-Lewis and Marcus, 2024).

The remainder of the paper is structured as follows. Section 2 briefly reviews the background of the US Ballast Water Management Act. Section 3 presents the data sources and descriptive statistics. Section 4 analyzes the main results concerning the regulation of water discharge (D1). Section 5 examines the mechanisms of BWTS adoption and Section 6 its consequences on invasive species (D2). Finally, Section 7 concludes the paper.

2 Background

The proliferation of seaborne IAS has a long history in the US, but began to cause concern only recently in the 1970-1980 period, precisely at the start of the era of hyper-globalization (Subramanian et al., 2023) and containerization of maritime transport (Bernhofen et al., 2016). One of the emblematic invasions of this period was the zebra mussel introduced by ocean-going vessels, which became established in the Great Lakes and infested 40% of American rivers, clinging to rocks, piers, and industrial pipes. The annual cost to combat this particular species has been established at 1 billion dollars (Pimentel et al., 2005), while the total cost against invasive marine species in general since the 1970s may reach US$166 billion (Cuthbert et al., 2021).

As a result, preventing the spread of invasive species quickly became a significant concern for the US administration. The first regulations on ballast water were introduced in 1990 under the Aquatic Nuisance Prevention and Control Act, concerning mainly the Great Lakes region, but were extended nationwide in 1996 with the National Invasive Species Act (NISA). However, these regulations do not introduce significant constraints for vessels, but mandate the establishment of research programs to assess the risk associated with ballast water. This led to the development of baseline data and risk assessments, which would later inform standardized treatment methods and management practices.

In particular in 2012, a new regulation defined in the US Coast Guard (USCG) Final Rule titled "Standards for Living Organisms in Ships' Ballast Water Discharged in US is enacted.

This policy is composed of two regulations, called D1 and D2.

2.1 The D1's regulation, an harmful non cooperative policy?

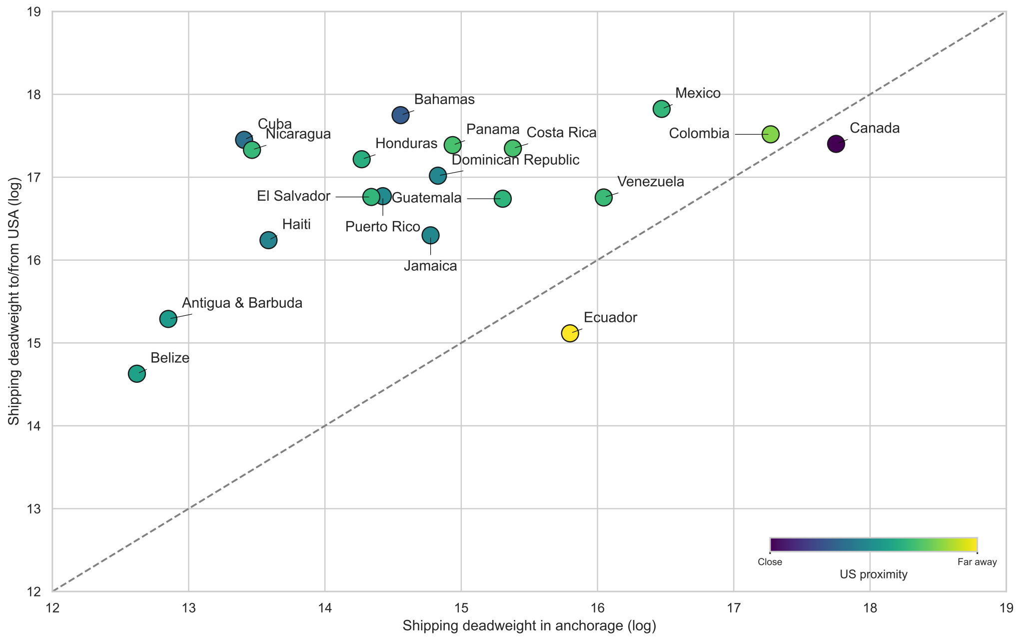
The D1 regulation focuses on minimizing the introduction of invasive species in the United States by mandating the exchange of ballast water at sea. The objective is to conduct this exchange in open ocean areas, reducing the likelihood of transferring harmful organisms to US coastal waters. Vessels are required to replace a substantial portion of their ballast water, typically 95%, with water from the open ocean before discharge into US waters (Miller et al., 2011). This exchange can be carried out through an Empty-Refill process or a Flow-Through process [2].

[2] Flow-through method of Ballast Water Management pumps mid-ocean water into a full tank, displacing coastal water out the top. The US Coast Guard requires pumping out 300% of the tank's volume to complete the exchange. The empty/refill method of Ballast Water Management involves emptying the tank by pumping until suction is lost, then refilling it with ocean water through gravity and pumping.

Whatever the process, such a policy has all the characteristic of a noncooperative game, improving the US situation but harming the neighborhood. With such a policy, the likelihood that vessels will exchange water near the coast of neighboring countries is high. This transboundary pollution is even more problematic from an economic (and moral) perspective, given that the number of ships heading to the US is much higher than those traveling directly to these countries. This may incur a substantial increase in IAS in these countries, which are poorer than the US and lack the financial resources to effectively combat the introduction of new IAS.

To analyze this, we calculate the share of vessels bound to or coming from the United States within each country's Exclusive Economic Zone (EEZ). We find that US ships represent the main users of the EEZs of many countries. For example, 90% of the vessels passing through the marine area of the Cayman Islands go to the United States, compared to 73% for Cuba and 80% for Belize.[3] The number of ships traveling to the US through a country's EEZ far exceeds the number of ships calling at its own domestic ports. Figure (1) illustrates this imbalance by comparing the intensity of US traffic within a country's EEZ to the intensity of traffic associated with its domestic trade. Almost all countries are located above the 45-degree line, indicating that they are potentially more exposed to ballast water discharges from US traffic than from their own national port activity.

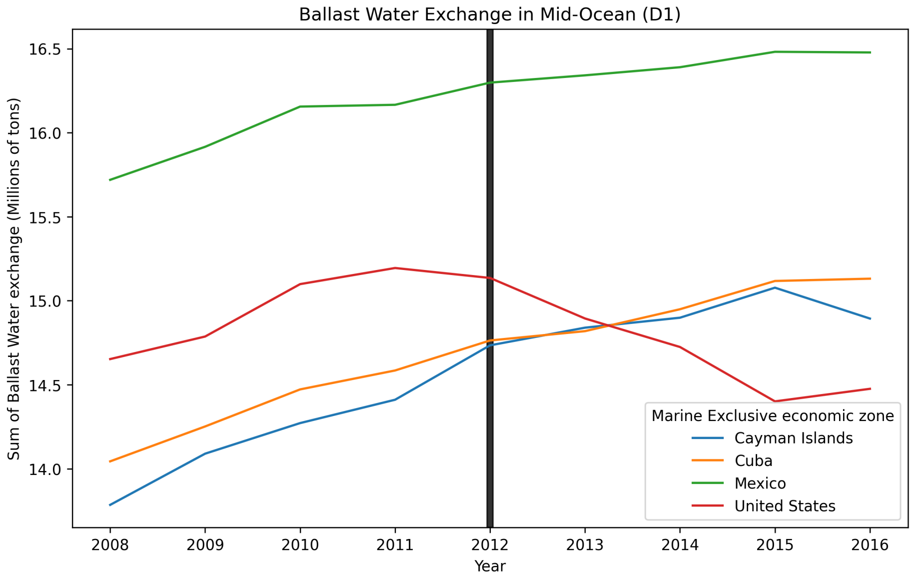
[3] See Appendix A for a detailed explanation on how we measure these stylized facts.



Note: This plot shows, for each marine economic zone considered and for bulker vessels, the exposure to U.S. shipping patterns relative to domestic shipping activity. Ballast water exchange is approximated by the total deadweight tonnage (DWT) of ships. Each point represents the ratio (in logarithmic scale) of the total DWT of U.S.-bound ships passing through a country's Exclusive Economic Zone (EEZ) to the total DWT of ships (U.S. or not) calling at that country's domestic ports. The values are averaged over the 2006–2012 period. Distances to the U.S. (in logarithmic scale) are based on the CEPII gravity database.

Figure 1: Exposure of US traffic

Quite logically, the D1 regulation may lead to an increase in the ballast water exchanged in other EEZs. This may explain the stylized facts of Figure (2), where water exchanges are reduced in the US after 2012, but increased everywhere else (within the marine areas of Cuba, Mexico, Jamaica, and the Cayman Islands). Finally, after 2015, one can observe a stagnation (or a decrease for some areas) in mid-ocean exchanges. This corresponds to the year during which treatment systems became available.



Note: This graph presents the Ballast Water Exchange inside each EEZ marine boundary by country. The variable is the sum of Ballast Water Exchange for tankers, bulkers, containers and general cargo ships.

