

## Research article

## The impact of invasions from ballast water: A life cycle impact assessment method

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## 1. Introduction

Maritime shipping drives globalization and accounts for more than 80% of world trade by both volume and monetary value, making it the cornerstone of the global trading system (Rodrigue, 2006; United Nations [UN], 2024). Shipping contributes to significant environmental stressors, including marine pollution, underwater noise, and the disruption of ecosystems through the spread of invasive species (Ruiz et al., 1997; Peng et al., 2015). For the latter, ballast water is the most relevant vector of introduction, specifically for aquatic invasive alien species. Ballast water is pumped in and out of the ship's ballast tanks during cargo load and unload, a process essential for maintaining stability, maneuverability, and fuel efficiency (International Maritime Organization [IMO], 2022). In doing so, they may have taken up propagules in one location and discharged any survivors in another, thereby facilitating the transport of aquatic organisms, that may become invasive species (Kaluza et al., 2010; Keller et al., 2011; Sardain et al., 2019; Saebi et al., 2020).

IMO published their first (voluntary) guidelines to address the potential impacts on marine ecosystems caused by the spread of invasive species through ballast water discharges in 1993. In 2004, the ballast water management (BWM) convention was adopted (David and Gollasch, 2015), but did not enter into force until 2017, and its practical implementation in the subsequent years has often been inconsistent (Gerhard et al., 2019). The convention means to regulate the spread of viable organisms by the D-1 or D-2 standards, roughly explained as: D-1) Exchanging ballast water with sea water 200 nautical miles from the coast; or D-2) limiting the concentration of organisms, or colony forming units, that can be discharged with the ballast water. Especially the latter standard greatly reduces risk of introduction, but requires greater effort (David and Gollasch, 2015).

The process for a species to become invasive starts with its deliberate or accidental transportation to a different ecosystem. Species transported by human activities to an ecosystem where they are non-native

are called *alien* species. Synonyms include exotic-, non-indigenous-, and foreign-species. *Invasive* species are distinct from *aliens* in that they successfully established themselves and lead to negative impacts in the new ecosystem (Russell and Blackburn, 2017). The IMO convention uses the term “harmful aquatic organisms and pathogens” (HAOP) to describe these invaders. In this publication we use invasive species – the distinction is that HAOP can be native, while invasive species as we describe them are always alien. Predation, competition, ecosystem engineering, parasitism, a mix of the above-mentioned, and additional secondary effects from trophic cascades are examples of negative impacts that can follow successful biological invasions in new ecosystems (Rilov and Crooks, 2009; Blackburn et al., 2014; Thomsen et al., 2014).

Invasive species, both aquatic and terrestrial, were the sole reason for 16% of recorded extinct species worldwide and additionally played a part alongside other drivers for another 44% of recorded extinctions (Roy et al., 2024). In 2019 alone, invasive species caused an estimated economic loss of around 423 billion USD with only 8% of this amount attributed to post-invasion management. Most costs resulted from the loss of ecosystem services, such as those seen for fisheries (Roy et al., 2024). Despite these consequences, international policy targets, like the Aichi target 9 for invasive species, were not met (Maney et al., 2024). Up until now, most documented extinctions caused by biological invasions have occurred on land, as monitoring and accounting for invasive species in oceans remain more challenging. There are few records of extinctions caused by marine invasive species, but 8.7% of the 23,696 marine animal and plant species assessed with a global scope by the International Union for Conservation of Nature (IUCN) are currently threatened by extinction, and there is overwhelming evidence of the adverse impacts of marine biological invasions (Ruiz et al., 1999; Geburzi and McCarthy, 2018; International Union for Conservation of Nature [IUCN], 2024).

Because shipping is the main pathway for the spread of marine invasive species and thereby the origin of the outlined impacts, IMO has mandated that the transport of alien species must be considered when

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assessing environmental impacts of any value chain (Sardain et al., 2019; IMO, 2022; UN, 2024). Environmental assessments of value chains can be achieved using life cycle assessment (LCA), but this framework has so far seen few developments in addressing biological invasions. Woods et al. (2016) described 7 major drivers of marine biodiversity loss, including invasive species, and proposed guidelines for how to quantify these in Life Cycle Impact Assessment (LCIA) – a key component of LCA.

Hanafiah et al. (2013) made the first attempt at characterizing the impact on freshwater species by biological invasions spread by inland

shipping, but scarcity of data limited the upscaling of their method. More recently Borgelt et al. (2024) extended the approach to characterize the impact of biological invasions in the terrestrial environment, revealing that some international trade routes could have higher impacts on biodiversity from introducing invasive species than from climate change-related emissions on the same route. There is, however, no model available that quantifies the impact of marine invasive species in the Ocean. To address this gap, there is an urgent need to develop a method for assessing the biodiversity impacts of biological invasions in marine environments, enabling a more comprehensive evaluation of the

