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A spatially explicit data-driven approach to calculating commodity-specific shipping emissions per vessel

Wendela Schim van der Loeff [a], [*], Javier Godar [b], Vishnu Prakash [a]

[a] UCL Energy Institute, University College of London, Central House, 14 Upper Woburn Place, London WC1H 0NN, United Kingdom
[b] Stockholm Environmental Institute, Linnégatan 87D, 115 23 Stockholm, Sweden

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ABSTRACT

Oceangoing ships carry approximately 80% of the world's traded goods by volume, which translates into more than 10 billion tonnes in shipped traded volumes per year (UNCTAD, 2017). Despite its importance, the maritime shipping sector has been traditionally overlooked in climate mitigation discussions, since this sector was largely neglected in the 1997 Kyoto Protocol. Key barriers for successful implementation of CO2 abatement measures in the sector include the lack of reliable emissions data and the inherent difficulty of attributing responsibility for international shipping emissions to the involved countries, companies and commodities, as well as the threat to global trade interests. We argue that the data paucity on maritime emissions from international trade can be addressed by linking and integrating a large wealth of data, previously used in isolation. By linking per vessel cargo composition data, individual vessel journeys from the Automatic Identification System and a bottom-up methodology to estimate emissions, using vessel specifications and details on their movements and operations, this paper describes and demonstrates this new approach for the case of Brazil's shipping manifests in 2014. We find that the maritime transportation associated with these trades is responsible for 25.99 million tonnes of CO2, an addition of 5% to Brazil's total CO2 emissions of 2014 (reported by the World Bank, currently excluding international shipping and aviation). We discuss the contribution of all traded commodities, as well as the role of the first destination ports and countries. The voyage- and commodity-specificity of this method allows us to showcase those commodities and trading routes which contribute the most towards this emissions account, in relation to those that are most valuable to Brazil's economy. We go on to discuss the implications of scaling up this methodology for global greenhouse gas abatement efforts and demand-side footprint calculations, as well as to improve accountability mechanisms for the maritime sector as a whole.

1. Introduction

Sustainability science increasingly acknowledges the role teleconnections play in socio-environmental impacts globally (Liu et al., 2013). In recent decades, long-distance interactions and material flows associated with international trade have increased significantly (Wiedmann et al., 2015), while improved shipping logistics and sector-wide use of containers facilitated a spatial decoupling of production and consumption (Peters et al., 2009; Levinson, 2008). Whether directly or indirectly, this has immensely shaped human development, global resource geopolitics and biophysical conditions. International trade acts as a catalyst, where demand patterns and socio-environmental dynamics in one place become drivers of a large variety of socio-environmental dynamics elsewhere, often in countries which are more vulnerable toward climate change related weather extremities (Kreft et al., 2016). Meanwhile, growing intricate multi-party trade relations are increasing the complexity of causal relations and links between producers, consumers and other global supply chain actors. The magnitude of these environmental impacts is ultimately determined by the characteristics and ongoing dynamics at the specific locations where goods are produced (Godar et al., 2016), as well as the specific transport modalities and conditions of these goods (Cristea et al., 2013). Consequently, precise accounts on both aspects is an essential basis for reducing impacts associated with

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[*] Corresponding author.
E-mail addresses: wendela.loeff.15@ucl.ac.uk (W. Schim van der Loeff), javier.godar@sei.org (J. Godar), vishnu.prakash@ucl.ac.uk (V. Prakash).

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global demand and achieving sustainable resource supply systems.

Research however focuses predominantly on emissions from production by, for example, investigating how trade reallocates production between countries with different emission intensities, or how trade teleconnections undermine the effect of national emission policies due to carbon leakages (Cristea et al., 2013). Emissions from transportation are often unaccounted for or merely roughly approximated in trade discussions, while they are argued to be one of the four main factors describing the impact of a country on the stock of carbon dioxide (CO_2) in the atmosphere (Kanemoto et al., 2011; Peters et al., 2009). Additionally, transport emissions are sometimes able to offset the emissions avoided during the production of a good, due to the comparative advantage experienced in carbon intensity differences between trading partners (Dalin and Rodriguez-Iturbe, 2016).

Although maritime transport offers by far the most energy efficient mode of long-distance mass cargo transportation, it has a significant responsibility for anthropogenic climate change as its contribution to global greenhouse gas (GHG) emissions continues to grow (Gritsenko, 2017). Oceangoing ships carry approximately 80% of the world's traded goods by volume, which translates into more than 10 billion tonnes in shipped traded volumes per year (UNCTAD, 2017). Global trade has been growing approximately 4% annually in recent years and global maritime trade follows suit and is expected to continue to increase significantly considering forecasted growths in population and economic affluence. The Third International Maritime Organization (IMO) GHG Study estimates that international transportation by sea produced approximately a billion tonnes of CO_2-equivalent emissions annually between 2007 and 2012 globally (Smith et al., 2015a, 2015b) and the latest update on this study projects that these emissions will increase 35–210% by 2050 under a business-as-usual scenario (CE Delft, 2017). The shipping sector is also accountable for driving local air pollution in coastal areas, given that an estimated 70% of a ship's emissions are discharged at less than 400 km from land, and maritime shipping accounts for around 15% of global anthropogenic NO_x emissions and 5–8% of global SO_x emissions (Viana et al., 2014; Endresen et al., 2003).

Despite the significance of its emissions, international shipping has low visibility in climate change discussions and it has a separated treatment from other emitting sectors (Goundar et al., 2017). In the 1997 Kyoto Protocol, the first agreement in which the United Nations Framework Convention on Climate Change (UNFCCC) parties agreed to reduce GHG emissions, the commitments made by industrial nations applied to domestic shipping only, neglecting international maritime shipping (UNFCCC, 1997). The lack of consensus on how to attribute responsibility per country, company and commodity type, along with the threat to global trade interests and the potential to hinder the growth of transitioning and developing countries, were used as arguments for overlooking international transportation in climate policies, but possibly most importantly, the sector lacks the necessary, reliable emissions accounts and general transparency in these discussions (Morel and Shishlov, 2014). The IMO was entrusted to work with parties to limit emissions from the international shipping sector (United Nations, 1998), but it has taken two decades to approve a ‘Roadmap for developing a comprehensive IMO strategy on reduction of GHG emissions from ships’ (Roadmap). This Roadmap includes an initial GHG emission reduction strategy, which was implemented in April 2018, and stipulates the adoption of a final strategy in 2023, aiming to reduce annual GHG emissions by at least 50% by 2050 compared to 2008 levels (IMO, 2018). International shipping remains a challenging topic in global climate change abatement discussions and was left out from the Paris Agreement, something considered as a major hindrance to keeping a temperature increase under two degrees Celsius (Meinhard, 2016). Additionally, shipping emissions continue to be omitted from national GHG emission accounts, as they are only referred to as supplementary information in national inventories for communication to the UNFCCC (Nunes et al., 2017).

The need for improved data availability to support maritime transport decision-making at both national and regional levels has long been identified as a critical barrier for the sector's sustainability and environmental performance (Goundar et al., 2017). We argue that currently there is sufficient data available to accurately estimate emissions associated with transporting any commodity from a number of countries with good maritime cargo data availability, to its respective destination country. This would help overcome current data barriers and lack of transparency in international shipping emission accounts. Our approach provides a robust standard for accounting shipping emissions among commodities by value and weight, which is a vital stepping stone to defining criteria to allocate responsibility to traders, carriers and consumer countries, thus informing policy efforts how to increase the accountability and sustainability of international shipping.

The purpose of this paper is to describe a novel, spatially explicit, bottom-up approach to calculate emissions associated to specific legs of the maritime transportation of traded goods globally. By linking per vessel cargo composition data, individual vessel voyages and a method estimating emissions using vessel specifications and details on their movements and operations, we pilot this new approach for the case of Brazil's maritime exports in 2014. This trade portfolio includes 350,000 individual cargoes, equal to approximately 510 million tonnes (93.4% of all exports, including non-maritime) and we discuss the contribution of the different commodities to total shipping emissions (up to 8-digit code (HS8) level according to the Harmonised Commodity Description and Coding System[1] (HS) (UN Trade, 2017)), as well as the role of the import countries, in an effort to improve transparency. These data could subsequently help inform policy discussions on maritime emission apportion criteria (Bows-Larkin, 2015). We pilot this approach in Brazil, given its importance in global trade, its significant presence in global sustainability discussions, and the link between many of its most important exported commodities (such as soy beans, mineral ores, corn, sugar cane or petrol) and globally relevant environmental degradation, including deforestation concerns (Gasparri and le Polain Waroux, 2015; Sonter et al., 2017). In addition, ahead of key IMO meetings in 2018, Brazil was one of the three parties, along with Saudi Arabia and the USA, to strongly oppose setting tough climate targets for the maritime transport sector, citing trade concerns (Darby, 2018).