Figure 2: Ballast Water Exchanges in Mid-Ocean (D1 regulation)

To conclude, one can mention that according to the literature, even the positive effect of a reduction in IAS in the United States due to the D1 policy is not certain. Indeed, while the beneficial effect of Ballast Water Exchange (BWE) is clear when the difference in salinity is high (e.g. between fresh and salt water), the results are less certain in other cases (Gerhard et al., 2019). Gollasch et al. (2007), Macdonald (1998) and McCollin et al. (2001) even report that after some exchanges more organisms were found in the ballast water, in particular in areas where the ocean is not deep enough or during periods of high organism concentration (e.g. algal blooms). Furthermore, the law sets that 95% of the ballast water in the tanks should be replaced, but the remaining 5% can still have an impact on the increase of IAS. Gollasch et al. (2007) also points out that due to the design of ballast tanks, there is always water and sediment in the tank that cannot be pumped out, which can play a role in the spread of IAS.

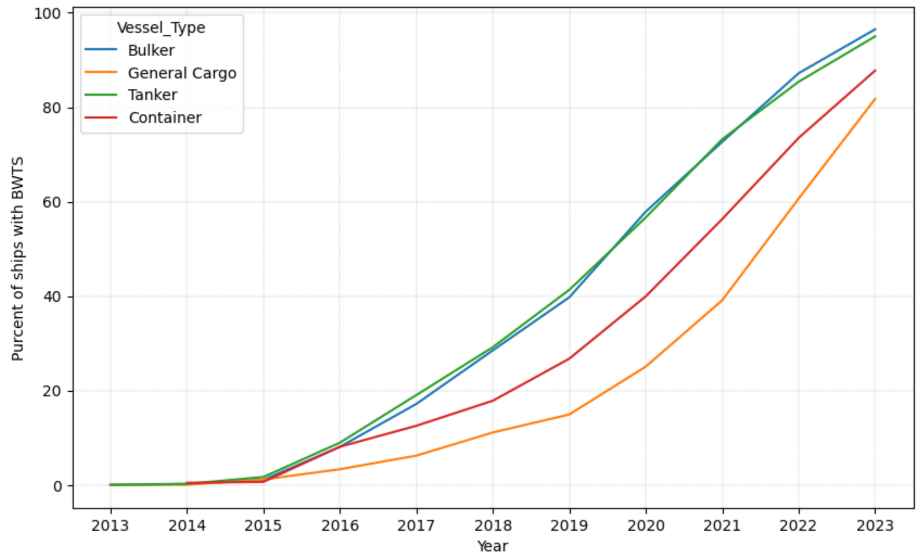
2.2 Adoption of a green technology: the D2's regulation

The D2 regulation focuses on the implementation of effective onboard ballast water treatment systems to establish strict discharge standards for living organisms in ballast water. Indeed, the ballast water treatment system has to reject water containing i) less than ten viable organisms per cubic meter (with greater than or equal to 50 micrometers in minimum dimension), ii) less than ten viable organisms per milliliter (with less than 50 micrometers and more than 10 micrometers in minimum dimension). This policy is expected to reduce IAS in US ports, but contrary to D1, it can also have positive spillover effects on US trade partners.

To enforce compliance, the USCG conducted inspections of the vessels. Non-compliance with ballast water management regulations could result in significant penalties, fixed at $35,000$ dollars, with each day of continued violation considered a separate offense and pursuit of the civil penalty.

In parallel, the International Maritime Organization (IMO) adopted in 1991 international guidelines focusing on invasive species brought in by ship's water ballast and sediment discharges. These international guidelines have provided a basis for the "International Convention for the Control and Management of Ship's Water Ballast and Sediments" (BWM Convention). The BWM Convention only came into effect in 2017 for the D1 part, and introduced a delay until September 2024 for the adoption of BWTS (D2 part) by old ships. But by 2017, all new ships must comply with the D2 part for countries that have ratified the IMO (Čampara et al., 2019). In 2019, the treaty was ratified by 81 countries, representing more than 80% of the global tonnage of merchant ships (*Status of Treaties* n.d.)

To illustrate the adoption of this technology, Figure (3) represents the share of ships with a ballast water treatment system in the total number of ships arriving in the US between 2013 and 2023. One can notice that before 2015, the share of vessel with a treatment system was null, indicating that the technology was not yet adopted, and then the vessels may comply with the 2012 law only via water exchange in the mid-ocean between 2012 and 2015. After 2015, a steady increase in ships equipped with a treatment system is observed. In 2017, on the date of implementation of the IMO convention, only about 20% of bulkers and tankers and about 10% of containers and general cargo arriving in the United States had installed BWTS.



Note: This figure represents the share of ships with the Ballast Water Treatment System (BWTS) in the total number of ships that enter American ports between 2012 and 2023. Each vessel is counted on the date of implementation of its ballast water treatment or at the date of its first trip.

Figure 3: Share of ship with Ballast Water Treatment System (in %, by type)

By 2023, almost 100% of the ships arriving in the US from overseas were equipped with a treatment system.

This shift gradually phased out ships without treatment systems in the US and with its direct partners. The multilateral effect of this policy, that is, where vessels without treatment have been reallocated, remains an open question that we address here.

3 Data

In this section, we describe the source and computation of our two main dependent variables, the occurrence of Invasive Species and the ballast water system installed by ships. As explanatory variables, we use several data among which the ballast water exchanges.

3.1 Dependent Variables

3.1.1 Marine Invasive Alien Species

To analyze invasive alien species, we use the World Register of Introduced Marine Species (WRiMS).[4] WRiMS identifies species that have been introduced by human activity into areas beyond their native distribution.

We consider three different measures of IAS: i) the occurrence of all IAS, ii) the occurrence of IAS that are present throughout the entire period, or at least detected twice (called "regular"), and iii) the occurrence of new IAS detected for the first time (called "new"). Appendix B provides some descriptive statistics about IAS.

The database offers access to species occurrence records at different spatial resolutions, such as maritime zones, countries, and specific georeferenced points. The definition of IAS used here is taken at the "eco-region" level over the period 2006-2019.[5] Since eco-regions are delineated by bio-geographic characteristics that are relatively homogeneous inside each spatial unit, we obtain a more relevant definition of IAS than an alternative measure based on administrative boundaries.

In order to obtain data at the port level, we apply a 30 km buffer around each port inside each eco-regions to identify occurrences of invasive species. This means that we have the same definition of IAS for two ports that are located in close proximity in the same region, but the number of IAS obviously varies from one port to another.

This database, which represents the dedicated work of many experts around the world, nevertheless has the usual drawbacks of this type of collection: invasion records are undoubtedly geographically biased; more expert reports are funded in rich countries to study IAS (Saffer et al., 2024). Furthermore, the database does not account for species that have expanded their range through natural dispersal mechanisms.

3.1.2 Adoption of BWTS

To analyze the impact of the US Ballast Water Management Act, we need to know when and where BWTS have been adopted at the ship level. We get these data

[4] This database was built by the Invasive Species Specialist Group (ISSG) of the International Union for Conservation of Nature (IUCN), based on the World Register of Marine Species (WoRMS) database. WRiMS provides information on whether species listed in the WoRMS registry are considered invasive.

[5] Eco-region as defined by the Marine Ecoregion of the World (MEOW) classification system. This system is produced by the Nature Conservancy (TNC) and the World Wildlife Fund (WWF). The world's coastal waters are divided into 232 eco-regions nested within broader provinces.

from the National Ballast Information Clearinghouse (NBIC). The NBIC was established in 1997 following the National Invasive Species Act (1996). This program is a two-way collaboration between the Smithsonian Environmental Research Center (SERC) and the US Coast Guard, that collect and analyze ballast water from vessels in American waters.

From these data, we know the ballast treatment systems used by vessels and the date of adoption of these systems. However, we do not know if the date of adoption is also the date when ships start to effectively use these systems. To know this, we track vessels with BWTS and we consider that the system is effectively used when there is no longer water exchanged in mid-ocean. Data on mid-ocean water exchanged are also available from NBIC. This work on data allows us to accurately identify the date on which these systems came into operation. This computation is essential to determine the "treated" vessels that use these systems and the effect of BWTS on IAS.

We also identify ships that traveled to the USA but never installed BWTS, i.e. those that continued to perform exchanges beyond 200 nautical miles.

When we analyze the impact of the D2 regulation on invasive species *in the US*, we do not need any other data than the one contained in the NBIC database. However, this database does not provide information on the destination of ships leaving US waters. This is important for analyzing the external effect of US regulations on *partner countries*. In particular, we want to analyze on which routes vessels equipped with BWTS have been affected. To do this, we use NBIC to identify BWTS equipped ships and then track their movements from port to port with the Lloyd's List Intelligence (LLI) database for the period 2016-2021 between May and October. This database provides the shipping routes of almost all bulk carriers and general cargo ships in the world. The database includes the port of arrival, the port of departure, the respective arrival and departure times, as well as other specific information linked to each vessel in operation (IMO, MMSI, etc.). We are then able to identify which American partners' ports are used by ships that have BWTS installed.