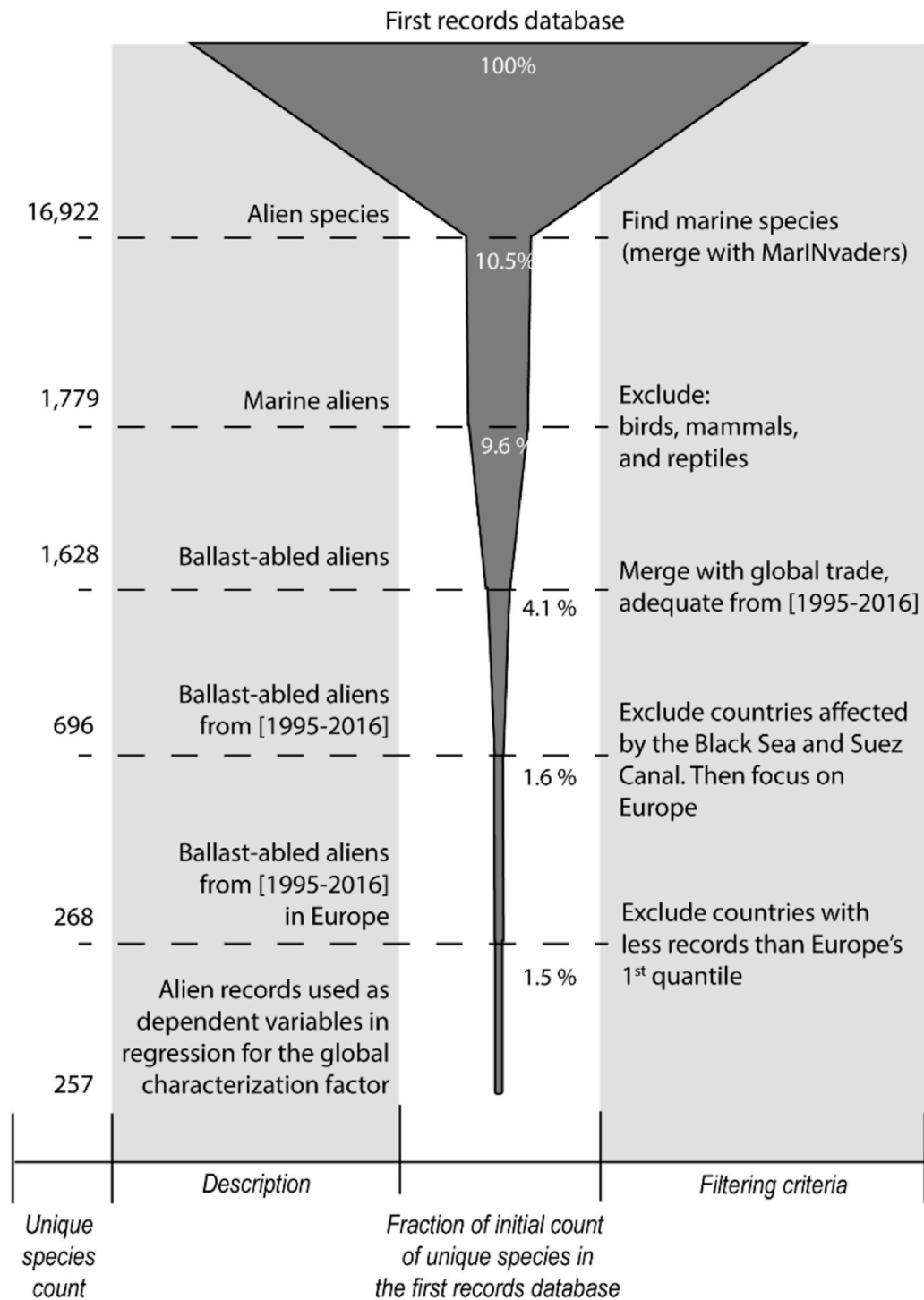


Fig. 1. Refinement of first records of alien species by (Seebens et al., 2017) to ensure that counts of alien introductions included in the regression are marine ballast-abled species, to match the trade data from (Gaulier and Zignago, 2010), and to account for bias.

environmental consequences of shipping and its role in global trade.

To be meaningful in the context of LCIA, the spread of alien species must be causally connected to a measurable industrial activity. Because ballast water is discharged when ships take on weight during cargo loading, we use the export of goods (expressed in mass units) as explanatory variable, while the number of newly introduced alien species recorded at the location of ballast water discharge represents a response variable. This relationship captures the fact that more exports generally require more ballast water adjustment. However, introductions can also occur via other pathways – including aquaculture, hull fouling, rafting on marine debris, or migration through man-made canals (ICES, 2005; Kannan et al., 2023). These other introductions are excluded from our model. To reduce this confounding influence, we refine our dataset by focusing on countries where ballast water discharge can be considered the dominant vector of spread. This allows the response variable (alien introductions) to be more reliably linked to the explanatory variable (export mass).

In this paper, we present the first midpoint characterization factor (CF) for LCIA, addressing the spread of alien species by ballast water discharge and this phenomenon's relation to international exports. We then combine it with existing effect factors (EFs) from (Gjedde et al., 2024) to calculate the first regionalized endpoint CFs addressing biological invasions in the marine realm.

## 2. Materials and methods

We refined the data from the Global Alien Species First Record Database (henceforth “alien records”) by Seebens et al. (2017) to account for bias and to match it to data of exported goods from Gaulier and Zignago (2010). An overview of this process is presented in Fig. 1 and further detailed in the following paragraphs 2.1 to 2.3. Subsequently, we conducted quantile regressions between countries' export (explanatory variable) and alien introductions (response variable), as further described in section 2.4. The slope of this regression is a midpoint characterization factor expressing the number of alien introductions we expect in a country per mass of goods exported (section 2.4), or per volume of emitted viable ballast water (section 2.6).

### 2.1. Alien species databases

There are multiple global databases that collect records of alien introductions and invasions, for example the Global Invasive Species Database (GISD), the World Register of introduced Marine Species (WRiMS), the Europe-focused European Alien Species Information Network (EASIN), or the MarInvaders toolkit and database (Verones et al., 2023). MarInvaders harmonize geographic and alien status data of marine species from several large global databases: It uses the Ocean Biodiversity Information System (OBIS) to locate species found in the World Register of Marine Species (WoRMS), GISD, and the Nature Conservancy database (NatCon), thereby including most records of alien marine species in the world, although without specifying the timing of their first record. Optimal data for evaluating the state of alien species introductions should be constant in space, time, and across taxonomic groups (Zenetos et al., 2020). Unfortunately, all databases are both taxonomically and geographically biased, and sampling is mostly conducted in bursts during larger projects or at random when funding permits. But while the aforementioned databases refer to the sources of an occurrence, and occasionally directly state a date of first record, the main focus of the alien records by Seebens et al. (2017) was finding the first recorded occurrence of an alien species, resulting in more certainty of the time of introduction, and this was therefore our database of choice.