This paper is organised as follows, section 2 discusses the shortcomings of current non-spatially explicit approaches, introducing our proposal to overcome these limitations in the context of current policy discussions. Section 3 details the data and methods used, with a special focus on how key datasets are linked. Detail on how emissions are calculated for each vessel, as well as how those emissions are accounted to a commodity and country of destination are also discussed. Section 4 provides a detailed assessment of the resulting emission accounts, per commodity and import country. Section 5 examines the uncertainties, advantages and limitations of

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[1] The HS is an international nomenclature developed by the World Customs Organization for the classification of goods (WCO, 2017). The HS comprises circa 5300 commodity descriptions, arranged in 99 chapters. The first two digits (HS2) identify each chapter in which the goods are classified. The next two digits (HS4) identify headings within a chapter, with more specific descriptions. The next two digits (HS6) correspond to subheadings and are even more specific. Up to six digits, the description is common to all countries. Countries use two extra digits (HS8) at their discretion, providing the highest level of specificity possible (UN Trade, 2017).

our approach. Furthermore, we discuss the potential of our approach in contributing to a new standard of transparency within shipping and including international transportation in today's footprint efforts, as well as carbon reporting mechanisms. We argue for the need to integrate this information with that of other transparency efforts, to help allocate shipping emissions to the actors involved along a given supply chain, such as producers, traders, carriers and investors, in an effort to push forward global emission reduction efforts that account for all emission sources.

2. Shortcomings of non-spatially explicit shipping emission accounts and ways forward

Currently, international shipping emissions associated to specific traded commodities are mainly modelled using non-spatially explicit average calculations of fuel use and distance covered by vessels (e.g. footprint calculations often depending on life-cycle assessment (LCA) methodologies) (Weber and Matthews, 2008). These methods do not reflect the inherent heterogeneity of supply-chain pathways. They lack the ability to discriminate between efficient and inefficient ships and shipping pathways – which depend, among other factors, on differences in fuel efficiency, economies of scale utilised, land-based logistics and fleet specifications. Neither do they differentiate between transport emission intensities caused by operational choices (such as speed, loading and route design), commodity types (such as volumetric mass density) or transportation modality (such as bulk carrier versus containerised shipping). As a result, current analyses assume that the socio-environmental impacts associated with international shipping emissions are the same per tonne of traded product, for any given trade route, weighted by average transportation distance. As they lack spatial-explicitness and association with a specific vessel and its operations, existing approaches hardly capture the causal links between the demand for a commodity from a certain region, and its associated transportation-related impacts and potential for GHG emission abatement. The lack of consideration of this existing heterogeneity hampers the policy relevance of current estimates and the creation of the necessary cost-effective policies, as well as incentives and rewards for better practices (Burniaux et al., 2008).

To tackle this issue, we argue that the current trade-specific maritime emission data paucity can be addressed by linking and integrating a large wealth of data, previously used in isolation. This includes: (i) shipping manifests and bills of lading, which describe per vessel cargo compositions (Godar et al., 2016). Shipping manifests list the cargo that a vessel is carrying, while a bill of lading is a document issued by a carrier to the shipper as a contract of carriage of goods; (ii) the collection of global vessel trajectories, where individual voyages of each vessel are estimated based on radio-frequency messages received via the IMO's automatic identification system (AIS), which consists of mandatory devices for vessels over 300 gross tonnage. AIS-use has significantly increased in recent years and has changed the landscape for monitoring the maritime transport sector as a whole (Eriksen et al., 2006). A vessel's on-board device broadcasts key information – such as position, heading and speed – which can then be used to identify port calls and thus the end points of voyages, by exploiting algorithms used and developed in, amongst others, Smith et al. (2015a, 2015b) and Prakash (Forthcoming); (iii) specific fuel use and other technical specifications per vessel, obtained from global repositories, such as Clarksons' World Fleet Register (WFR) (WFR, 2017). The AIS information can be combined with these vessel-specific emissions following the Third IMO GHG Study's bottom-up approach. Pioneered by Jalkanen et al. (2009), this method estimates the pollutants emitted by each ship, as it calculates their fuel consumption using vessel activity information. This is possible because fuel consumption can be expressed as a function of displacement, speed and ship specifications (including fuel type), whilst emissions can be calculated using knowledge of the fuel type and its emissions factors (Jia et al., 2017; Smith et al., 2015a, 2015b), which subsequently can be assigned to specific trade routes and cargo, reported in the shipping manifests.

Previous attempts linking customs data and AIS activity observed a clear alignment, but as they lacked per shipment resolution, i.e. knowing what is carried on a vessel, on which day of the month, their results are aggregated, making it impossible to accurately link a specific trade with a single vessel movement (see Adland et al., 2017; Prakash, Forthcoming). Moreover, a key difficulty of customs data is identifying a trade's transport modality (for example, crude oil could be leaving the country by pipeline or vessel). On the other hand, shipping manifest data, as used in this paper, offer a per-shipment resolution at port-level, meaning transport modality is identified, the quantify of a specific commodity carried on an identified vessel is specified, as well as the exact port of loading and discharge.

3. Data and methods

We used Brazilian shipping manifests for the year 2014, which describe all commodities and volumes leaving Brazil via maritime transportation. For a specific vessel, they detail the port of departure and arrival, the travel date and the cargo composition, aggregated at the HS8 level. This dataset includes 350,734 cargo-specific trades, shipped on 4089 vessels, describing 124,173 voyages moving goods from Brazil to 112 countries (Table 1). Comprehensiveness of the data was tested by cross-referencing it with official custom declarations from the Ministry of Trade and Industry (MDIC) and bills of lading provided by a different vendor. Beyond some discrepancies in dates between official custom declarations and the shipping manifests, the data entries referred to mostly identical volumes by the same trader-port-country-commodity combinations, where slight differences could be explained by the fact that cargo weight is often estimated from volume records in an independent way by the Brazilian government and the vendors of shipping manifests and bills of lading. Based on their respective reported weight, we independently calculated each cargo's value using average freight on board (FOB) prices per kilogram of the commodity at its 4-digit code (HS4) level, using port level data for the same year made available by the Brazilian Ministry of Trade (MDIC, 2017). This allowed us to estimate the FOB values for 99.4% of Brazil's volume of maritime exports, multiplying price per kilogram and weight values from the shipping manifests. A remainder of 0.6% of exported trade volume was estimated using the 2-digit code (HS2) level of aggregation (at Brazil's scale), due to ambiguity in commodity codes in the shipping manifests.

For the individual ship movement, we scoped all global AIS voyages for the year 2014. From the approximately 2 billion AIS messages containing information on the vessel's IMO identification, geographic location, speed over ground and the corresponding timestamps, we identified the sequence of stops made by each vessel across the world's ports in 2014. Position and speed are reported on average every hour though the frequency varies spatially. Extending the methods from Jia et al. (2017), we classified a port call based on whether a vessel is stationary for a sustained period of time at a location close to coast – defined here as a sailing speed of less than one knot and within 1 decimal degree of a port. A total of 1,387,859 stops were identified for 28,948 vessels including the entire dry bulk, general cargo, tanker and container fleets (Table 1).

Following the bottom-up methodology described in the Third IMO GHG Study, CO_2 emissions for each vessel were estimated

Table 1
Summary of processed datasets.

		Trade Export Data		Shipping Voyages Data
Coverage		Brazil, 2014		Global, 2014
Dataset		Shipping Manifests	Custom Declarations	Voyages found using AIS data
Source		Collected by shipping lines and agents[a]	Aggregated information from Brazilian customs office[b]	Raw AIS data from exactEarth[c] that has been processed using methods from Prakash (2018)
Key Information		IMO identification – date of departure – port of departure – port of arrival – commodity code (HS8) – weight of commodity	Date of departure – port of departure – commodity code (HS4) – weight of commodity – calculated freight on board value of commodity (scaled up to HS8 level)	IMO identification – date of travel (estimated) – coordinates of identified stops – estimated sailing and idle emissions (CO_2) – estimated distance sailed
Commodity Detail		HS8 Level	HS4 Level	n/a
Entries		350,735	406,058[d]	1,387,859[e]
Pre-processed entries		n/a	n/a	approximately 2 billion
Vessel Types	Tankers	151	n/a	417,241
	Gen. Cargo	2510	n/a	436,790
	Containers	336,607	n/a	312,875
	Dry	5248	n/a	220,953
IMO Vessels		4089	n/a	28,948
Vessel Types	Tankers	86	n/a	5243
	Gen. Cargo	339	n/a	8472
	Containers	293	n/a	5030
	Dry	3003	n/a	10,203
Departure Countries		1	1	195
Arrival Countries		112	198	195
Total Tonnage		510 million tonnes	546 million tonnes	n/a
Total Value		$178 billion[f]	$185 billion[g]	n/a

[a] This dataset was purchased from a shipping and trade intelligence company that covers the South Cone of South America, for the Trase project (see www.trase.earth). It includes a comprehensive account of all shipping manifests in 5 countries.