See Map (7) in Appendix A for the ports studied here with the Lloyd's database, Ducruet et al. (2018) for a detailed description of this database, and Ducruet et al. (2024) for a historical analysis.

3.2 Explanatory variables

3.2.1 Ballast water exchanged and discharged

A central variable to explain the proliferation of IAS under the D1 regulation is the amount of ballast water exchanged and discharged by the vessels. We also get these data from the NBIC.

This database provides the volumes and locations of the ballast water exchanged and discharged into the ocean. For each voyage, the vessels must report the amount and source location of ballast water, the location and quantity of exchanges performed in the open ocean, as well as the location and amount of ballast water discharged at the port.

The NBIC database distinguishes between two types of ballast water. Ballast waters exchanged are waters taken on at the origin of the trip and discharged in mid-ocean (after the law) or at US destination ports (before the law). These ballast waters are the target of the law because they are likely to contain IAS. Ballast waters discharged refer to waters that have been pumped in mid-ocean and later discharged at the port. The authority assumes that these ballast waters do not contain IAS; however, several studies have emphasized that invasive species can remain in tanks and then rejected with these waters in ports (see Gerhard et al. (2019) for a review). We therefore use the NBIC variable that adds these two types of water in our estimation of the D1 regulation.

We use exclusively the NBIC database to analyze the D1 regulation not solely for the United States but also for neighboring countries (the Lloyd database is not required). More specifically, for these neighbors, we identify ships bound for the United States that exchange their waters into foreign zones delimited by a 30 km buffer around neighboring ports. We then extract the volume of ballast water exchanged by these ships in these locations. The neighborhood should be understood here in a broad sense all the ports that are near a direct maritime route to the US and near its maritime border are named ”neighbors”, the list of these countries is given in Appendix C.

3.2.2 Control variables

We use a set of environmental variables, from the WRiMS database, to better control the ecological background of the proliferation of invasive species. More precisely, we use sea surface temperature, sea surface salinity, and bathymetry.

The sea surface temperature matters because during mid-ocean replacement of ballast water, temperature can influence the death rate of IAS. For example, alien species of algae can proliferate during a period of high sea temperature. Bathymetry (depth and topography of underwater environments) also has an impact on IAS. Some studies show a proliferation of them after water ballast exchange in shallower seas (McCollin et al., 2007). Finally, salinity has an effect on IAS (Gerhard et al., 2019), in particular for species that come from a different level of salinity (e.g. from fresh to salt water).

4 The effects of ballast water exchanges

4.1 Empirical strategy

To investigate the impact of ballast water exchanged and discharged (regulation D1) on the occurrence of IAS in American ports and neighboring countries, we estimate the following equation:

$$IAS_{sikt} = \alpha + \beta_1 * Policy_t * BWE_{it} + \beta_2 * BWE_{it} + Z_{ikt} + f_i + f_t + f_s + \varepsilon_{sikt}. \quad (1)$$

The dependent variable, IAS_{sikt}, measures the occurrence of invasive species s observed in an area of 30 km around the port i at location k during the year t between 2006 and 2015. We stop the analysis in 2015 because at that time vessels start to use BWTS - as shown in Figure (3) - then it becomes harder to isolate the role of ballast water exchanges after that date.

We use three different measures of occurrence: the occurrence of regular IAS, of new IAS, and all the occurrence of IAS (described in the data section). These dependent variables are regressed for US ports and for neighboring ports of the United States. $Policy_t$, is a dummy variable equal to one for years following the implementation of the US mid-ocean ballast water exchange policy in 2012, zero otherwise.

We capture the impact of ballast discharges through BWE_{it}, which represents the volume of ballast water exchanged and discharged in the vicinity of the ports i at time t.

In addition, we include a vector of covariates Z_{ikt}, defined at the level of the observations of IAS in k around the port i, which are the sea surface temperature, salinity and bathymetry. This regression includes fixed effects for year (f_t), species (f_s), and port (f_p) to control for time trends, species-specific traits, and unobserved port-level heterogeneity. We cluster standard errors at the of ports to account for heteroskedasticity and autocorrelation within clusters.

The aim of this empirical strategy is to first understand the effect of ballast water exchange and then to measure what happens after the enforcement of the D1 regulation.

4.2 Results

Ballast water exchange is the oldest IAS management policy, and although the literature has shown that it is not always effective in some locations, our analysis does not convey such a negative message for the US. According to our results reported in Table (1), the D1 regulation enforced in 2012 has had the effect expected by policy makers. The exchange of water in mid-ocean and then the discharge of clean water in US port led to a decrease of IAS (Column 1 and 3) that has been magnified after the implementation of the law.

	Invasive Alien Species Occurence		
	All	Regular	New
D1 Policy * BWE	-0.0849**	0.0150	-0.162***
	(0.0355)	(0.0201)	(0.0366)
BWE	0.0946	0.0212	0.181***
	(0.0599)	(0.0190)	(0.0670)
Bathymetry	-0.466***	0.0273	-0.491***
	(0.0682)	(0.148)	(0.0710)
Sea Surface temperature	2.491*	-0.671	4.536***
	(1.314)	(1.443)	(1.744)
Salinity	-2.918**	-6.577	-2.963**
	(1.166)	(4.562)	(1.262)
Year FE	✓	✓	✓
Port FE	✓	✓	✓
Species FE	✓	✓	✓
Observations	186700	19836	166857
Log-Likelihood	-598482.0	-62283.6	-521073.6
Pseudo R2	0.517	0.299	0.546

Notes: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. BWE: Ballast water exchanged and discharged. All: entire set of occurrence of IAS (Invasive Alien Species) around ports. Regular: IAS observed at least twice over the period. New: IAS detected for the first time.

Table 1: Effect of the Regulation on Invasive Species in the US

If we now consider the effect of this law on partners that are on the maritime road to the USA, we observe a spill of IAS before the US maritime zone (see Table 2). Columns 1 and 3 show a sharp increase in IAS correlated with ballast water exchanged in neighboring countries after 2012. The coefficient obtained is much higher in this case than for the United States, indicating the strong negative externality that such a policy can have on neighboring countries. This confirms the possibility of IAS leakage from American imports due to the Ballast Water Act.

	Invasive Alien Species Occurence		
	(1)	(2)	(3)
	All	Regular	New
D1 Policy * BWE	0.0698***	-0.0687	0.0512***
	(0.0187)	(0.0427)	(0.0189)
BWE	-0.145***	-0.487***	-0.105**
	(0.0522)	(0.0792)	(0.0517)
Bathymetry	0.0611***	0.126***	0.0548***
	(0.00648)	(0.00803)	(0.00593)
Sea Surface temperature	1.742*	4.213***	1.712
	(0.931)	(0.528)	(1.196)
Salinity	7.717***	14.45***	6.730***
	(0.734)	(1.914)	(0.706)
Year FE	✓	✓	✓
Port FE	✓	✓	✓
Species FE	✓	✓	✓
Country FE	✓	✓	✓
Observations	249918	2598	247301
Log-Likelihood	-491870.2	-6125.3	-484809.6
Pseudo R2	0.130	0.525	0.121

Notes: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. BWE: Ballast water exchanged and discharged. All: entire set of occurrence of IAS (Invasive Alien Species) around ports. Regular: IAS observed at least twice over the period. New: IAS detected for the first time.

Table 2: Effect of the American Regulation on Invasive Species in Neighboring countries

5 Ballast water treatment adoption

To show how the composition of ships has changed over time outside the US since the implementation of the ballast policy, we propose using a Staggered Difference-in-Differences estimator based on the adoption by ship of the treatment systems.

As explained in the data section, here we use the date when the system is effectively used and not just officially adopted. Each time we use the word "adoption" or "adopted", we are talking about an actual use of the system, and not an administrative declaration.

The database tracks vessel changes over 12 time periods (years) and includes significant variation in treatment timing, with the first group adopting BWTS in 2015 and the last in 2019. We consider vessels that make at least one trip to the US in the year. We also exclude to the sample the entry of new ships that may have BWTS for a reason unrelated to the US law (e.g. the 2017's IMO rule on new ships). Appendix B provides the number of observations and other descriptive statistics for each treatment group.

Concerning the estimator, the presence of treatment effect heterogeneity leads us to reject the use of a classical Two-Way Fixed-Effects (TWFE) estimator, due to 'forbidden comparisons' that it makes by (mis)using already treated units in the control group (Borusyak et al., 2024). We apply the Staggered DiD method developed by Chaisemartin and D'Haultfœuille (2020) to address these potential heterogeneous treatment effects. As a robustness check, we present in Appendix D the same regression using the estimators of Callaway and Sant'Anna (2021) and Sun and Abraham (2021).

The regression of the staggered adoption of BWTS can be written as follows.

$$A_{vt} = \sum_{\ell} \beta_{\ell} 1 \{t - o_v = \ell\} + f_v + f_t + \varepsilon_{vt}. \tag{2}$$

As the outcome variable, we use A_{vt} the ratio of trips made by BWTS ships s coming from the US to the total number of all trips in the year t in each ports. The objective is to analyze the BWTS adoption process that can explain the occurrence of invasive species in the ports of the partners.