The alien records dataset consists of first recorded occurrences of alien species across multiple taxonomic groups and geographic regions. It includes 47,542 records of 16,922 unique alien species, covering terrestrial, freshwater, and marine environments from before AD until

and including 2016. The database is derived from an extensive literature review on more than 100 studies. In our study, we only fit to records of marine species that may be transported in ballast water, that is, species also found in the MarInvaders database (Verones et al., 2023) but excluding birds, mammals, and reptiles who although they may be marine are not found in ballast water (see also Fig. 1). Of the original 16,922 species in the alien records, 1779 were marine, and 1628 may be transported in ballast water.

### 2.2. Shipping activity databases

We used data prior to 2016 as IMO's BWM convention began taking effect in 2017, which presumably has a significant impact on the introduction rates of alien species introduced by ballast water. Using older records also reduces bias from detection lag, as more time has passed for introduced species to be recorded (Bailey et al., 2020). Therefore, our study covers 1995–2016, henceforth “our timeframe”. Due to a lack of historic shipping data, international trade volumes were utilized as a proxy, as maritime transport facilitates over 80% of global trade (Fournier et al., 2018). The CEPII BACI database (Gaulier and Zignago, 2010) provides export data for 200 countries at the product level for 5000 products in the “Harmonized System” nomenclature (6-digit code) from 1995 to 2023.

The traded products were each assigned to a ship type based on their physical and logistical characteristics, such as size, weight, and transport requirements, based on the work of Kramel et al. (2024) and Wang et al. (2021). Bulk goods like coal and grain were assigned to dry bulk carriers, liquid commodities like crude oil to tankers, and containerized goods to container ships. For ambiguous cases, expert judgment was applied to ensure accurate ship type allocation. Trade volumes were then aggregated by ship type and country-pair, allowing the estimation of shipping demand and flow of dead-weight-tonnage (dwt), between exporting and importing countries, for different ship types.

The trade data was geographically presented in ISO country-codes while the alien records additionally mentioned another 19 islands that are sub-regions of ISO countries (see appendix B for all island names). Hawaii belongs for example to the USA, but only the latter is an ISO code, and while we have alien records for Hawaii, trade data is only available for the USA, including Hawaii. We therefore excluded alien records on these 19 islands from our model, as we expect most of the trade to take place from and to the mainland.

### 2.3. Refining data to reduce bias

Literature and data on biodiversity is heavily biased, geographically and taxonomically, especially for the marine environment (Millar et al., 2019; Christie et al., 2021; Hughes et al., 2021; Watkins et al., 2021). The alien records data from our time frame is also geographically biased, having significantly more records in Europe and west-Asia, see Appendix Figure A.1. Regional databases (e.g., NEMESIS for the United States) can report higher counts of alien species than the alien records dataset by Seebens et al. (2017), suggesting that areas more comprehensively represented in our dataset, are areas with more records. Accordingly, we refine our analysis to Europe, where coverage is strongest. We then also exclude 5 European landlocked countries.

European countries and those bordering the Black Sea and Mediterranean waters are among the most researched regions regarding marine invasions (Watkins et al., 2021). However, the Black Sea is geographically unique – both due to its isolation from the oceans, and because marine invasions there are likely affected by a drastically lower salinity compared to all other seas of such size. As we focus specifically on invasions caused by ballast water discharges, we wish to exclude data points where other factors are likely to play a significant role in determining the rate of alien introductions – and this caused us to exclude the countries bordering the Black Sea. We also excluded countries likely to be affected by interoceanic man-made connections like the Suez Canal as

it causes a significant increase in alien introductions in the Mediterranean, and it is difficult to assess which species are introduced by ballast water discharge, hull fouling, fouling on floating debris, or simply carried by the currents through the canal (Occhipinti-Ambrogi and Savini, 2003; Ragkousis et al., 2023). The exclusion of these countries and its implications are discussed in detail in Appendix A.

#### 2.4. Quantile regression

Following the assumption that areas with more records are better represented in our dataset, we also excluded countries whose count of alien records is below the 1st quartile among the remaining European countries to account for research bias within Europe. The latter excludes countries with under eight new alien records within our time frame. Alien introductions per mass of exports for the remaining countries are then represented by a regression that defines the midpoint characterization factor. Figure A.2 maps European countries that are included or not in the regression.

Regressions are computed using the Levenberg-Marquardt algorithm in the Scipy Python package trying to fit a linear, Michaelis-Menten, power and logarithmic function to the 18 datapoints remaining after data refinement. The best fit function is indicated by evaluating the lowest root mean squared error (RMSE) and the residual standard error (RSE) in addition to arguments given throughout the Results and Discussion sections. A fit was also made for the 23 datapoints that remain before the lowest quartile is removed, see code repository (link in section 10).

#### 2.5. Endpoint characterization factors and country aggregation

The introduction of alien species per mass of exported goods is multiplied with the potentially disappeared fraction of native species (PDF) per introduced alien species from Gjedde et al. (2024) resulting in an endpoint characterization factor (CF) in units of PDF per exported goods in its native geographic scale (“marine ecoregions” by Spalding et al. (2007)). The native CFs are then aggregated to country scale for each of the following types of ship in Table 1 as these had available data, as described in section 2.2.