[b] http://www.mdic.gov.br/.

[c] https://www.exactearth.com/.

[d] It includes non-maritime exports.

[e] After initial processing has taken place on the received AIS messages.

[f] Estimated value from the FOB prices per kilogram of each commodity (HS4 level) from custom declaration.

[g] The custom declarations report on the final country of import, hence they report more countries than the shipping manifests, which refer to the country in which the port of discharge is located. This has no implications for our method given that they are used just to calculate FOB prices per commodity.

based on a ship's calculated fuel consumption, which in turn relies on the ship's fixed technical specifications – its deadweight, design speed, engine power and fuel consumption rate – and its operational voyage data from its AIS messages. Technical vessel specifications were provided by Clarksons' WFR and allowed us consider a ship's engine type, rating and efficiency in these calculations. As in the Third IMO GHG Study, engine load factors based on the WFR data were adjusted to reflect the operational mode of a ship, i.e. whether sailing or idle for main and auxiliary engines, as well as boilers, to estimate a ship's fuel consumption more accurately. CO_2 emissions are subsequently estimated by multiplying fuel consumption with the emission coefficient factors of the fuels consumed, which are subject to fluctuations based on fuel quality and engine conditions. We used the latest figure for CO_2 from the Third IMO GHG Study 2014 detailed in Smith et al. (2015a, 2015b).

By matching the exported cargo composition observed in the shipping manifests with the appropriate sailed voyage, as identified by AIS, we were able to obtain the shipping emissions associated with the transportation of each traded commodity and arrival country. The integration was possible through the vessel's IMO identification number, common to both datasets. The algorithm to do this, required two methodological stages, resulting in primary and secondary matches (see Fig. 1).

First, we sought all primary matches – defined as a match where IMO identifications corresponded between the two datasets – under three different sets of criteria (cases 1–3). We examined whether the vessel-specific voyage, as described in the shipping manifest, occurred in the AIS database, i.e. whether the same ship departed in the proximity of the Brazilian port as stated in the shipping manifests, travelled within the month itself or one month after (incorporating delays), and navigated in the direction of the expected destination, so that the arrival ports also corresponded. As the entries in the shipping manifests only included port names and not location, we started matching these with their respective geographical coordinates from the World Ports Index[2] and a variety of map services. This allowed us to match both departure and arrival port coordinates at a 2° radians range in latitude and longitude, which is equal to approximately 220 km. A ship leaving the manifest-reported origin port was permitted to travel through up to 10 ports before it reached its reported destination port, as per the manifest. The date of departure criterion varied, where case 2 took a ±2-month range, only if a match could not be found in case 1 and case 3 considered all AIS voyages in 2014. Our process systematically matched shipping manifest voyages with AIS trajectories in cases 1 and 2, where its chronological aspect made sure that even if the time frame was wider than one would expect (a maximum of 60 days), the voyage we matched did not correspond to another voyage of the same vessel between Brazil and the same country, by identifying the departure dates of all voyages for a given vessel in the same year. Case 3, however, allowed those vessels which repeat a certain trajectory, to match with a voyage made at a

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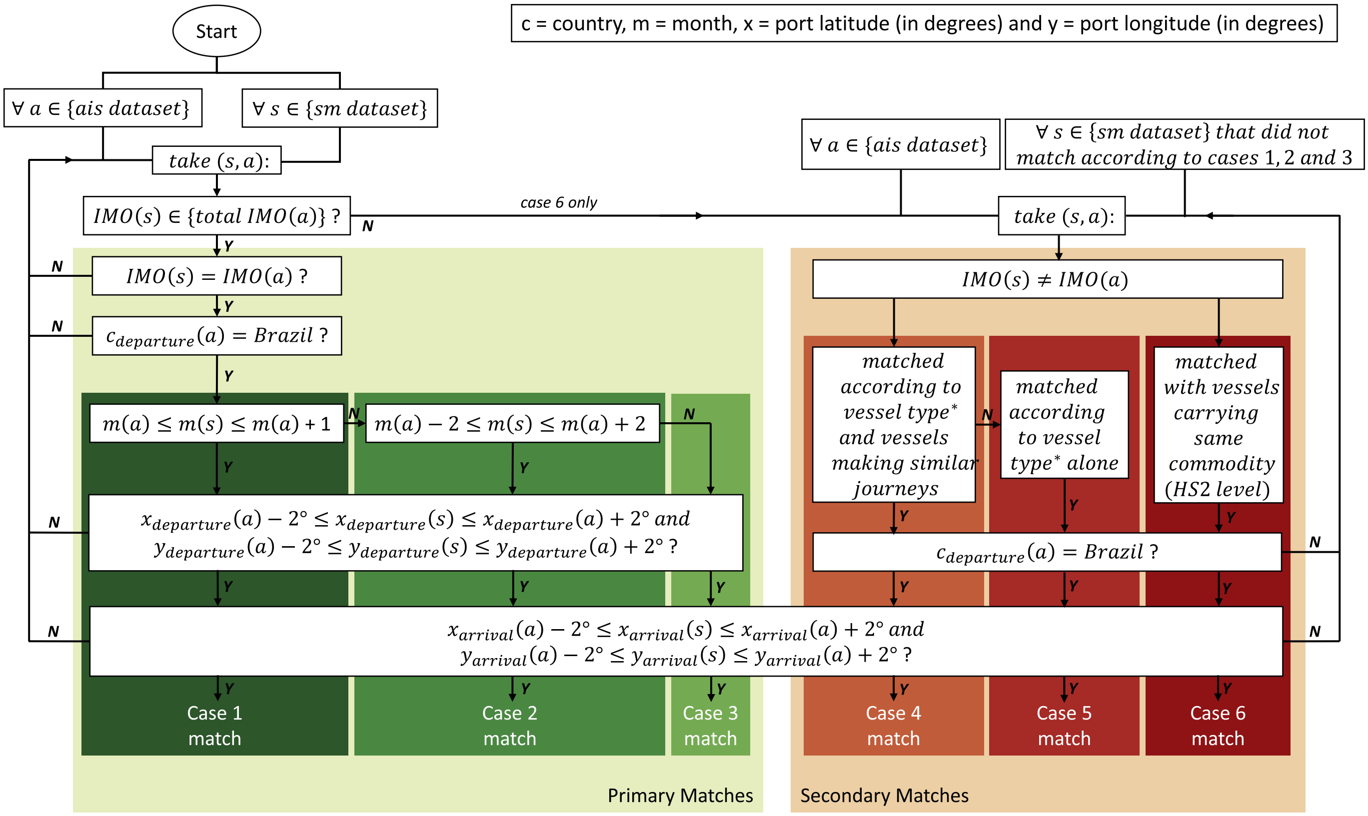
[2] The World Port Index covers thousands of ports throughout the world, describing their location and characteristics (National Geospatial-Intelligence Agency, 2017).

[3] Exports are listed at HS2 level of aggregation (see https://www.foreign-trade.com/reference/hscode.htm).

[4] Voyages are identified by the country of first arrival and referred to by their ISO 3 country code (see https://unstats.un.org/unsd/tradekb/knowledgebase/country-code).



* i.e. dry, container, tanker and gen. cargo

Fig. 1. Algorithmic portrayal of matching process, depicting the difference between primary and secondary matches and the 6 cases.

different time in the year if AIS records were incomplete at the manifest reported voyage time. We expect that these cases are often related to departure dates in the shipping manifests in 2014 and AIS voyages from 2015 (excluded from our AIS sample). This is confirmed by the fact that November and December witness a percentage of case 3 matches, which is double that of the other months (see Figure A.2), a problem that would be tackled by analysing multiple years of AIS data. For the remainder of shipping manifest trades (8.1% of the total), which did not find a match according to our primary matching criteria, emissions were obtained from voyages of vessels carrying similar cargo on the same routes, and therefore provide an approximation of the emission account. This matching process includes cases 4–6, where case 6 was applied to the 6218 (1.8% of total) entries for which no IMO was observed in the AIS dataset and therefore immediately had to be matched with alternative vessels' voyages.

After assigning an AIS observed voyage with its corresponding emissions to each export described in the Brazilian shipping manifests, we allocated the total emissions of a voyage to the specific commodities being transported in each vessel. To do this, we allocated the emissions proportionally to both the weight of the commodity (at HS8 level) with respect to the total cargo carried on the vessel, based on the deadweight of the ship, and the FOB value of each commodity in US dollars. As seen in the following section, we weigh both criteria by distance travelled (as recorded by the AIS data), in order to be able to compare emissions per kilogram or US dollar regardless of differences in length of voyage.