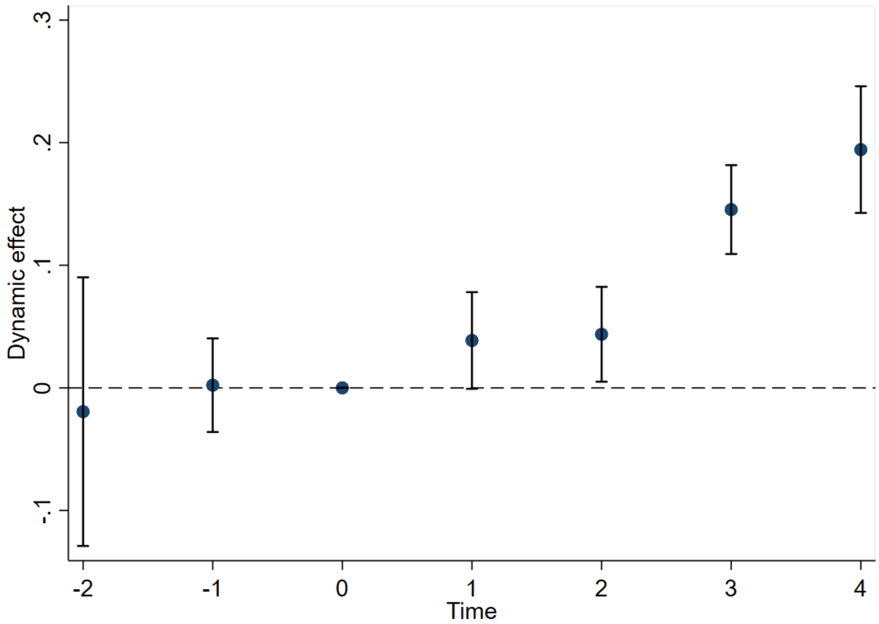
Vessels are classified into different cohorts according to their initial treatment. Binary treatment is indicated by B_{vt} and the earliest period of treatment is given by $o_v = \min\{t : B_{vt} = 1\}$. The time defined relative to the timing treatment is $\ell = t - o_v$. Time and individual fixed effects are introduced *via* f_v and f_t.

We do not introduce any variable of control for several reasons. The most interesting variables of control are time-varying, and as stated by Caetano et al. (2022) and Caetano and Callaway (2024) the conditional parallel trend assumption is hard to respect in that case, leading to a biased average treatment effect on the treated (ATT). Moreover, many of the covariates we are thinking about are also affected by the treatment, and then their introduction can lead to dubious results (see the literature on the "mediator case" in directed acyclic graphs, for example Wysocki et al., 2022).

5.1 Results and identification issues

Figure (4) plots the findings of the staggered adoption of BWTS in the main partners of the US. We observe a significant positive adoption of BWTS after 2015, which, moreover, increases over time.

This causal impact is based on several assumptions. The hypothesis of parallel trends cannot be tested and we cannot rule out its violation. The first adopter of BWTS certainly does not have the same characteristics as the not-yet treated, and this not-yet treated certainly does not represent the situation of the first adopter if the American policy had not been enforced. However, by considering in this sample the main partners of the US, and by controlling by fixed effect at the level of ships, we select group and we control for many difference between treated and untreated vessels. This can be observed by noticing the nonsignificant difference in the pretreatment period in Figure (4).



Note: This figure shows the dynamic effect of BWTS adoption. The dependent variable is, for each ship, the share of connections between the US and its top 30 partners over total connections. The panel is restricted to ships with at least one US–top partner connection per year. The estimation (2015–2019) uses De Chaisemartin's method without the dummies of control.

Figure 4: Staggered dynamic adoption effect for ships

Another related issue is that this adoption should not have been driven by other factors that vary over time and destination, and then between the different treated groups. The most obvious source is the ballast policies of partner countries. By excluding new ships, we do not introduce in the sample the ballast policies of countries concerning new ships after the enforcement of the IMO convention in 2017.

Finally, to establish a causal relationship, one should have no anticipation of the treatment (the D2 US's policy) and no spillover effects between the control and the treated. Although the assumption of no (or weak) anticipation may be valid in 2015, because the technology was not available before that date, the total lack of spillover is more difficult to defend. In particular, the transposition of this assumption for groups not yet treated is a concern because vessels who adopt BWTS later do not have the same information on the application of the policy and on the technology as the first-movers. They may have better knowledge on the cost of maintaining the ballast water system and they may also choose a more efficient system. This is all the more likely in a shipping company, where shipowners own several vessels and therefore stagger adoption according to the learning curve they have achieved on the first vessels on which they installed these systems. However, we have only 5 ships in that sample that belong to the same owner thus such a mechanism cannot explain the growing adoption of BWTS in our study.[6]

Keeping these limits in mind, it seems possible to argue that if the causal link between the US law and the adoption of BWTS is not certain, it is at least credible. Robustness checks carried out with the staggered DiD methods of Callaway and Sant'Anna (2021) and Sun and Abraham (2021) confirm the growing adoption of BWTS that becomes significant, regardless of the estimators, in the second year after the first wave of adoption.

5.2 Where do ships without BWTS go?

In the previous section, we analyzed the negative externality of the D1 policy; here we propose to study whether the D2 policy might not also have negative side-effects. The law may have had a crowding-out effect, with shipowners deciding to move vessels without BWTS to countries with few links to the United States.

This represents an attrition bias in the previous analysis. If more vessels that should be treated drop out due to adverse effects, the treatment effect may appear more favorable than it actually is. However, for our analysis of IAS, the conse-

[6] We do not discuss the possibility of spatial spillovers (Butts, 2023; Butts, 2021) since local competition and spatial externality on BWTS seems unlikely and unknown to us, however we certainly cannot rule out totally this possibility.

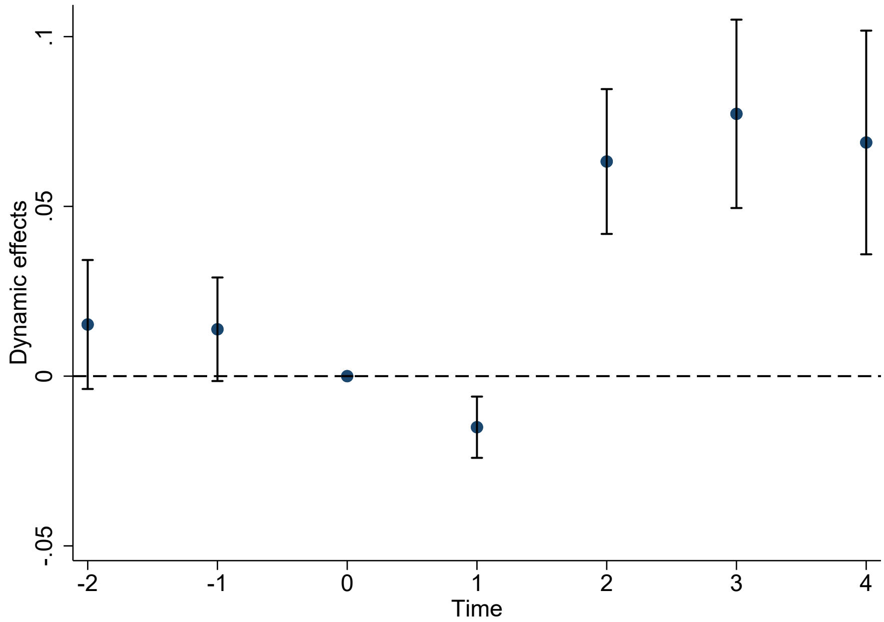
quence is the same, if less ships without BWTS are assigned to countries with high connection to the US, then one can expect less invasion there.

We again estimate Equation (2) by tracking where ships without BWTS, and no longer identified in the US, are located. We focus on countries that are not in the top 30 partners of the US, called "intermediate and bottom 30". The year 2015 is taken as the enforcement of the BWTS policy in the US.

Figure (9) shows the staggered DiD estimation using the estimator of Chaisemartin and D'Haultfœuille (2020). There is a difference between the control and treatment groups, as illustrated by the positive coefficients in the pre-treatment period, which are not, however, significant.

In the second year after the availability of BWTS, the number of ships without treatment withdrawn from the US maritime zone and assigned to routes linking weak/intermediate US trading partners increased strongly. This shows that policy D2 is not free of negative externalities. However, the consequences are certainly less critical than those of the D1 policy. Indeed, ships without BWTS relocated from the US to other countries are likely to replace older ships that also lack BWTS. As a result, this crowding-out effect may not have an impact on IAS in these countries (as we will see in the next section).

Not reported here, we find a similar result when focusing exclusively on low-trade partners, albeit with a less significant effect at $t = 3$. Introducing intermediate partners improves the analysis, showing that these countries are also affected by this relocation of ships.