Impact to biodiversity from marine invasive species introduced through shipping takes place at the port that exports a good (since ballast water is released to load a good). The country CF of each ship type is the weighted average of the CFs of the country's ports, with the ship traffic of the specific ship type in each port as weight (equation (1)). Ship traffic in a port is represented by the accumulated dead-weight-tonnage (dwt) of ships passing through the port – dwt is a measure of how much a ship can carry, e.g., cargo, personnel, fuel – everything except the hull itself.

$$CF_{type, country} = \frac{\sum_{port \in country} (dwt_{type, port} \cdot CF_{port})}{\sum_{port \in country} (dwt_{type, port})} \quad \text{Equation 1}$$

**Table 1**

Ship types used to aggregate the endpoint CFs into countries and the corresponding EcoInvent activity of that ship type.

| Ship type          | EcoInvent inventory label                                                                                       |
|--------------------|-----------------------------------------------------------------------------------------------------------------|
| bulk dry           | transport, freight, sea, bulk carrier for dry goods, heavy fuel oil                                             |
| container          | transport, freight, sea, container ship, heavy fuel oil                                                         |
| liquefied gas      | transport, freight, sea, tanker for liquefied natural gas, heavy fuel oil                                       |
| oil                | transport, freight, sea, tanker for petroleum, heavy fuel oil                                                   |
| other liquids      | transport, freight, sea, tanker for liquid goods other than petroleum and liquefied natural gas, heavy fuel oil |
| passenger          | transport, freight, sea, ferry, heavy fuel oil                                                                  |
| refrigerated cargo | transport, freight, sea, container ship with reefer, heavy fuel oil, cooling                                    |

#### 2.6. New life cycle inventory and elementary flow

For the inclusion of this impact pathway in LCA, we suggest a new activity for the life cycle inventory called “ballast water operation” (BWO), an operation that is performed in a port when a good is exported. This activity has an elementary flow called “viable ballast water” (VBW) – calculated by a ratio of VBW per mass of goods exported during the BWO. Using EcoInvent as database example, the BWO activity is conveniently placed in a “market activity” along with transport activities. Thereby, the shipping activities in Table 1 will stay in units of tons.km, but the ballast water operation keeps only the unit “tons” (or converted to kg), while both the transport and BWO activities can scale with the reference flow (or production activity) linked to the market activity. The scaling of the BWO (and thereby emitted VBW) with the exported mass of the reference flow,  $x$ , and the elementary flow's translation to impact (in PDF) is illustrated in equation (2).

$$x \text{ [kg]} \cdot BWO \left[ \frac{\text{Liter VBW}}{\text{kg}} \right] \cdot CF \left[ \frac{\text{PDF}}{\text{Liter VBW}} \right] = \text{impact [PDF]} \quad \text{Equation 2}$$

We stress that the VBW elementary flow is an abstract quantity: The midpoint CF is derived from a relationship between recorded alien introductions and mass of exported goods. Meanwhile, the volume of VBW is in *not* a 1:1 ratio with mass of export (David et al., 2012), meaning that we cannot with currently available data know how much VBW was actually emitted in our timeframe. So, what is the benefit of a new elementary flow? The time frame for the CF modelling deliberately predates the enforcement of the BWM convention in 2017, so the technical development towards cleaner ballast water discharges is excluded from the impact. Therefore, the VBW elementary flow can be scaled within the operation activity, for example to represent when technologies are used to decrease the concentration of viable propagules. This will enable the modelling of regulation D-2 of IMO's BWM convention in the life cycle inventory modelling phase of an LCA, e.g., by using any technology approved by the BWM regulation D-3 (see IMO (2026)). Now, one can scale the VBW flow in the BWO activity, for example from 1 to 0.05 – representing a 95% reduction of viable ballast water per kg exported goods compared to what was *expected before the BWM convention was enforced* (see also figure A.3). But it is important to stress that this does *not* mean that 5 L of VBW is emitted per 100 kg export in absolute terms (we have no data for this), but rather that there is a *relative* decrease compared to whatever the absolute value was in our timeframe.

#### 2.7. Application example

We performed a simple, illustrative LCIA case study assessing the impacts of freight container ships (ship inventory datasets from EcoInvent 3.11, cutoff, see Table 1) arriving in an arbitrary choice of port (port of Tilbury, London) from multiple source locations (see Figure A.4). We calculated the impact from marine biological invasions using the native and country-aggregated CFs presented herein. Instead of using a scaling factor of 1 in the BWO described in section 2.6, we skip it entirely and units are therefore in PDF/kg export. That is, our application example is assuming no effects from the BWM convention, or any other development that could change the ratio of VBW per mass exported goods. These results were then compared directly to the potentially affected fraction (PAF) per kg.km caused by green-house gas emissions on these routes using CFs from Iordan et al. (2023). Iordan et al. calculated impacts for three representative calculation pathways (RCP) scenarios (2.6, 4.5 and 8.5), which we use as uncertainty range in Fig. 4 (section 3.3) while assuming PAF to PDF conversion is 1:1. We are not aware of any consensus regarding how to convert between PDF and PAF and stress that these are arbitrary choices. The length of each route was found on [www.searates.com](http://www.searates.com) and routes originating in the East of Africa travel south of the African continent (instead of through the Suez

Canal). See [Figure A.5](#) for an overview of this workflow.