4. Results

For the sake of readability and because of the methodological focus of this paper, we present our results at aggregated commodity levels (HS2 and HS4 levels) for describing total emissions. We do however include some HS8 level results to highlight those commodities that have significant associated shipping emissions or play a key role within Brazil's export portfolio (a complete list of HS8 level commodities can be accessed online at https://goo.gl/T8FfPr). Over 90% of Brazil's maritime exports is made up of 8 HS2 chapters and are broadly speaking commodities with a relatively low value per tonne, confirming that Brazil is a major exporter of commodities in bulk with low added value per tonne, i.e. raw materials (Table 2). Similarly, over 90% of the total exported volume are received in 28 countries (Table A.1). This can be explained by Brazil being a major exporter of raw materials to major production countries and/or major transhipment hubs receiving cargo which then continues its voyage on a different vessel. China is the largest recipient, where 41% of Brazil's exported goods in volume arrive, followed by Japan and the Netherlands with approximately 6% each; where the Netherlands acts as a continental hub for onward hinterland transport. Our results and discussion will focus on these selected commodities and countries, considering the significant role they play.

4.1. Matching results

Of all Brazilian maritime exports listed in our shipping manifest dataset, we were able to match 91.9% of trades according to our primary matching criteria, i.e. based on the exact vessel specifications and the associated AIS signals. Within these, 55.9% of total shipping manifest entries were matched according to case 1, with the strictest time-consideration, and 17.6% and 18.4% were matched using a two-month range and the entire 2014 AIS sample within the

Table 2
Top 15 commodity-specific CO_2 emission results, aggregated at HS2 level and ranked according to their CO_2 emissions. For each commodity chapter, the main weight-contributing commodities at HS8 level, its total exported weight and value are also highlighted.

Commodity Chapter (HS2 level) [main commodities at HS8 level, >750,000 tonnes, for illustration]	Total Weight		Total Value		Total CO_2		Average CO_2/Weight[a]	Average CO_2/USD[a]
	tonnes, million	%	USD, billion	%	tonnes, million	%	grams/tonne	grams/USD
Ores, slag and ash (HS 26) [non-agglomerated and agglomerated iron ores and concentrates (26911100, 26011200), aluminium ores and concentrates (2606011, 26060012), iron ores and concentrates including roasted iron pyrites (26011000), manganese ores and concentrates (incl. ferruginous) with a manganese content of ≥20% (26020010, 26020090), copper ores and concentrates (26030010, 26030090)]	326.22	64.12	29.24	16.44	14.67	56.46	48,700	474
Oil seeds and oleaginous fruits, grains, seeds and others (HS 12) [soya beans (12010090, 12010010]	43.43	8.54	22.24	12.51	3.18	12.22	64,200	101
Cereals (HS 10) [maize(corn) (10050000)]	21.80	4.28	4.58	2.58	1.46	5.62	62,400	236
Sugars and sugar confectionary (HS 17) [raw cane sugar in solid form (17011100), cane or beet sugar in solid form nes (17019900), cane or beet sugar and chemically pure sucrose in solid form (17011000, 17019000)]	23.56	4.63	9.32	5.24	1.37	5.27	50,000	94
Mineral fuels, mineral oils, bituminous substances, mineral waxes (HS 27) [petroleum oils and oils obtained from bituminous minerals crude (17090000, 17090010), petroleum oils etc (excl. crude), preparations thereof nes (27101000, 27101900, 27101911, 27101919, 27101921, 27101922, 27101929, 27101930, 27101931, 27101932, 27101991, 27101992, 27101993, 27101999)]	14.80	2.91	8.89	5.00	0.74	2.85	47,090	92
Pulp of wood or other fibrous cellulosic material, etc. (HS 47) [semi- or bleached non-coniferous and coniferous chemical word pulp soda, etc. (47032900, 47032100)]	10.45	2.05	5.00	2.81	0.72	2.79	69,330	149
Resides and waste from the food industries, others (HS 23) [oil-cake and other solid residues of soya-bean (23040010, 23040090)]	12.82	2.52	6.63	3.73	0.70	2.71	60,760	72
Iron and steel (HS 72) [semi-products of iron/steel <0.25% carbon of rectangular section (72071200), non-alloy pig iron containing ≤ 0.5% phosphorous in pigs blocks (72011000), iron and steel (72000000)]	11.54	2.27	8.96	5.04	0.61	2.33	62,930	80
Inorganic chemicals, organic or inorganic compounds of precious metals, others (HS 28) [aluminium oxide (other than artificial corundum) (28182010, 28182000)]	8.54	1.68	3.03	1.71	0.48	1.84	59,140	84
Meat and edible meat offal (HS 02) [frozen cuts and offal of chicken (02071400), frozen whole chicken (02071200), frozen boneless bovine meat (0202300)]	5.93	1.17	15.63	8.79	0.33	1.29	56,590	24
Wood and articles of wood, wood charcoal (HS 44) [coniferous wood in chips or particles (44012100)]	4.12	0.81	2.18	1.23	0.27	1.03	62,940	88
Salt, sulphur, earths and stone, plastering materials, lime and cement (HS 25) [kaolin and other kaolinic clays whether or not calcined (25070010, 25970090)]	3.48	0.68	0.64	0.36	0.21	0.82	59,180	200
Coffee, tea, mate and spices (HS 09) [coffee not roasted or decaffeinated (09011110)]	2.00	0.39	6.32	3.55	0.11	0.44	58,080	18
Preparations of vegetables, fruit, nuts or other parts of plants (HS 20) [frozen orange juice unfermented not containing added spirit (20091100)]	1.95	0.38	2.15	1.21	0.10	0.41	63,380	53
Animal or vegetable fats and oils, others (HS 15) [soya-bean oil (excl. crude) and fractions (15079000)]	1.67	0.33	1.50	0.84	0.09	0.36	68,350	89
Others	16.48	3.24	51.54	28.96	0.96	3.56	–	–

[a] Filters applied on distance and total CO_2 emissions to remove outliers and to only include non-null values.

matching process, respectively. Discrepancies in dates of departure are expected, given that dates expressed in the bills of lading that make up the shipping manifests are intended and not actual, while logistics and other reasons may advance or delay an expected date of departure.

About 1.8% of the manifest entries were transported by vessels not observed in our AIS dataset. We addressed these cases in the so-called secondary matching phase, as well as those exports that could not be directly matched under the stringency of the primary matching criteria, because of factors including imperfect AIS coverage (6.3% of total trades). In this secondary matching phase, non-matched shipping manifest entries were matched with voyages of similar type vessels and/or vessels carrying the same commodity at HS2 level (Fig. 1). Logically these secondary matches — 8.1% of the total records in the shipping manifests — have a larger level of uncertainty associated with their emission estimations. We accepted this to provide an estimate of the total emissions associated with all Brazilian maritime exports in 2014.

To assess the direct agreement between shipping manifests and AIS voyages, we compared the number of matches found relative to the number of unique matches. This showed the stringency of our criteria, with a small number of duplicate matches taking place within the three primary matching cases and an expected larger proportion of duplicate matches within cases 4–6.

4.2. Commodity and voyage-specific CO_2 emissions

Table 2 lists the main exported commodity chapters associated to the largest CO_2 emissions, including details on the significant HS8 level commodities within these chapters. The total amount of maritime shipping emissions from Brazilian exports in 2014 was 25.99 million tonnes of CO_2, representing around 3.2% of total international shipping emissions that year as calculated by the International Council on Clean Transportation (ICCT) (Olmer et al., 2017). As seen in Table 2, the largest emissions overall, are those of ores, slag and ash (HS 26), contributing 14.67 million tonnes of

CO_2 (56.5% of the total), with 73% of this amount emitted on voyages to China (8.5 million tonnes of CO_2). The export of oil seeds and oleaginous fruits, grains and seeds (HS 12) and cereals (HS 10) come 2nd and 3rd with their transportation emitting 3.17 (12.2%) and 1.46 (5.6%) million tonnes of CO_2, respectively. The export of mineral fuels and oils (HS 27) represents 2.85% of this CO_2 emissions account, of which the export of crude oil (HS 2709) represents 1.9% (0.50 of 25.99 million tonnes of CO_2).

More than 50% of total CO_2 emissions correspond to just three HS8 level commodities of which the first two fall in HS 26 (ores, slag and ash). The third is Brazil's most valuable export, namely soybeans (HS 12010090), with a value of 21.53 billion US dollar, and whose exporting activities are responsibly for 3.04 million tonnes of CO_2 (12.0% of total). Solid raw cane sugar (HS 17011100) and non-roasted, caffeinated coffee (HS 09011110) also account for a large share of value-based exports, at 7.37 and 6.81 billion US dollar, respectively. Although their exports represent similar values, their CO_2 contributions diverge sharply, with the shipping of exported sugar emitting 1.12 million tonnes of CO_2 (6th largest contributing commodity), and those of non-roasted or decaffeinated coffee accounting for just a tenth of this (16th largest contributor).