Note: This figure shows the evolution of ship connections no longer identified in the USA after the implementation of the Ballast Water policy in 2012, up to 2019. The variable used in this staggered analysis is the share of connections to intermediate and bottom-30 US countries destination, divided by the total number of connections, at the individual ship and time level. We use the "not yet treated" group and the De Chaisemartin estimator.

Figure 5: Staggered dynamic adoption effect for ships

6 The Consequences of the US Ballast Act on Invasive Species

We now turn to the impact of ballast water treatment systems due to the American law on the occurrence of invasive species.

6.1 Empirical strategy

To assess the impact of BWTS on IAS, we consider the following Fixed Effect (FE) model:

$$IAS_{sikt} = \alpha + \beta_1 * BWTS_{it} + Z_{ikt} + f_i + f_t + f_s + \varepsilon_{sit}. \tag{3}$$

The dependent variable, IAS_{sikt}, is the appearance of invasive aliens of species s, observed around the port i in the location k and the year t. The time period begins in 2015 when BWTS begins to be adopted and ends in 2019 because the COVID pandemic disrupts maritime trade in 2020.

The variable of interest is the ballast water treatment systems, referred to as $BWTS$ in the equation. As explained in the data section, we employ two distinct variables to estimate the effect of these systems. For the United States, we use the ratio between the volume of water treated by a ballast water treatment system and the total volume discharged (treated and exchanged) in each port, based on detailed data available from the NBIC database.

In the case of US trade partners, such detailed data is not available. We then use the Lloyd database to determine the country of destination coming from the US, which is merged with the NBIC data to compute the ratio of vessels equipped with a treatment system to the total number of vessels calling at each port.

In addition, we include a vector of variables Z_{ikt} which are defined at the level of the IAS observations in different locations k inside a buffer of 30 km of each port i, namely sea surface temperature, salinity, and bathymetry. We also introduce a dummy for the enforcement the IMO convention (see Appendix C) and the share of new vessels (without connection to the US) that due to the IMO convention enter in 2017 in the maritime trade with BWTS installed.

This estimate also includes fixed effects for year (f_t), species (f_s) and port (f_i) to control for temporal shocks, species characteristics and unobserved port heterogeneity.

This empirical strategy may not suffer from reverse causality, as the international trade relationship may not be affected by IAS. However, this strategy may be biased by unobserved factors that vary over individual and time and that both affect IAS and BWTS. One may think for instance that the observation of IAS increase in developed countries over time in a similar way that BWTS are adopted in these countries.

6.2 Results

The impact of BWTS is presented in Table (3). The more ballast waters are cleaned, the fewer IAS there are in the United States. This result is observed for all species (column 1), for species regularly found in American ports (column 2), and for new species detected for the first time (column 3). In addition, this table (column 4) shows the beneficial effect of this adoption for partner countries which benefit from a reduction of IAS in their ports. Doubling the share of water treated by ships coming from the US leads to a decrease of 3.05 occurrences of IAS in these ports. This impact is a good start compared to the continuous increase in IAS observed otherwise. The enforcement of the IMO convention does not explain the reduction of IAS in these partner countries. Not reported here, we also ran this regression without this variable; the coefficient of our main variable is not affected by this change, however, its level of significance increases (falling below the 0.01 threshold).

The D2 policy is not significant for neighboring countries, which may be explained by heterogeneous treatment effects in these countries, since some of them still receive ballast water exchanges with IAS. The IMO convention seems to have a strong impact in that case; however, few neighbors have signed it (Mexico, Bahamas, and Panama), thus this beneficial effect is highly concentrated.

	Invasive Alien Species Occurence				
		US		US Partners	US Neighbors
	(1)	(2)	(3)	(4)	(5)
	All	Regular	New	All	All
Share of Water Treated in the US	-0.743***	-2.510***	-0.210*		
	(0.248)	(0.905)	(0.127)		
Vessels with BWTS (Connected to the US)				-3.054**	1.699
				(1.420)	(2.620)
IMO Convention				0.105	-1.704***
				(0.199)	(0.345)
Sea Surface Temp Mean	-2.211*	-5.414	-0.804	-10.07***	1.891
	(1.181)	(3.785)	(0.793)	(2.285)	(2.405)
Sea Surface Salinity Mean	-2.383	-2.857	-0.824	0.126**	1.861
	(1.692)	(2.679)	(2.077)	(0.0567)	(1.674)
Bathymetry Mean	0.00111	0.0163***	0.00195*	-0.0116***	-0.00128
	(0.00174)	(0.00623)	(0.00101)	(0.00233)	(0.00298)
Constant	96.63**	139.4**	36.14	280.5***	-115.6
	(48.66)	(56.09)	(69.51)	(62.39)	(80.69)
Year FE	✓	✓	✓	✓	✓
Port FE	✓	✓	✓	✓	✓
Species FE	✓	✓	✓	✓	✓
Observations	12424	3481	8943	190843	1856
R2	0.645	0.651	0.179	0.127	0.428

Table 4: Effect of the D2 Regulation on Invasive Species in the US, US Partners and US Neighbors

Notes: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All: entire set of occurrence of IAS (Invasive Alien Species) around ports. Regular: IAS observed at least twice over the period. New: IAS detected for the first time. Time period : 2015-2019.

In Table (9) we test the heterogeneity of our results by considering three different subgroups of trade partners.

The column ”Bottom30” presents the result for partners that are ranked at the bottom of the distribution of trade partners. Our hypothesis is that countries that do not trade much with the US do not benefit from the positive externality of the US Ballast Water Act. This group can be considered as a placebo group, few ships with BWTS dock in these ports, so we expect no impact. This is precisely what is observed in Table (9), the share of vessels with BWTS has no impact on IAS in these countries.

For countries in the middle of the distribution, we observe a negative effect, which is, however, not significant (column 2). This indicates that the level of trade with the US should be large enough to reduce IAS. Finally, for the top 30 partners (column 3), we recover the strong significant decrease in the number of alien invasive species.

This result confirms our previous findings regarding the adoption of BWTS on ships that frequently travel to the United States. The adoption of BWTS is a rational investment for vessels that regularly go in the US. Once installed, BWTS are used in partner countries since this process enables one to skip ballast water exchange and then to save time and risk. By this mechanism, fewer IAS are rejected at ports. Not reported here, we have also introduced a control that takes into account the share of new ships with BWTS that enter the sample in 2017 due to the IMO convention. This variable is never significant, except for regressions performed by category of ships and reported in Appendix F.

In Appendix F, we pursue this analysis of the effect of the American policy on its main partners by distinguishing vessels by their size. We find that the largest ships, which treat more ballast water and then discharge a larger volume of clean water, have a greater impact than other ships. These larger ships are contributing to a substantial reduction in invasive species in the ports of the main American partners.

	Invasive Alien Species Occurence		
	US Partners		
	Bottom30	Intermediate	Top30
Vessels with BWTS	0.505	-0.773	-4.877**
	(0.671)	(0.495)	(2.430)
IMO	1.439***	0.893***	0.293
	(0.241)	(0.316)	(0.410)
Sea Surface Temp Mean	-0.645***	3.345***	-15.51***
	(0.204)	(0.696)	(3.463)
Sea Surface Salinity Mean	0.344*	-0.155***	2.469***
	(0.202)	(0.0320)	(0.357)
Bathymetry Mean	0.000204	-0.00176	-0.0175***
	(0.000322)	(0.00160)	(0.00448)
Constant	3.137	-39.11***	204.4***
	(7.770)	(9.488)	(59.77)
Year FE	✓	✓	✓
Port FE	✓	✓	✓
Species FE	✓	✓	✓
Observations	19045	42850	108919
R2	0.439	0.193	0.136

Table 6: Effect of the D2 Regulation on Invasive Species for US Partners category

Notes: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. The first column corresponds to countries that ratified the BWM Convention before 2017. The Top 30 represents the United States' 30 largest trading partners (column 3), while the Bottom 30 refers to the 30 countries with the lowest trade volume with the U.S. (column 2).

7 Conclusion

It is well known in international economics that a large country has a particular responsibility on the world market, since its trade policy can influence prices, quantities, and well being in the rest of the world. We show here a different kind of responsibility, an ecological one, by analyzing the consequence of the Ballast Water act implemented in the US in 2012 on invasive species in this country and in the rest of the world.

We find that the D1 regulation of the Ballast Water Act has been beneficial to the United States but at the expense of its neighborhood. We detect a significant increase in IAS after the implementation of this policy, around neighbors' ports where vessels going to the US discharge their water.

In contrast, the D2 policy consisting of making the use of BWTS mandatory has been beneficial for partner countries. We show that this policy has been well implemented, with an increasing adoption of ballast water system by vessels. However, adoption has been stronger on the main route of trade traffic with the US. Countries with weak ties to the United States have increasingly welcomed ships not equipped with ballast water treatment systems, illustrating the management strategy of shipowners.