3. Results

3.1. Midpoint characterization factor: Aliens per export

If the number of introductions per mass of transported goods take shape like a saturation curve instead of being linear, then that would indicate that the receiving ecosystem improves its tolerance and/or that the introduction vector(s) reaches saturation – meaning that the trade of that port has caused the alien introductions it is able to. In that case, the marginal CF would be the tangent (or derivative) of this function at some point on the x-axis, resulting in different marginal CFs depending on the export history of a country. We therefore tried fitting functions that resemble such saturation: A logarithmic, a Michaelis-Menten and a power function were fitted to the dependent variables (see [Figure A.6](#) and the code repository (section 10)). However, we received worse fits for all non-linear functions compared to the linear regression (see [Table 2](#)). Instead, a best fit from the linear function indicates that an intensively used trade route will have the same risk of introducing alien species per mass of traded goods as a less intensively used trade route – that is, we see no evidence of saturation of the introduction vector nor increased tolerance in the receiving ecosystems.

[Fig. 2](#) shows the linear relationship between export of goods, in kg, and the number of recorded alien species in our timeframe (details in [Appendix B](#)). We are confident that the slope of the linear regression (“a” in  $ax + b$ ) is a non-zero positive value (p-value  $\approx 7.7 \cdot 10^{-5}$ ). Specifically, we expect an increase in alien establishments from ballast water discharges by approximately  $(4.7 \pm 1.9) \cdot 10^{-12}$  (95% confidence interval) alien species per kg goods exported (Pearson’s  $R^2 \approx 0.63$ ). Or following section 2.6, the unit can also be alien introductions per liter discharged VBW – keeping in mind that this elementary flow is a relative value tied to the mass of exported goods. In terms of LCIA, this slope is a global midpoint characterization factor (CF) that characterizes the number of alien species introduced in a country due to emissions of ballast water caused by exporting goods from that country.

The regression intersects with the y-axis at  $11.9 \pm 6$  alien species (95% confidence). These alien introductions cannot be explained by export, even in the dependent variables. We interpret the y-intercept as the number of alien species expected in a country that would have no exports, that is, a country that would have no ballast water emissions. Instead, these aliens are introduced by biofouling on ships or debris, aquaculture, or releases from aquariums, among others.

We eventually used 18 European countries for the regression (blue dots in [Fig. 2](#)). Of European coastal countries, five were excluded due to too few alien records (light blue cross) and four were affected by the proximity to the Black Sea (red circles). We stress that the herein derived midpoint CF is based on mainland countries – but we expect the invasiveness of ports on islands to be higher than indicated by this CF as remoteness promote biological invasions, also in marine ecosystems ([Moser et al., 2018](#); [Carlton, 2019](#)). We further discuss datapoints that are outliers to the regression because of their geographic relation to the Suez Canal or Black Sea in [appendix A](#), and compare with non-European data to support the use of the midpoint CF as a global estimate under

rigid assumptions. Half of the alien species in the 18 countries used for calculating the CF are crustaceans (28.4%) or fish (21.4%), while the rest are invertebrates (17.8%), algae (15.7%), mollusks (10.6%), vascular plants (4.3%), and a few insects, arthropods, amphibians, bacteria and protozoans (sums to 1.7%), see [Figure A.7](#).

3.2. Endpoint characterization factors

Regionalized impacts on native biodiversity in units of PDF per alien introduction are presented as effect factors (EFs) in [Gjedde et al. \(2024\)](#). Multiplying our midpoint CF with these EFs results in regionalized endpoint CFs within the native range of the EFs (marine ecoregions, see [Spalding et al. \(2007\)](#)). These CFs range from  $7.8 \cdot 10^{-18}$  to  $5.9 \cdot 10^{-14}$  PDF per liter VBW. Country-aggregated endpoint CFs for each ship types in [Table 1](#) have impacts ranging from  $4.7 \cdot 10^{-18}$  to  $5.0 \cdot 10^{-14}$  PDF per liter VBW and are plotted in [Figure A.8](#). All CFs are available in [Appendix B](#). In [Fig. 3](#) they are grouped in continents and presented as a boxplot with additional details in [Appendix B](#) (see continents in [Figure A.9](#)). Some countries have CFs of zero due to the surrounding ecoregion’s EF also being zero ([Gjedde et al., 2024](#)). Notable variations in impact exist across regions. And while the first and third quartiles, as well as extreme values, do not fluctuate within each continent, the medians within continents still vary across ship types. Therefore, we expect a difference in impacts across continents independent of the ship type. And while intracontinental ranges vary less, the different ship type medians indicate different skews of distributions, meaning that the specific ship type is also still relevant.

As the midpoint CF is global the geographic variation of the endpoint CFs across continents stems from the regionalized EFs only. However, there is still variation between ship types within continents. This is because certain types of ships have an affinity with some ports over others, and the location of these ports can be within different marine ecoregions, the native scale of the EFs. Therefore, when the weighted impact in a country or continent varies across ship types it is because of the ship type’s affinity to ports in different marine ecoregions. This phenomenon is pronounced in [Fig. 3](#) for refrigerated cargo exports in Africa. The reason is that refrigerated cargo from Africa is exported more from the west coast than from the east coast (see [Appendix B](#)). Meanwhile, effect factors are significantly lower on the African west coast as invasive species in these regions make up a relatively small part of the total biodiversity pressure compared to other threats in these regions (like global warming or pollution) that also causes pressures on marine biodiversity (i.e., the “relative threat frequency in [Gjedde et al. \(2024\)](#)). Similarly, extreme values observed for “other liquids” in Africa, Oceania, South America and North America are caused by being exported by few countries, and so the distribution within these continents are dominated by the few exporters (see also [Appendix B](#)), also resulting in a smaller variation. In Oceania for example, only one country exports goods of “other liquids”.