Discrepancies between total weight, value and associated emissions are notable. While ores, slag and ash (HS 26) accounts for a large proportion of exported weight (64.1%), its relevance to Brazil in terms of value is about four time smaller (16.4%), and its contribution to total emissions is about ten percentage points smaller (56.5%) than its weight proportion. This emphasises the importance of considering both emission allocation criteria. Fig. 2(a) and (b) show these discrepancies for the 20 largest contributing commodities and countries, respectively.

Our observed emissions per weight (at HS2 level) range between 48,000 and 70,000 g of CO_2 per tonne of shipment (g/t), while this range is 32,000 to 113,000 g/t for voyage-specific observations. Commodities which have a low-density and therefore may require more transits per weight unit, result in higher emissions relative to weight, such as cereals (HS 10), cotton (HS 52) or wood and wood pulp (HS 44/47) (Fig. 2(a)). Likewise, there are commodities for which their relative value surpasses their importance in total shipping emissions. This is the case for meat (HS 02) and coffee and tea (HS 09), while for commodities such as cereals (HS 10) and ore, slag and ash (HS 26), this is the opposite. Though varying ratios between weight and emissions may be related to aspects such as bulkiness and density of the exported commodity, there are other factors involved too, such as the vessel type and size

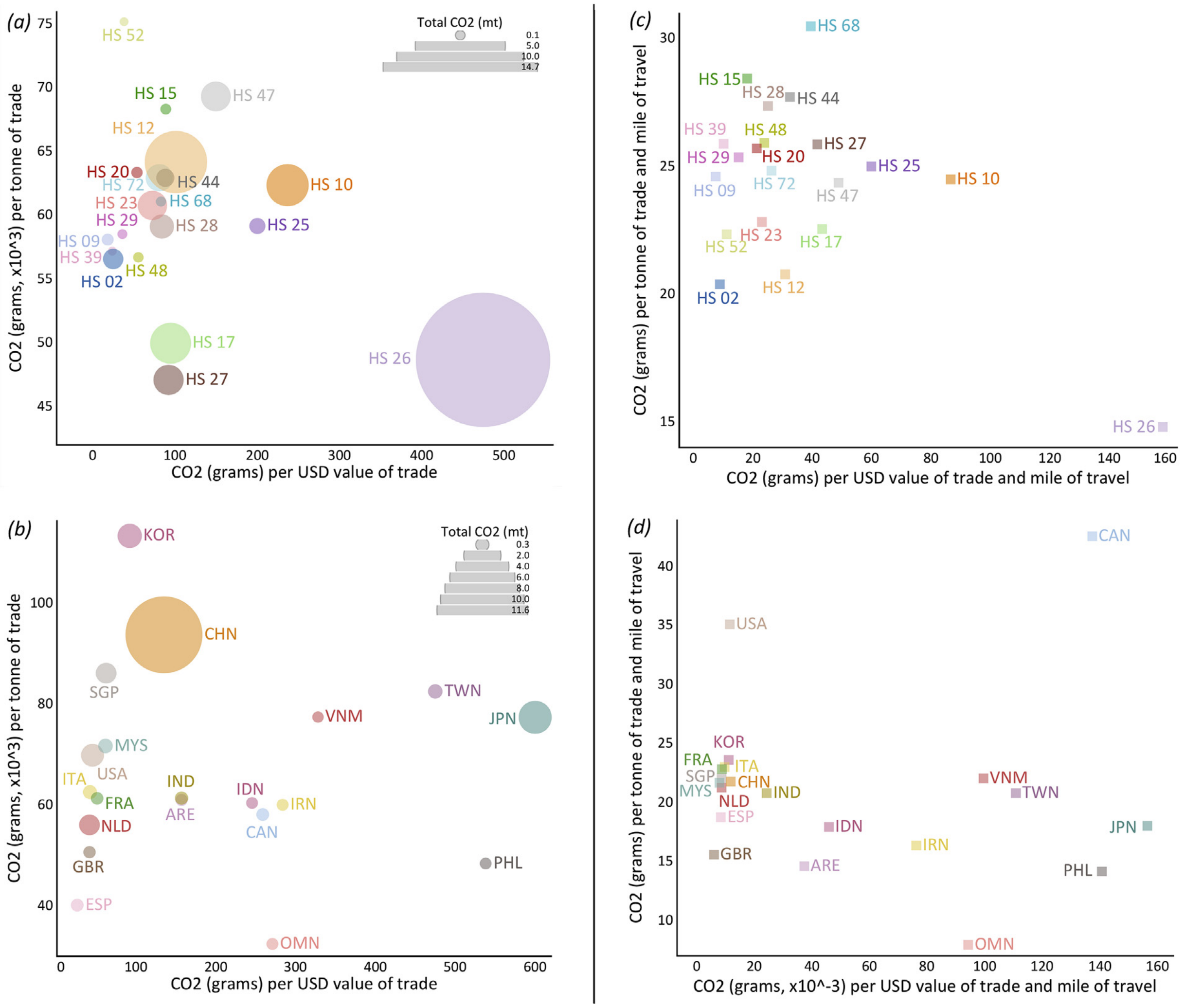


Fig. 2. *(a)* Top 20 Brazilian exports[3] contributing to shipping emissions. *(b)* Top 20 voyages[4] contributing to Brazilian export shipping emissions. Values weighted by both weight and financial value, on the y- and x-axis, respectively. The area of the circles represents the total amount of CO_2 emissions accounted for by the commodity or voyage. *(c)* and *(d)* showcase these values with the distance dimension taken into account, i.e. CO_2 emissions per tonnage mile or USD mile (medians). Visit https://goo.gl/T8FfPr for a complete list of HS2 level commodity chapter descriptions and HS8 level commodities contained within.

on which a certain commodity is carried. For example, container carriers typically make more stops over shorter distances and sail faster than tankers (MEPC, 2015). This affects commodity-specific shipping emission trends, as different goods tend to be carried in different vessel types (e.g. high value goods are often transported by container while raw commodities are often transported in dry bulk carriers), as well as voyage-specific trends, as certain trading routes might be sailed by specific vessel types and sizes and each country has its unique trading portfolio. As shown in Fig. 2(b), Brazilian exports to China account for the largest proportion in 2014, with 11.6 million tonnes of CO_2 (45.6% of total CO_2), while this represents only 19.1% of Brazil's outgoing trade in value. Japan and South Korea follow, representing 8.43% and 4.56% of shipping emissions respectively (see Table A.1 for a complete list).

By factoring the average distance travelled by a given commodity vis-à-vis total associated emissions, it is possible to dissociate emissions from distance and take into account that some commodities show different demand in relation to transport distance. For example, without considering distance, cargo arriving in South Korea and China accounts for most CO_2 per tonne of trade — at 113,000 and 94,000 g/t respectively — but when distance is weighed in both are part of a cluster of countries, where emissions per tonnage range between 18 and 24 g/t per nautical mile (nm) travelled (g/tnm) (Fig. 2(d)). In fact, the formation of a notable cluster where the majority of voyages emit approximately 22.5 g/tnm of CO_2 is observed (Fig. 2(d)). When looking at the entire dataset, instead of only the top 20 emitting voyages, we found that 95 routes of 112 emit CO_2 between 11 and 48 g/tnm. Voyages to the USA and Canada are outliers with significantly higher CO_2 emission intensities. A reason for this could be that a much smaller proportion of their trading portfolio is ore, slag and ash (HS 26), which has a very low CO_2 per tonnage and nautical mile sailed as observable in Fig. 2(c). Another reason could be that there is a clear difference in the typical vessel size used on each of these three bilateral trading routes; the vast majority (>75%) of trade from Brazil to China is carried by dry bulk carriers larger than 100,000 tonnes of dead weight tonnage (dwt), whereas on both the Brazil-Canada and Brazil-USA routes more than 82% and 40% of trade in weight, respectively, is transported in dry bulk carriers smaller than this. Differential average fuel efficiency of vessels sailing between country pairs could also play a role, which could be explored using the Clarksons' WFR. These are just examples about how the data provided by our method opens the exploration of specific drivers of shipping emissions, creating entry points for targeted emission reduction interventions.

By analysing commodity- and voyage-specific emissions in conjunction, the above-described strong allocation of emissions to a very limited number of products and actors becomes even more evident, as shown in Fig. 3. China's imports of iron ores and soy, as well as Japan's, South Korea's and the Netherland's imports of iron ores dominate the top 5 country-commodity pairs in total CO_2 emissions. Ranked very highly, there are also some less expected trades, such as the import of corn (HS 1005) by Iran and Vietnam, with 0.25 and 0.19 million tonnes of CO_2, respectively, ranking these pairs 10th and 15th.