Obviously, all these results have to be taken with caution, BWE and BWTS are not distributed at random, and then the causal impact of the US Ballast Water Act are difficult to establish. More work is necessary on the US policy, but also on the IMO convention that we just take as a control here, but that deserves a full investigation with a detailed analysis of BWTS installed due to this convention.

At least two policy implications can be discussed from this work. First, with respect to the ballast water exchange policy (which is the main and traditional policy for managing IAS in many parts of the world), our research encourages a better design. Authorities should define specific zones in places where rejected IAS are effectively destroyed (deep sea, far from other ports) to not affect the ecosystem of other countries. These zones should be regularly monitored to verify their effectiveness. Second, BWTS is certainly the first best policy, and the effort to implement it worldwide by the IMO should be pursued.

Many works remain to be done on this topic. We need to better analyze the costs of BWTS, in order to understand how these systems can be financed even on seaways that are not very profitable, going to poor and peripheral countries. These countries should be protected by the future colonization of IAS.

Furthermore, we have only analyzed the number of occurrence of IAS here, but these variables do not indicate the level of threat to the native biota or the damage already caused. More research is needed on this to better measure the past and future consequences of maritime trade.

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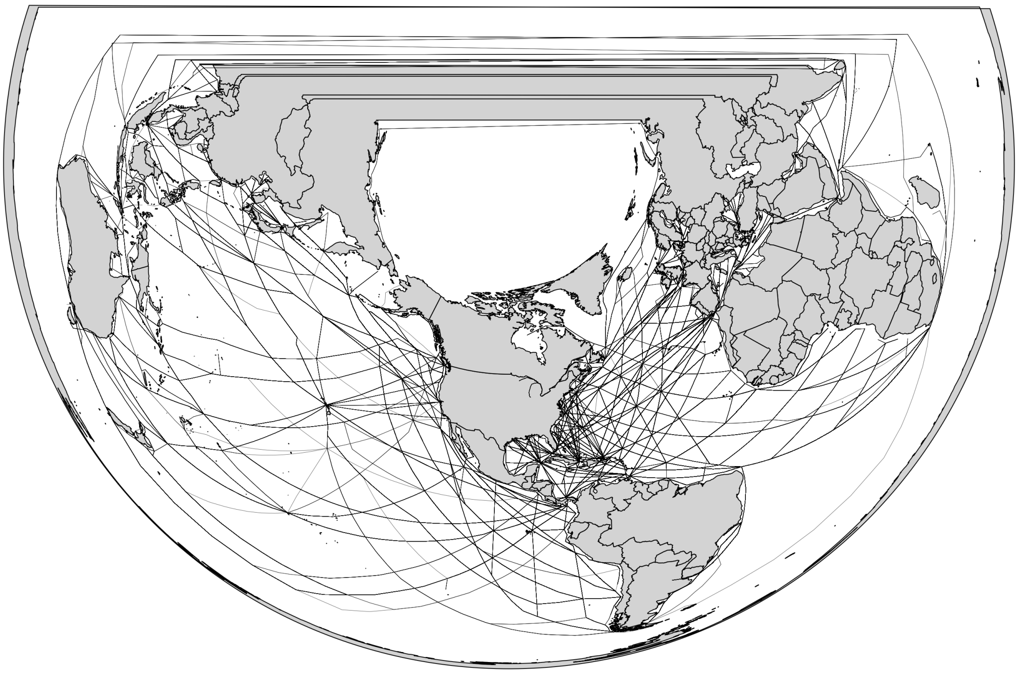
Appendix A: routes connectivity

To accurately identify and quantify maritime routes that go through Exclusive Economic Zones (EEZs) of countries neighboring the United States, we reconstructed global ship trajectories using the Searoutes routing algorithm. This tool allows for the estimation of realistic shipping paths between port pairs, taking into account navigational constraints such as coastlines and common maritime corridors.

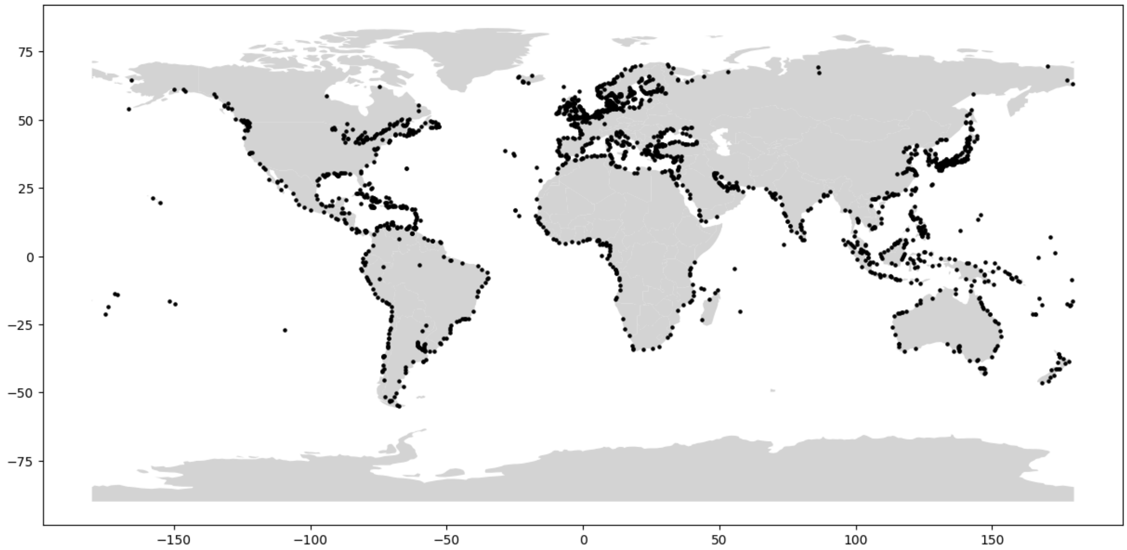


Map 6: Maritime routes creation

Note: This figure displays all maritime routes passing through the Exclusive Economic Zones (EEZ) of countries neighboring the USA, as well as routes within the USA. These maritime routes are generated using the Searoutes algorithm, which minimizes shipping distances between ports. All spatial data are projected using the EPSG:5070 coordinate reference system (WGS 84).

Our reconstruction is based on the Lloyd's List Intelligence (LLI) database, described in detail in Section 3, which provides comprehensive data on vessel-level movements between ports of origin and destination from 2006 to 2021. Using this dataset, we developed a global maritime network composed of more than 4,300 ports, enabling the identification of more than one million port-to-port connections around the world.

Using this global shipping network and the origin-destination ship flows from actual ports, we reconstruct the number of connections and total deadweight to/from the US or to/from other countries, passing through each country's maritime EEZ. Map (7) presents the different ports finally studied.



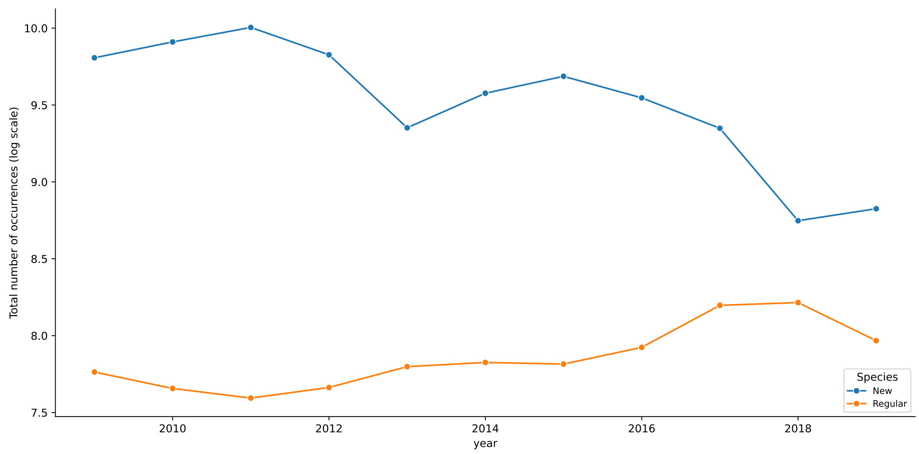
Map 7: Ports used in ship movements from LLOYDS

Note: The main ports in the dataset of bulk carrier and cargo movements from 2006-2021.

Appendix B: Descriptive Statistics

Invasive species

Figure (8) shows the change in the occurrence of new and regular IAS. One can observe a decreasing trend for the detection of new species in the world, while the number of already detected species tends to increase.



Note: This figure shows the yearly evolution of IAS (Invasive Alien Species) between 2006 and 2019, divided into two variables: new invasive species discovered during the period ("New") and regularly present IAS throughout the entire period. The occurrences of these two variables are summed in logarithmic scale.

Figure 8: Regular and New invasive species

Adoption of BWTS

Table (7) presents different descriptive statistics about the treated and control groups. The small number of treated vessels in the first and second cohorts can be a source of the weak statistical power obtained for these first periods.