3.3. Case study and endpoint comparison to global warming

In [Fig. 4](#) we compared the impact on biodiversity by either invasive species or global warming for different shipping routes all headed to London in the UK, but different origins (see section 2.7). As we compare PDF/kg.km from greenhouse gas emissions with PDF/kg from marine invasive species from shipments of 1 kg, the change in global warming impacts is caused by different lengths of the routes, while the change in impacts from invasive species is caused by different local EFs. We see once more that the difference between using the native and the country-aggregated scale can vary greatly (Indonesia) – or not (Kenya). Sometimes the invasion impacts are neglectable compared to global warming impacts (from New York or Shanghai to London), but they can also be even larger than global warming (from Buenos Aires), keeping in mind that we assume a 1:1 PAF to PDF conversion. [Borgelt et al. \(2024\)](#) also

**Table 2**  
Different functions fitted to the data following the methodology described in section 2.4, and the indicators of goodness of fit: Root mean squared error (RMSE) and residual standard error (RSE). See code repository (section 10) for code.

| Function to fit  | RMSE | RSE  |
|------------------|------|------|
| Linear           | 7.58 | 8.04 |
| Michaelis-Menten | 9.34 | 9.91 |
| Power            | 8.24 | 8.74 |
| Logarithmic      | 9.05 | 9.60 |

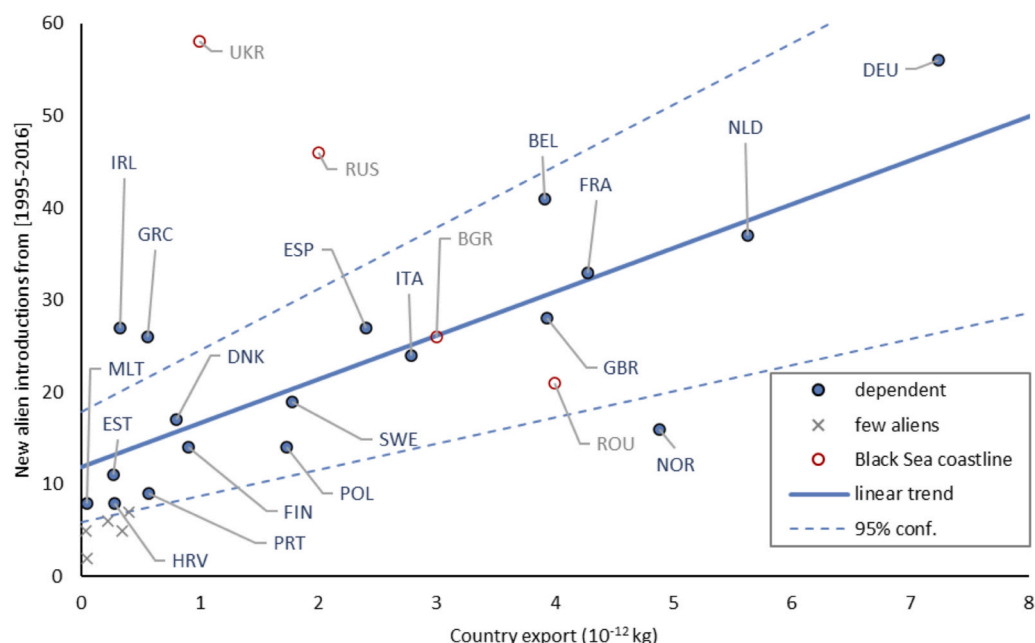


**Fig. 2.** Quantile linear model of alien counts per export in coastal European countries. We exclude countries with a Black Sea coastline. Then, European countries above the European 1<sup>st</sup> quantile in total alien counts are included as dependent variables for the characterization factor (blue dots). European countries below this quantile have too few invasions (grey crosses). The linear trend is expressed as  $\hat{y} \sim 4.7 \times 10^{-12} + 11.9$  aliens per kg exported goods, with  $R^2 \sim 0.63$ . Marine alien counts are from Seebens et al., (2017) and export from Gaulier and Zignago (2010).