Our approach allows for an in-depth focus on specific commodities. For example, there is a growing interest in improving the sustainability of forest-risk commodity supply chains (e.g. New York Declaration on Forests 2014), leading to increasingly more comprehensive analyses of deforestation and carbon emissions, but those so far do not include shipping emissions given the lack of data for specific commodities, countries of import and even traders. Fig. 4 is an example of the way our results can highlight direct geographic demand, where Fig. 4(a) shows how the vast majority of

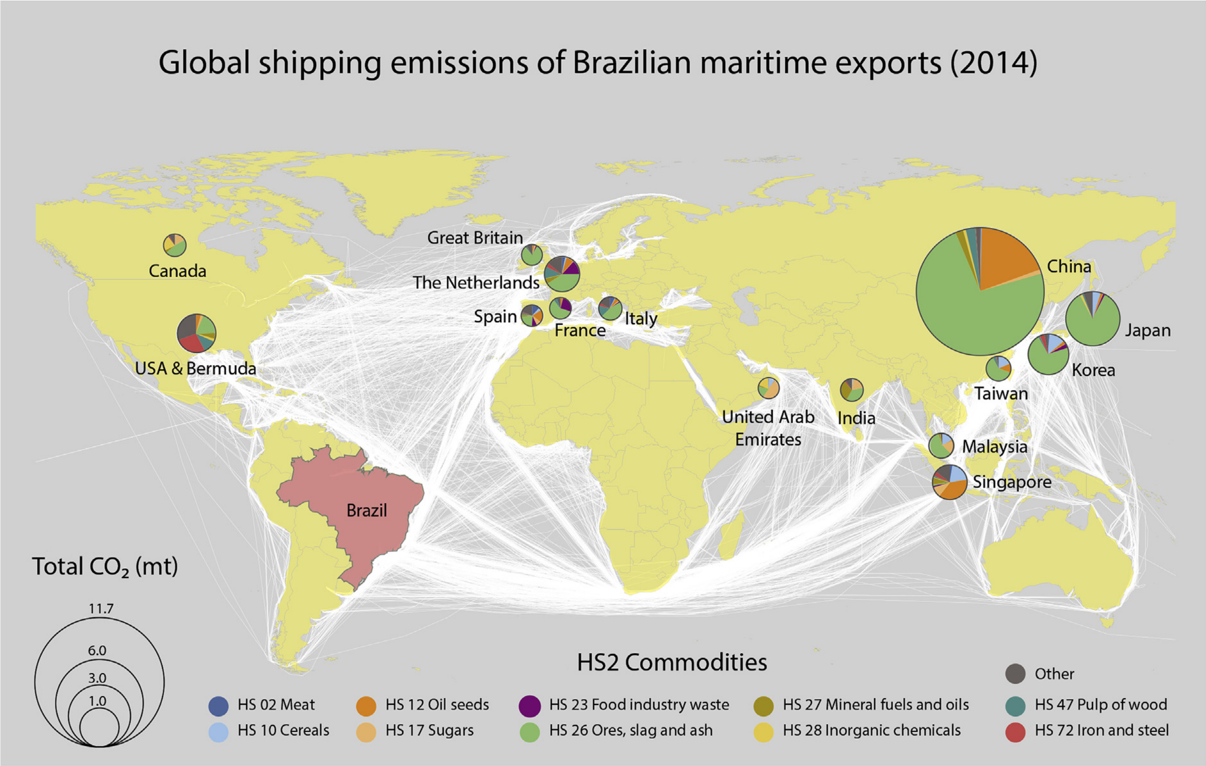


Fig. 3. Global shipping emissions from Brazilian exports in 2014.

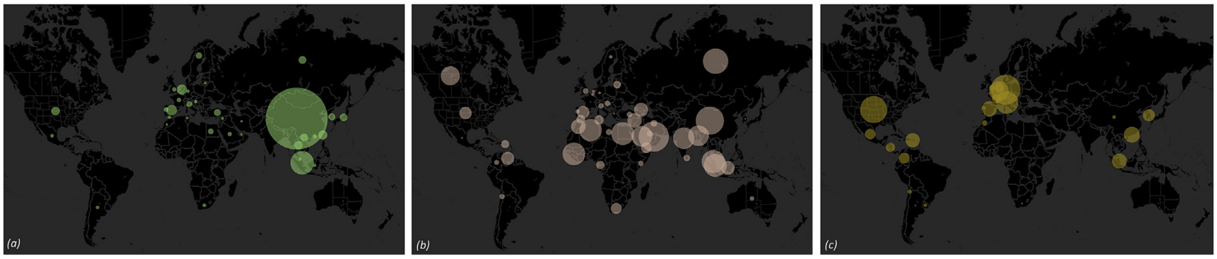


Fig. 4. Country allocation of the shipping emissions associated to the export of selected commodities, where *(a)* represents soybeans (HS 1201), *(b)* sugar (HS 1701) and *(c)* coffee (HS 0901).

emissions associated to soybean (HS 1201) transportation are linked to exports to China. Additionally, our method can show the geographical allocation of shipping emissions associated to some of the more valuable exported commodities such as sugar (HS 1701) and coffee (HS 0901), ranked 3rd and 7th in value (Fig. 4(b) and (c)).

5. Discussion

5.1. Comparison with previous estimations

This study showcases how available data can be used to accurately calculate maritime emissions per commodity type and trade route. For Brazilian exports in 2014, we found that maritime trade shipping accounted for 26 million tonnes of CO_2, representing 3.2% of global international shipping emissions. It is difficult to compare this figure, obtained using data-intensive methods and wall-to-wall coverage of both vessel movements and cargo composition, with estimations precisely provided for Brazilian exports in the same year. However, Prudêncio da Silva et al. (2010) and Castanheira et al. (2013) use LCA approaches to estimate that soy exports from specific ports in the Brazilian port mix to the port of Rotterdam (selected as one of the most likely routes to Europe) and find the maritime transport footprint of soy production to be approximately 95 kg of CO_2 per tonne of soybeans. Our approach finds that the route between Brazil and the Netherlands emits approximately 47 kg of CO_2 per tonne of soybeans, with the emission intensities of top 50 Brazilian trade partners ranging from 43 to 102 kg of CO_2 per tonne of soybean. Although these LCA calculations fall within the upper end of our range, this discrepancy is expected. LCA methods (e.g. using Ecoinvent coefficients) assume a fixed emissions coefficient per cargo tonne and nm covered and an average transport distance (without port discrimination), while our spatially explicit approach considers the real distances and fuel consumption, as well as the vessel modalities and the variety of pathways (e.g. different amounts of soy exported per Brazilian port, which are situated at considerable distance from each other). For example, Godar et al. (2016) found a preference for Brazilian exports to Europe to be shipped from the Northeast, due to its logistic proximity, which decreases distances versus country to country distances. Furthermore, the strong soy trading relation — the Netherlands being the third biggest importer of Brazilian soybeans — results in large dry bulk vessels exporting soy to the Netherlands, improving emission's efficiency per tonne of soy. A non-LCA study that uses per vessel data produces results that are much closer to our findings. University College London's report on CO_2 efficiency of the current shipping fleet, by the Energy Institute, estimates vessel type and size specific CO_2 emissions, emitted per tonne of cargo carried and nm travelled. Smith et al. (2015a, 2015b) found the efficiency of container ships and dry bulk carriers ranging between 5-44 and 13–34 g of CO_2 per tonne carried and nm travelled, respectively. As both Fig. 2(c) and (d) show our commodity- and voyage-specific clusters fall close to these ranges at 15–25 and 20–30 g of CO_2 per tonne carried and nm travelled.

5.2. Uncertainties in our approach and ways forward

While in our Brazil pilot we observed a high primary match rate between shipping manifest and AIS data, our emissions account comes with associated uncertainties. Firstly, despite increasingly better AIS coverage, this satellite-dependent system cannot yet obtain readings of each vessel's activity 100% of the time. Low penetration of the AIS monitoring system can occur, whether due to disruption of satellite signals or shore-based reception of AIS messages, limitations inherent to the satellite orbits, and interruptions of a ship's AIS transponder's operation (Smith et al., 2015a, 2015b).

With regard to the nature of ocean shipments, our methodology assumes that goods were discharged in the reported port and not at a near location at sea. It is however worth noting, that some cargo handling operations take place by way of ship-to-ship transfers and never actually enter the country of destination reported in the shipping manifest (Jia et al., 2017). Additionally, our current method does not solve some of the inherent difficulties of emission allocation in the maritime transport sector related to ports acting as transhipment hubs, where cargo is unloaded to be subsequently loaded on to a different vessel and re-exported at a later date. An example of such a hub is Singapore, where approximately 85% of incoming cargo gets transhipped to another port (Lam, 2016). For tackling transhipment issues our method would need to be extended by means of considering all shipping manifests from all countries. In doing so the second and subsequent legs of a cargo's maritime voyage would be cross-referenced and accounted for in our emission estimates. As Brazil's export mix is raw-material heavy, with likely less transhipments, in absence of this global account of national shipping manifests in our pilot, the picture of the start-to-finish cargo voyages may be more accurate than, for example, China's export portfolio would have been, which is more container-heavy.