Year	**Group**	Individual	**Connection**	**Total connection**	**Deadweight**
cohort 2015	control		205	699	74824.76
cohort 2016	control		218	630	103531.70
cohort 2017	control		205	573	104173.89
cohort 2018	control		225	714	84789.70
cohort 2019	control		203	647	94305.11
cohort 2015	treated	26	18	70	86095.00
cohort 2016	treated	28	29	99	49383.43
cohort 2017	treated	108	49	198	54698.47
cohort 2018	treated	180	84	350	51930.00
cohort 2019	treated	289	107	482	50932.09

Table 7: Descriptive statistics about treated and untreated cohorts

Appendix C: Lists of countries

Maritime Neighborhood of the United States

We consider as neighbors all countries whose ports are close to a direct maritime route to the United States and/or to its maritime border, that is, all countries reported in Table (8). For example, Panama is in this sample because vessels going to the US exchange their water at the entry of the canal and then directly go to US ports without other exchanges. Canada is not included because it has a common policy with the US on ballast waters linked to trade in the Great Lakes. Finally, we have excluded Russia due to the small number of vessels that cross the Bering Strait.

Country Code	Country
ABW	Aruba
ATG	Antigua and Barbuda
BHS	Bahamas
BLZ	Belize
BRB	Barbados
CRI	Costa Rica
CUB	Cuba
CYM	Cayman Islands
DMA	Dominica
DOM	Dominican Republic
GRD	Grenada
HND	Honduras
HTI	Haiti
JAM	Jamaica
KNA	Saint Kitts and Nevis
LCA	Saint Lucia
MAF	Saint Martin (French part)
MSR	Montserrat
MEX	Mexico
NIC	Nicaragua
PAN	Panama
PRI	Puerto Rico
TCA	Turks and Caicos Islands
TTO	Trinidad and Tobago
VEN	Venezuela
VGB	British Virgin Islands
VIR	U.S. Virgin Islands

Table 8: List of US neighbour for D1 variable

IMO Convention

When controlling for the IMO convention in the analyses of BWTS adoption, we consider countries that have enforced the policy in 2017. The list of these countries is given in Table (9) with the year of enforcement.

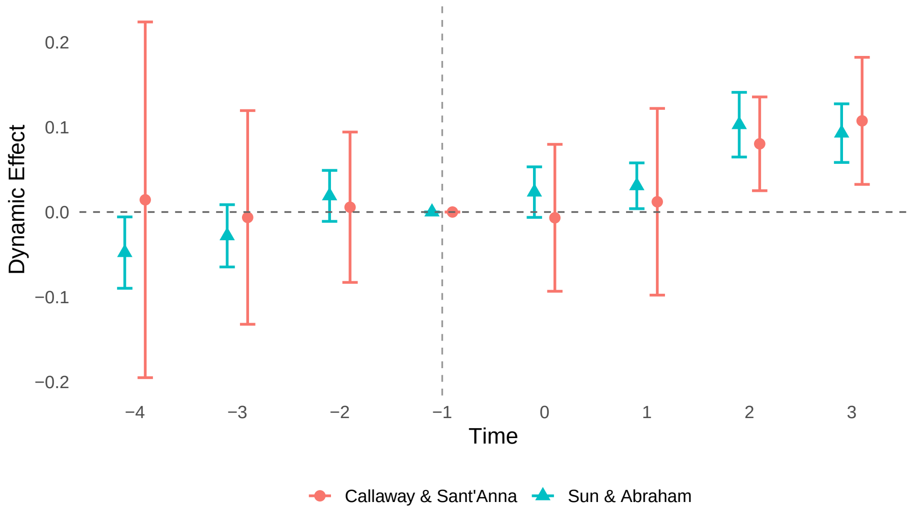
Country	Year	Country	Year
Lithuania	2018	Albania	2017
Madagascar	2017	Antigua and Barbuda	2017
Malaysia	2017	Argentina	2017
Maldives	2017	Australia	2017
Malta	2017	Bahamas	2017
Marshall Islands	2017	Bangladesh	2018
Mexico	2017	Barbados	2017
Mongolia	2017	Belgium	2017
Montenegro	2017	Brazil	2017
Morocco	2017	Bulgaria	2018
Netherlands	2017	Canada	2017
New Zealand	2017	China	2019
Nigeria	2017	Congo	2017
Niue	2017	Cook Islands	2017
Norway	2017	Croatia	2017
Palau	2017	Cyprus	2018
Panama	2017	Denmark	2017
Peru	2017	Egypt	2017
Philippines	2018	Estonia	2018
Portugal	2018	Fiji	2017
Qatar	2018	Finland	2017
Saudi Arabia	2017	France	2017
Serbia	2018	Georgia	2017
Seychelles	2018	Germany	2017
Sierra Leone	2017	Ghana	2017
Singapore	2017	Greece	2017
South Africa	2017	Grenada	2018
South Korea	2017	Honduras	2017
Spain	2017	Indonesia	2017
St. Kitts and Nevis	2017	Iran	2017
St. Lucia	2017	Jamaica	2017
Sweden	2017	Japan	2017
Switzerland	2017	Jordan	2017
Syria	2017	Kenya	2017
Togo	2018	Kiribati	2017
Tonga	2017	Latvia	2019
Trinidad and Tobago	2017	Lebanon	2017
Turkey	2017	Liberia	2017
Tuvalu	2017		
UAE	2017		

Table 9: IMO Convention

Appendix D: Robustness of the Staggered DiD

Other estimators

Figure (9) presents staggered DiDs for the adoption of BWTS using the estimators Callaway and Sant'Anna (2021) and Sun and Abraham (2021). We find results similar to those presented in the text, one more time the first period is not significant, and the standard errors are higher with Callaway and Sant'Anna (2021), but overall the dynamic adoption is in progress after the enforcement of the D2 policy.



Note: This figure shows the dynamic effect of BWTS adoption. The dependent variable is, for each ship, the share of connections between the US and its top 30 partners over total connections. The panel is restricted to ships with at least one US–top partner connection per year. The estimation (2015–2019) uses Sun and Abraham's method, controlling for IMO signature (dummy) and total number of connections (dummy).

Figure 9: Staggered dynamic adoption effect for ships

Appendix E: A different measure of environmental concern

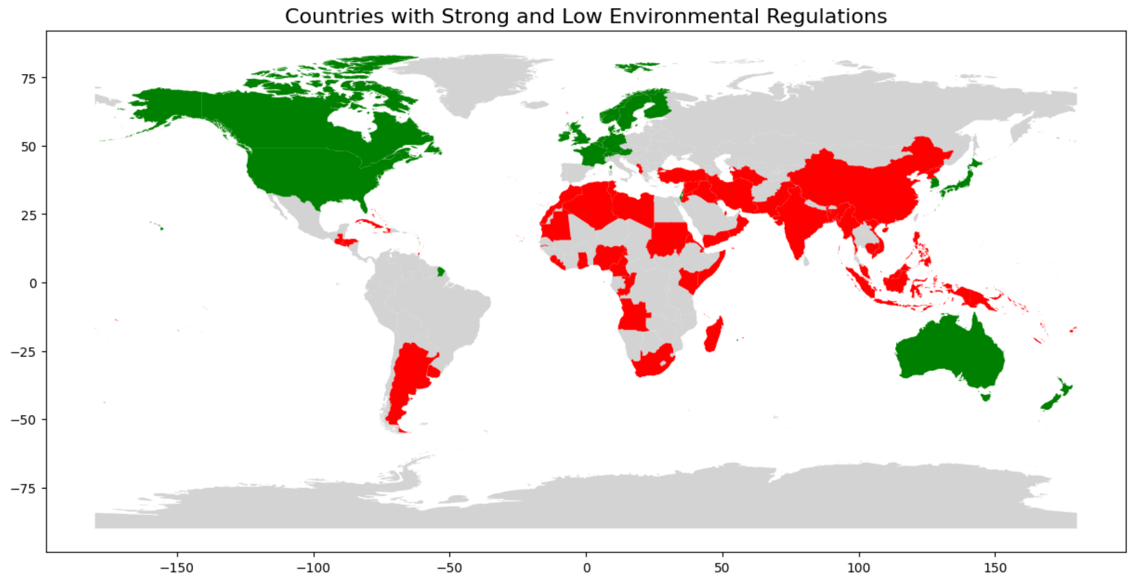
Environmental Performance Index

We test here whether the results obtained in the text are robust to a different classification. A possible direct determinant of the reallocation of ships with BWTS is the environmental concerns of the destination countries. It is likely that shipowners reallocate their ship with BWTS toward countries where they anticipate an increase in environmental norms, and thus a law on ballast waters. Thus, we use an indicator of environmental performance to classify the different countries of destination and again estimate the staggered DiD analysis presented in Equation 2. It should be noted that the EPI index is strongly correlated with the level of GDP, and since the US trade more with countries of high level of GDP, this analysis does not enable us to discriminate between the role of being a trading partner presented in the text and the role of environmental standards analyzed here.