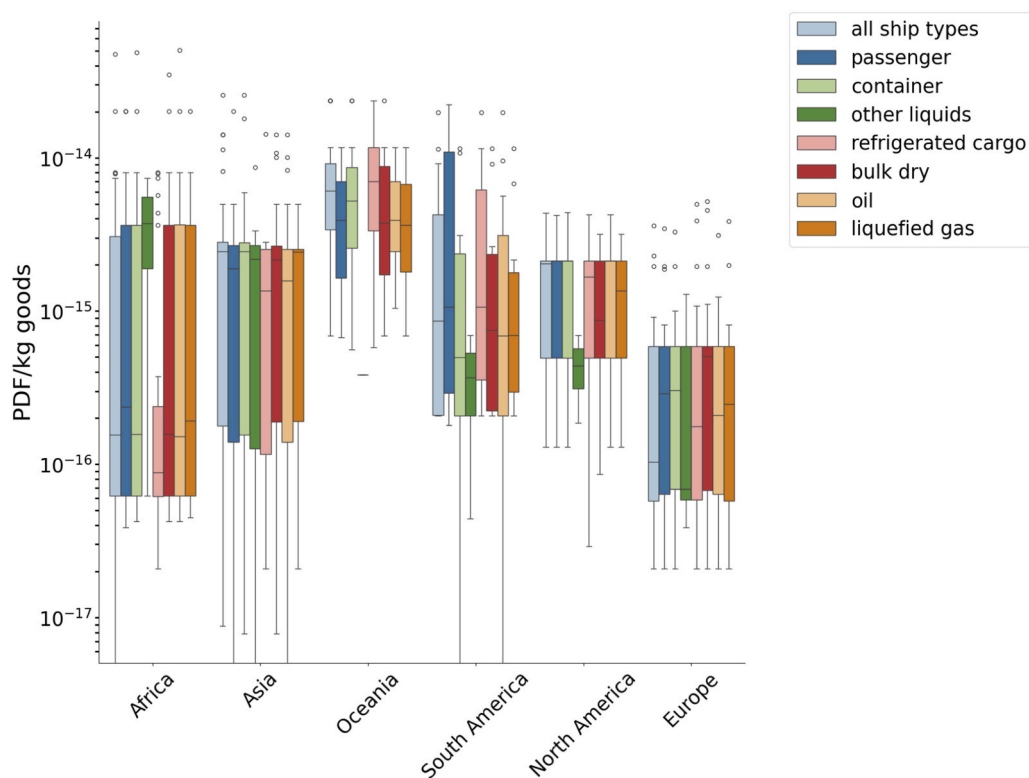


**Fig. 3.** Boxplot of country-aggregated endpoint characterization factors for different ship types, grouped within 6 continents (Antarctica is excluded as there are no exports). The factors represent biodiversity impacts in units of potentially disappeared fraction of native species (PDF) per kg goods exported, shown in a logarithmic scale to present the whole range of impacts.

found higher impacts from terrestrial invasive species for some routes, compared to the global warming impacts of the routes. This shows that failing to include the impacts of marine invasive species in LCA can potentially lead to problem shifting.

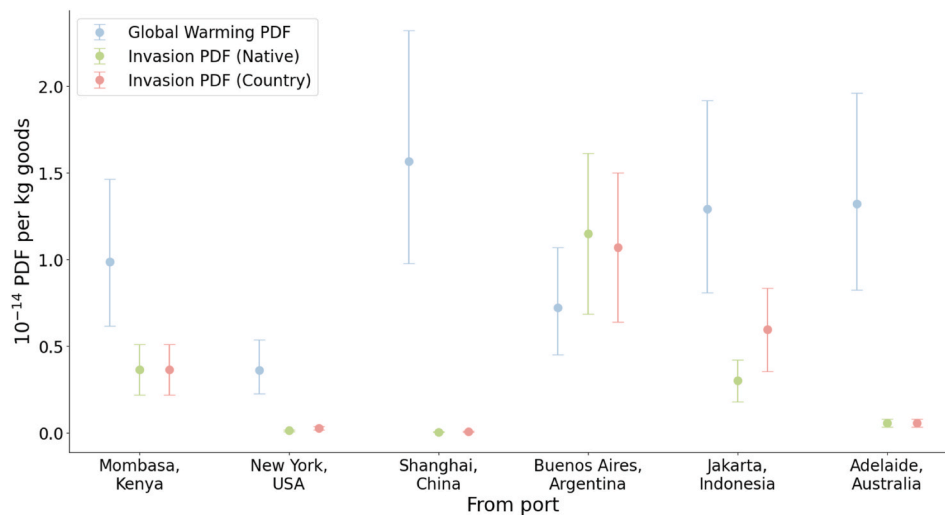


**Fig. 4.** Comparison of biodiversity impacts from marine biological invasions and global warming (PDF/kg goods) of specific shipping routes from the locations on the x-axis to London, UK. Impacts calculated from country-aggregated CFs and native (marine ecoregions) CFs are shown.

## 4. Discussion

### 4.1. Multiple vectors of spread affect the same response variable

We have found a relationship between the export of goods and alien introductions by refining our data to geographies where export of goods is the most relevant explanatory variable to a response in number of recorded alien species. Countries that we excluded, such as those near the Suez Canal and the Black Sea, are expected to have alien records because of vectors of spread other than those caused by exports. Therefore, they would only be noise in the regression leading to the midpoint CF. For a more accurate prediction of the accumulation of alien species in future studies, it is essential to integrate multiple explanatory variables in regions where the introduction of alien species can be attributed to multiple pathways. Therefore, apart from ballast water, herein proxied by exports, we must in future work consider vectors of spread like hull fouling, aquaculture, fouling on debris, natural dispersion, and how physiochemical parameters affect these – and the potential synergistic effects in relation to the same dependent variable (alien introductions). Once a method for each relevant vector of spread has been developed, they can all be compared to the same response variable: alien records. Until such a suite of models is developed, a regionalized model for the midpoint CF with a resolution relevant to LCIA does not seem feasible.

Our endpoint CFs assess the expected number of aliens introduced in a source location, independent of where a ship came from before this. However, as future midpoint CFs are likely to be in “donor-recipient” geographic units, the risk of introducing alien species will relate to parameters of each location, like temperature and salinity, as well as parameters related to the connection itself, like the time spent in a ballast tank (Seebens et al., 2017). Borgelt et al. (2024) also made regionalized CFs in the geographic units of “routes”, thereby incorporating a source and destination country. But we end up with many CFs if the regionalized impacts depend on at least two locations and their connection. Just for country-aggregates, the binomial coefficient of 195 countries would result in up to 18,915 CFs. Therefore, it is important that the inventory databases are developed in parallel so that the expansion of the LCIA method can be connected to the life cycle inventory. Additionally, it is crucial to reduce geographic biases from alien species record databases. In failing to do so we risk modeling the bias itself rather than accurately identifying how these explanatory variables interact with location-specific factors.

Future work can also incorporate how the relationship between the

export of goods and alien introductions vary between ship types, e.g., by modelling each ship type as a different vector of spread. Two factors are currently included: i) The aggregated CFs include the variation of shipping network patterns of different ship types. ii) Different ballast water operations can be modelled in LCA studies by scaling the viable ballast water (VBW) elementary flow according to how the ship conducts ballast water operations (BWO). However, future studies must incorporate how these operations affect alien introduction numbers when deriving the CFs, as data after 2017 must be assumed to be affected by this.