It is also important to highlight that we currently only consider the laden leg of a voyage in our current emissions accounting, while the ballast leg, may be required to accurately assess the total emissions associated to the demand of a given commodity due to trade imbalances. This is particularly significant for Brazil's iron ore and soy exports, whose maritime transport emissions would look worse if these ballast voyages were included, as many vessels are sourced directly from China on shuttle services, creating an extremely long roundtrip voyage. This could be resolved by searching back from the loading point in Brazil to the previous discharge point, using draught recordings, within a vessel's AIS trajectory. The reason this was not pursued here, is that draught records within the AIS dataset tend to be unreliable and difficult to use to determine loading conditions across all vessel types and sizes, especially containerships. Hence, this would potentially reduce the number of matched voyages (with the ballast emissions added), thereby reducing clarity on the impact of the commodities (Prakash, Forthcoming). Future applications of this paper's approach, to a global sample of shipping manifests which include historic records, may provide a clearer view of a vessel's trade carrying activities, and allow for the accurate identification of ballast legs, provided that information on a vessel's idle and non-operating states is available.

Another source of uncertainty is associated with the various degrees of spatial-temporal alignment of the information provided by AIS and the shipping manifests for the same vessel. These misalignments included (i) differences in date of travel, due to possible unexpected delays, a very common occurrence in specific Brazilian ports where, freight movements are sometimes delayed by weeks (see Bottasso et al., 2017; Beuren et al., 2018) and (ii) disparities in AIS recorded port locations. Spatially, we choose a proximity of $\pm 2^\circ$ in longitude and latitude within our matching. This was done as the GPS coordinates of each port were manually extracted and representative of the approximate centre of the port, whereas some ports have multiple terminals situated quite far away from each other and smaller ports are often reported as belonging to the main port hubs due to their relative proximity. Despite this large matching area, we know from the shipping manifests the specific departure port and therefore the AIS-reported location is merely used to confirm what the shipping manifest reports and used to calculate the distance the vessel covered until the foreign destination port. Temporally, our chosen time considerations also play a significant role in the uncertainty of our methods. Justifications for the large time window in case 2 include the discrepancies in dates between the two datasets (in- and exclusion of voyage time), the anticipated delays in Brazilian ports and the voyage delays inherent to shipping. Discrepancies between the actual port call date and the date for when a vessel is expected are common, which is usually larger for bulkers, followed by tankers and tends to be much smaller for containerships, operating on liner services (Ting, 2006). Our results saw 19% of trades directly matched with an AIS voyage which took place between 30 days and 2 months after, of which dry bulkers had a large proportion of case 2 matches (15%) and tankers and general cargo slightly smaller proportions (12% and 9% respectively). While these three vessel types corresponded with the previously described trend, our container matches did not, with a higher proportion (19%), indicating a larger uncertainty among containerised matches and a possible smaller functionality of the described method for containerised transportation. Reasons for this finding could include the larger sample size of containerised entries, the increased uncertainty related to the larger number of stops inherent to container transportation and the frequent reoccurrence of container routes in shorter time periods (which may have lead to case 3 matches to be categorised as case 2 matches). In further applications of this method, the time window may be adjusted according to the departure and arrival locations, which could increase further understanding of the discrepancies between shipping manifests and AIS derived voyages and provide insight into shipping punctuality.

The total number of stops during a voyage was limited to 10. While this was found to be a reasonable assumption (see Appendix A.2), it caused trade routes that took more than 10 stops to not match directly, but to vessels of similar characteristics and cargo, to provide an approximate estimate of the emissions based on the real-life data. While as discussed in section 3 the potential mistakes introduced with this assumption are expected to be small, future iterations of our methodology could increase this threshold, which was imposed exclusively for computational purposes. Similarly, the use of approximated matches in cases 3–6, where shipping manifests were linked to either similar AIS voyages of the same or a similar vessel, avoided the deployment of algorithms to estimate the unobserved activity and routes of vessels in AIS.

Of lesser importance, given their intrinsic nature, we should highlight both the uncertainties associated to the technical parameters — used to characterise a vessel, the operational specifications the vessel witnesses on its voyage and the physics and relationships used to calculate fuel consumptions and hence emissions — and the empirical parameters involved. A vessel's fuel use and therefore emissions depend on both, where the technical parameters are mainly look-up data, including for example engine information and vessel ages and the operational specifications are empirical data, such as emissions factors. For more information on these two uncertainties see Smith et al. (2015a, 2015b). Lastly, for the allocation of emissions per USD, we estimated FOB prices at HS4 level. Although this surely added increased uncertainty in the valuation of the commodities, the nature of HS8 codes is generally quite similar to that of the HS4 level, with acceptable discrepancies.

5.3. Applications and further perspectives

When scaled up to cover larger areas of the world, the approach demonstrated in this paper has the potential to offer a reliable global account of trade-related maritime transport emissions, with a small lag of weeks in getting the input data. As the coverage of AIS data has improved significantly over the past years and continues to improve, a comprehensive database on per vessel maritime emissions has become accessible. As for the cargo manifests, whilst it is possible to purchase shipping manifests and bills of lading with vessel specification in other geographies, to date there is not yet global coverage, and for parts of the world this information is currently not publicly purchasable. There are however increasing number of still incipient initiatives to collect manifests (such as the Blue Belt in the European Union).

This paper argues that a spatially-explicit approach – with vessel-, voyage- and commodity-specificity – is needed to lay the groundwork for a comprehensive shipping emissions accounting system, while also providing robust emission allocation standards, either based on the relative weight or the value of a commodity with respect to each vessel's total cargo. In conjunction with an appropriate and fair emissions apportionment method — which reconciles both ‘the common but differentiated responsibilities’ and the ‘no more favourable treatment’ concepts (see Miola et al., 2011; Keen et al., 2013) — this method could become an invaluable contribution to environmental accountability efforts at a national and corporate level, improving foot printing accuracy by for example providing more accurate estimations of shipping intensities for LCAs, and could be a stepping stone in informing discussions on ways to apportion responsibility for shipping emissions. This is particularly timely as the IMO is undertaking its GHG reduction Roadmap, the shipping sector's response to both the outcomes of the UNFCCC's COP21 and the political pressure on the IMO to provide a response to the Paris Agreement. Following on from its Initial Strategy for GHG Reduction in April 2018, stating overall objectives for the sectors CO_2 emissions reduction and a list of candidate policy measures to achieve them, a more detailed evaluation and implementation will follow in 2018–2023, with a Revised GHG strategy at the end of that period. This paper's spatially-explicit approach is relevant to a number of areas of work that are likely to be undertaken, including improving aggregate GHG emission accounts of different ship types, sizes and geographies; assessing the role of different commodities in driving shipping emissions; evaluating the environmental effectiveness of certain candidate policy measures (e.g. speed reduction, route optimisation) and assessing the impact of policies on states (particularly developing states, small island developing states (SIDS) and least developed countries (LDC)) including unintended consequences of policies to mitigate GHG emissions, to name a few.

More specifically, in line with the national action plans, suggested as one of the candidate measures in the IMO's Roadmap, trade-route specific accounts offer countries' detailed breakdowns of both their export- and import-related shipping emissions. This would require geographically and temporally extending our method to gain a global multitemporal perspective, allowing for differentiation between maritime transport emissions from consumption and production-related activities, cutting down on potential emission leakages, which are particularly relevant in today's economy where huge foreign trade inequalities between countries exist (Chatham House, 2017). Additionally, our approach contributes to a more comprehensive and complete environmental assessment of supply chains. The data it provides can improve transparency (Gardner et al., 2018), offering consumers a more accurate and detailed environmental footprint of the consumed product, which may promote consumer awareness and inform discussions about the efficiency of trading specific commodities in relation to domestic or more local sourcing.

While in this paper we haven't included analyses on cargo ownership, it is straightforward using this approach to map the exporter and importer companies that participate in each shipment, as reported in the shipping manifests — providing a micro level perspective. By allocating maritime emissions to supply chain actors such as traders and carriers, it is possible to strengthen accountability up- and down-stream of the supply chain for a particular demanded good. The direct targeting of specific commodities, by a better informed organised civil society, could lead to concrete improvements and more sustainable practices, while increased accountability may also contribute to a race to the top that could incentivise shippers to ship more sustainably. Furthermore, if these accounts are adopted by wall-to-wall analyses of entire supply chains (see http://trase.earth), it is possible to produce an accurate and spatially-explicit comparison of emissions between different supply chain steps, setting the shipping sector's environmental impact discussions in a wider context, which may help raise the issue in climate discussions. Integration of this methodology into LCA methods could improve current emission estimates of entire economic processes which lead to our consumption of goods and services. This could allow policy-makers, consumers and producers to specifically zoom in on the trade-offs between alternative emission mitigation options throughout a product's supply chain, by accurately comparing the emissions at the different life stages (e.g. land-based emissions from production vs. maritime shipping emissions from transportation vs. industrial emissions of transforming the raw commodity).