Data

To determine the environmental objectives of US trade partners, we use the Environmental Performance Index (EPI), provided by Yale University. This database includes 58 indicators in 11 categories, providing data on the regulations of air, water, chemicals, and toxic waste of countries (this list is not exhaustive). We construct a yearly indicator, based on the 2022 EPI for 220 countries from 2006 to 2022. We focus our attention on the Ecosystem vitality (ECO) variable. This variable includes six categories, namely biodiversity and habitat, forests, fisheries, air pollution, agriculture, and water resources. These categories take into account marine habitat, species protection, marine trophic components, NO_x and SO_x trends, pesticide pollution. This indicator is never used directly as an explanatory variable, but to separate countries with a high level of environmental standards, defined by a level above 55 (the median of the ECO EPI), from others with a more lax environmental regulation (below 35).

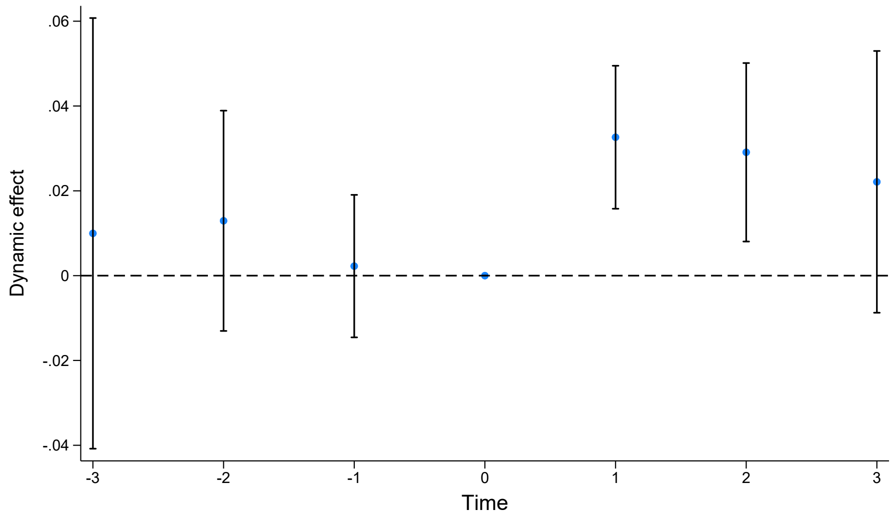
Figure (10) presents the different countries considered as entities with high and low environmental standards. This categorization obviously overlaps with that of the main trading partners - European countries, Canada, Japan and Australia being both countries with close trading links with the United States and with a high level of environmental regulation. However, there are some notable differences; for example, Mexico and China are major trading partners, but not characterized by high environmental standards.



Map 10: Countries with low (red) and strong (green) environmental regulation index

Results

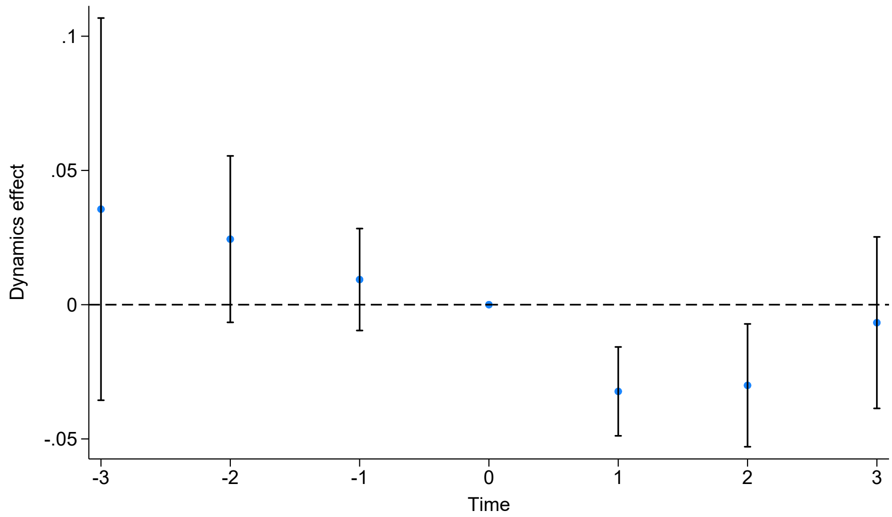
Figure (11) displays the findings of the staggered DiD estimation of Equation 2. The coefficients are not significant in the pretreatment period ($t < 0$), suggesting that the assumption of a parallel trend is verified. In the immediate post-treatment period, in particular in t=1 and to a lesser extent in $t = 2$, the coefficients are significant and positive. This indicates a strong adoption of BWTS for vessels that connect the US to countries with high environmental standards. Finally, in the last period, the effect is no longer significant. This may be explained by the fact that vessels without systems have been crowding out, and then the process of adoption becomes limited.



Note: Staggered difference-in-differences for ballast water treatment systems adoption in ships going to countries with high environmental standards defined by the Environmental Performance Index (EPI indicator > 55) of Yale University. Chaisemartin and D'Haultfœuille, 2020 estimator with not-yet-treated and never-treated bulk and general cargo ships serving as controls.

Figure 11: Adoption and Allocation of Ballast Systems in Countries with High Environmental Standard

Figure (12) shows the findings of the same regression, but for a sample of countries with weak environmental standards. The coefficients are significantly negative in the first periods, indicating a reallocation of ships to other trips, maybe to countries with higher environmental standards.



Note: Staggered difference-in-differences for ballast water treatment systems adoption in ships going to countries with low environmental standards defined by the Environmental Performance Index (EPI indicator < 35) of Yale University. Chaisemartin and D'Haultfœuille, 2020 estimator with not-yet-treated and never-treated bulk and general cargo ships serving as controls.

Figure 12: Adoption and Allocation of Ballast Systems in Countries with Low Environmental Standard

Finally, Table (10) shows the effect of the share of ship connections with BWTS on IAS in countries with these different levels of environmental standards. We get what the result on adoption predicts, IAS are significantly reduced in countries with high EPI and not affected by this share in countries with low EPI where few ships have adopted BWTS.

	Low EPI	High EPI
Vessels with BWTS	-3.456	-0.748***
	(2.175)	(0.270)
Share of new vessels	0.153	0.382
	(0.822)	(0.475)
Sea Surface Temp Mean	-17.30***	0.832***
	(4.399)	(0.113)
Sea Surface Salinity Mean	0.714***	-0.0921***
	(0.172)	(0.0193)
Bathymetry Mean	-0.0174***	-0.000218
	(0.00367)	(0.000255)
Constant	460.3***	-16.00***
	(117.4)	(3.235)
Year FE	Yes	Yes
Port FE	Yes	Yes
Species FE	Yes	Yes
Observations	81939	88875
R2	0.131	0.563

Table 11: Effect of the D2 Regulation on Invasive Species in countries classified by EPI

Notes: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All: entire set of occurrence of IAS (Invasive Alien Species) around ports. Regular: IAS observed at least twice over the period. New: IAS detected for the first time. Time period : 2015-2019.

Appendix F: Robustness on the D2 regulation

Size of Ships

We estimate the effect of BWTS on US main partners, given by Equation (3) by distinguishing the effect of ships by their sizes. The categories are defined as follows: Category 1 includes vessels with a gross tonnage of less than 2,986; Category 2 includes vessels with a gross tonnage between 2,986 and 7,743; Category 3 includes vessels with a gross tonnage between 7,743 and 26,057; and Category 4 includes vessels with a gross tonnage greater than 26,057. These thresholds were determined on the basis of a quantile distribution. Table (12) provides the results commented on in the text: large ships (categories 4), which treat more ballast water and then discharge a greater volume of clean water, have a greater impact than medium-sized ships (categories 2-3).

	Invasive Alien Species Occurence		
	US Partners		
	(1)	(2)	(3)
	Category 2	Category 3	Category 4
Vessels with BWTS	-3.210**	-3.844	-25.23***
	(1.294)	(3.671)	(8.517)
Share of new vessels	-0.479	-0.552	-4.658**
	(1.233)	(1.677)	(2.257)
Sea Surface Temp Mean	-5.834***	-16.16***	-17.10*
	(1.245)	(5.934)	(8.871)
Sea Surface Salinity Mean	0.0332	0.300**	0.432**
	(0.0642)	(0.123)	(0.211)
Bathymetry Mean	-0.00174**	-0.0145***	-0.0333***
	(0.000834)	(0.00535)	(0.0111)
Constant	166.8***	445.5***	463.4*
	(33.87)	(161.7)	(242.3)
Year FE	Yes	Yes	Yes
Port FE	Yes	Yes	Yes
Species FE	Yes	Yes	Yes
Observations	54458	35741	23375
R2	0.110	0.128	0.158

Table 13: Effect of the D2 Regulation on Invasive Species for US Partners and Category of vessels

Notes: Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. All: entire set of occurrence of IAS (Invasive Alien Species) around ports. Regular: IAS observed at least twice over the period. New: IAS detected for the first time. Time period : 2015-2019. Regressions by category of vessels. Category 1 is not estimated and omitted from the table.