### 4.2. Perspective to other work

The first attempt at including alien species in the LCA framework is by Hanafiah et al. (2013) who calculated how the change in fraction of alien species in river basins change in relation to the increase of transported goods along the Rhine-Meuse-Danube canal. Hanafiah et al. were focused on inland shipping and the construction of canals rather than marine shipping activities. Like in this study, they focused on one variable that best explains the alien introductions in that study: Transport of goods. They extracted two fate factors from their analysis:  $1.1 \cdot 10^{-12}$  and  $1.7 \cdot 10^{-11}$  aliens per kg. Our midpoint CF, which unit-wise corresponds to these, is in comparison  $4.7 \cdot 10^{-12}$  aliens per kg and thus similar to Hanafiah et al.’s value.

To our knowledge, the hitherto most comprehensive global model on the spread of alien species is by Sardain et al. (2019). They combined data of over 50 million voyages over 9 years with historical variables and socioeconomic predictors, and a probabilistic invasion prediction model by Seebens et al. (2017) to estimate global marine invasions in relation to the size and pattern of the global shipping network between 15 country-aggregated social-economic regions. By aggregating countries to larger regions, they mask some geographic bias but also risk aggregation bias. And like in this study, remove the possibility to understand how different vectors of spread are affected by their location. Their model is a useful forecasting tool of the global shipping network and estimation of marine invasions in general but cannot be connected directly to any specific vector of spread, for example by differentiating between hull fouling or ballast water. However, it can very well be used in future work for prospective LCA.

### 4.3. A note on inventory management

We have modelled the biodiversity impacts of maritime shipments,

which are often, but not always where products originate. One example where an LCA would benefit from further life cycle inventory analysis and potentially using native CFs, is for shipments of iron ore or rare earth elements from the large Swedish mine, Kiruna. Exports of iron ore from here will cause impacts through ballast water discharges into the waters of Narvik in Norway and Lulea in Sweden, as minerals are transported from the mine to both ports by train (see Figure A.10). Narvik is in northern Norway and has a higher native effect factor than ports of the south. In this case therefore, it is important to also regionalize the inventory of Swedish iron ore so that the appropriate amount of maritime shipping is from Norway, or even more accurately Narvik, depending on the use of CF. We make this note to underline the usefulness of using native CFs instead of only country aggregates and hope that practitioners make use of them, e.g., by editing and moving sensitive shipping activities to the foreground of their life cycle inventories – thereby making improvements to the accuracy of the LCIA, following the iterative nature of LCA.

## 5. Conclusion

This study provides the first Life Cycle Impact Assessment (LCIA) model to assess the impact of biological invasions caused by ballast water discharge. By refining data on alien species records (Seebens et al., 2017) and trade data (Gaulier and Zignago, 2010) to best explain introductions from ballast water, we establish a link between export volume and alien introductions ( $R^2 \approx 0.63$ ). This finding thereby reveals that there is indeed a positive relationship between a country's exported goods and number of recorded alien species. Additionally, for countries where ballast water discharge is arguably the most relevant vector of spread, the relationship can be explained to a certain degree solely by export of goods as a proxy. This relationship is used as a midpoint CF that estimates  $(4.7 \pm 1.9) \times 10^{-12}$  alien species per liter VBW emitted, a new elementary flow relating to the mass of exported goods (kg), while regionalized endpoint CFs quantify biodiversity loss in Potentially Disappeared Fraction (PDF) per unit of VBW or exported goods.

Life cycle assessment (LCA) is known for being a holistic assessment and meant to cover any relevant part of a product life cycle. International shipping occurs between any two processes that take place in different countries, and often by ship. Therefore, LCA is practically tailored to capture the cumulated potential impacts from the spread of alien, and potentially invasive, species on a system-wide scale, whether on product, industry, or global level. The endpoint CFs can be used to compare biodiversity impacts from shipping to that of other industrial activities – thereby making them relevant in a global context and for regulatory purposes. The midpoint CF is however also useful on its own, as it is a direct translation of a measurable industrial activity (export) to a number of alien species, and therefore a relevant tool for benchmarking, e.g., to compare with UN's sustainability goals or Aichi targets (UN's SDGs, 2022; Maney et al., 2024).

Our findings show that marine invasions can, in some cases, exceed the biodiversity impacts of global warming on certain trade routes. Our analysis focuses on Europe due to research biases in alien species records, while excluding countries where other variables play a dominant role. Having observed such geographic variations, we emphasize the need for more and improved data. Yet these results contribute to the LCIA methodology and towards future research on regionalized invasion modeling. Additionally, the CFs enhance environmental assessments of global shipping by enabling the modelling of the D 1,2 and 3 standards of IMO's BWM convention, and through this guide strategic decisions towards minimizing the biodiversity impact of the maritime industry.

## CRedit authorship contribution statement

**Philip Gjødde:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Diogo Kramel:** Writing – review & editing, Formal analysis,

Data curation. **Johan Berg Pettersen:** Writing – review & editing, Supervision, Methodology. **Anders Hammer Strømman:** Writing – review & editing, Data curation. **Francesca Veronesi:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

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## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Philip Gjødde reports financial support was provided by European Research Council. Philip Gjødde reports article publishing charges was provided by Norwegian University of Science and Technology. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jenvman.2026.129449>.

## Data availability

Python code and data can be found in the GitHub repository: [https://github.com/PGjødde/Code\\_marine\\_invasion\\_LCIA](https://github.com/PGjødde/Code_marine_invasion_LCIA). Code and data are also uploaded to Zenodo at 10.5281/zenodo.15114079. A database collected using the MarInvaders toolkit is used in the code, this is available upon request. All other data and results used by excel is found in appendix B and C.

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