We acknowledge that further research is necessary to refine the robustness of our approach, and more specifically the chosen matching criteria. It would be in particular useful, to assess emissions of a larger sample of shipping manifests, covering more countries and more years. This would allow for comparison in trends and more robust voyage- and commodity-specific emission intensities. The proposed approach will benefit from future research on how to consider re-exports and embedded exports of a given commodity in other commodities (Kastner et al., 2011), as well as the inclusion of aspects within the shipping manifests, such as cargo ownership, carrier and contract modalities, to enrich the picture offered in this paper. Integration of this bottom-up approach with top-down approaches (such as multi-regional input-output based analyses) to account for emissions, would also be beneficial for improving national input-output based emissions estimations. Lastly, a time series on how observed commodity-specific emissions, allocated by company, evolve through time, vis-à-vis a specific policy mix implementation, could offer instrumental insight for policy impact assessments, cost analyses and the development of alternative environmental policies within the shipping sector and production in general.

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Appendix A

Table A.1
Country-specific CO_2 emission results, ranked according to their CO_2 emissions. For each country, the main weight-contributing commodities at HS8 level, its total exported weight and value are also highlighted.

Country	Total Weight		Total Value		Total CO_2	
	tonnes, million	%	USD, billion	%	tonnes, million	%
China	207.88	40.86	33.87	19.05	11.66	44.85
Japan	32.37	6.36	3.46	1.95	2.15	8.26
South Korea	17.79	3.50	3.60	2.02	1.16	4.46
United States of America	21.10	4.15	18.66	10.49	1.04	4.02
Singapore	11.53	2.27	8.09	4.55	0.84	3.24
Netherlands	31.07	6.11	12.11	6.81	0.84	3.23
Malaysia	8.20	1.61	1.58	0.89	0.42	1.61
Taiwan	5.95	1.17	0.94	0.53	0.41	1.58
Italy	10.66	2.09	5.36	3.02	0.38	1.48
India	6.64	1.30	2.83	1.59	0.35	1.34
Canada	6.11	1.20	2.16	1.22	0.32	1.25
Spain	9.94	1.95	8.27	4.65	0.32	1.24
France	10.11	1.99	2.58	1.45	0.31	1.21
United Kingdom	9.40	1.85	2.07	1.16	0.30	1.14
United Arab Emirates	5.37	1.06	1.36	0.77	0.29	1.12
Iran	4.57	0.90	1.03	0.58	0.28	1.09

(continued on next page)

Table A.1 (*continued*)

Country	Total Weight		Total Value		Total CO_2	
	tonnes, million	%	USD, billion	%	tonnes, million	%
Oman	9.89	1.94	0.75	0.42	0.28	1.08
Indonesia	4.89	0.96	1.42	0.80	0.28	1.06
Philippines	5.50	1.08	0.47	0.27	0.27	1.04
Vietnam	3.35	0.66	0.89	0.50	0.25	0.97
Germany	5.68	1.12	7.54	4.24	0.25	0.95
Hong Kong	2.84	0.56	5.78	3.25	0.24	0.91
Egypt	4.95	0.97	1.11	0.62	0.23	0.88
Belgium	4.76	0.94	4.82	2.71	0.19	0.74
Turkey	4.95	0.97	0.83	0.47	0.19	0.74
Thailand	2.30	0.45	1.11	0.63	0.17	0.67
Saudi Arabia	3.91	0.77	0.78	0.44	0.16	0.61
Russia	2.03	0.40	0.98	0.55	0.14	0.53
Norway	1.96	0.39	1.78	1.00	0.12	0.47
Bahrain	3.16	0.62	0.29	0.16	0.12	0.45
Algeria	2.18	0.43	0.81	0.45	0.11	0.44
Trinidad and Tobago	4.44	0.87	0.86	0.48	0.11	0.43
Colombia	2.09	0.41	4.90	2.76	0.10	0.38
Argentina	6.15	1.21	6.18	3.48	0.10	0.37
South Africa	2.81	0.55	2.82	1.59	0.09	0.35
Morocco	2.25	0.44	2.31	1.30	0.09	0.35
Bangladesh	1.83	0.36	0.77	0.44	0.08	0.31
Venezuela	1.66	0.33	2.16	1.21	0.08	0.30
Bonaire, Sint Eustatius and Saba	1.66	0.33	1.03	0.58	0.08	0.30
Nigeria	1.91	0.37	0.72	0.40	0.07	0.25
Mexico	1.14	0.22	3.21	1.80	0.07	0.25
Chile	1.49	0.29	1.52	0.86	0.06	0.24
Senegal	0.53	0.10	0.30	0.17	0.06	0.23
Panama	1.06	0.21	2.35	1.32	0.05	0.20
Ireland	1.33	0.26	0.60	0.34	0.05	0.19
Qatar	1.36	0.27	0.18	0.10	0.05	0.18
Libya	1.44	0.28	0.31	0.17	0.05	0.18
Portugal	1.19	0.23	0.66	0.37	0.04	0.17
Iceland	0.92	0.18	0.26	0.15	0.04	0.16
Peru	0.49	0.10	1.08	0.61	0.04	0.14
Georgia	0.52	0.10	0.21	0.12	0.04	0.13
Slovenia	0.82	0.16	0.30	0.17	0.03	0.13
Greece	0.51	0.10	0.26	0.15	0.03	0.13
The Bahamas	0.62	0.12	0.82	0.46	0.03	0.13
Others	9.53	1.88	6.71	3.73	0.48	1.84

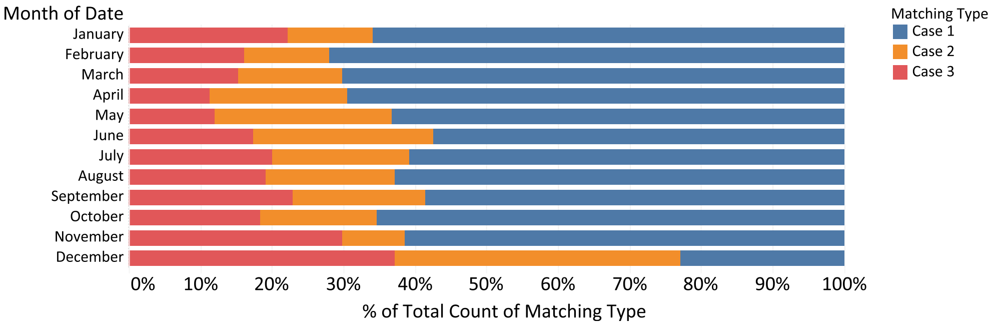

Fig. A.2. This figure shows the percentiles of the count of matching cases 1, 2 and 3 by month. It highlights that December witnessed a higher percentage of case 3 matches than the other months did, which can be explained by these cargoes having departure dates in the shipping manifests in 2014 and AIS voyages in 2015.

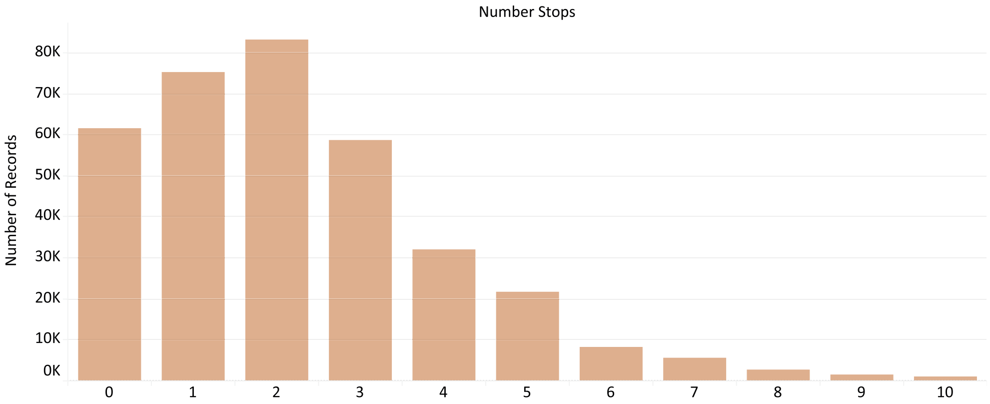

Fig. A.3. During the matching process, we started off without a cap on the number of stops but as the figure shows, it became very clear that around 10 stops, the number of matches tended to zero. Implications of capping this number were that there may have been a few trade routes out of Brazil of more than 10 stops, which were not able to match directly due to the cap and therefore were matched using one of the less stringent matching criteria. This is therefore an uncertainty specifically related to the 8.10% of total shipping manifests which were matched with a different vessel with similar characteristics.

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