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Ecological unequal exchange: quantifying emissions of toxic chemicals embodied in the global trade of chemicals, products, and waste

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Abstract

Ecologically unequal exchange arises if more developed economies (‘core’) shift the environmental burden of their consumption and capital accumulation to less developed economies (‘periphery’/‘semi-core’). Here we demonstrate that human populations in core regions can benefit from the use of products containing toxic chemicals while transferring to the periphery the risk of human and ecological exposure to emissions associated with manufacturing and waste disposal. We use a global scale substance flow analysis approach to quantify the emissions of polybrominated diphenyl ethers (PBDEs), a group of flame retardants added to consumer products, that are embodied in the trade of chemicals, products and wastes between seven world regions over the 2000–2020 time period. We find that core regions have off-loaded PBDE emissions, mostly associated with the disposal of electrical and electronic waste (e-waste), to semi-core and peripheral regions in mainland China and the Global South. In core regions this results in small emissions that mostly occur during the product use phase, whereas in peripheral regions emissions are much higher and dominated by end of life disposal. The transfer of toxic chemical emissions between core and periphery can be quantified and should be accounted for when appraising the costs and benefits of global trade relationships.

1. Introduction

Due to the potentially serious health impacts of exposure to toxic chemicals (Colborn *et al* 1996), environmental justice would require that populations that benefit from the use of a product containing chemicals are also bearing the risk of exposure to the chemical emissions associated with those products. A prominent example is that indigenous people in the North having a traditional diet are highly exposed to pesticides and industrial chemicals as a result of long-range environmental transport (LRET) (Kuhnlein and Chan 2000, Undeman *et al* 2018), but they are not the direct beneficiaries of the use of these chemicals. The ethical issues that this divergence raises were one of the key driving forces for the Stockholm Convention, which seeks to globally regulate any chemical that is likely as a result of its LRET to lead to significant adverse human health and/or environmental effects.

Traditionally, without international trade, the only way in which a country may be affected by chemical emissions occurring in another country is through LRET. With globalization, domestic demands for neat chemicals and products can be met by drawing from non-domestic sources through international trade, leading to an increasing global division of production and consumption where products and chemicals therein are often manufactured in places different from where they are used. With some regions becoming increasingly reliant on the importation of chemicals and products from other regions for domestic consumption, the environmental burden associated with the production of these chemicals and products is transferred from the importing regions to the exporting regions. Furthermore, as disposal of some end-of-life products can occur in jurisdictions different from where the products had been used (Theis 2021), the benefits associated with product consumption and the environmental burden associated with end-of-life product disposal are decoupled, leading to further displacement of environmental and health ramifications through international trade.

The separation of populations benefitting from the use of a product from those bearing the burden of the chemical emissions associated with the manufacturing and disposal of that product reflects the theory of ecological unequal exchange (EUE). This theory examines unequal trade relationships whereby more-developed economies, or 'core' countries, externalize their ecological costs to poorer, 'peripheral'/'semi-core' countries (Hornborg 1998). While previous work has sought to quantify EUE 'by tracing and comparing flows of trade-embodied wealth and pollution along global supply chains' (Zhang *et al* 2018), there has been no attempt to quantify the chemical emissions embodied in the international trade of chemicals and chemical-containing products and waste. The pollution explored in previous analyses has mostly focused on greenhouse gas emissions or air pollution (e.g. particulate matter such as PM2.5) and the associated public health impacts (e.g. Peters and Hertwich 2008, Prell and Sun 2015, Zhang *et al* 2017). Chemical-specific studies were focused on substances emitted as part of fuel combustion (Chen *et al* 2016, Li *et al* 2022). However, industrial chemicals embedded in consumer products, briefly chemicals in products (CiPs), also deserve attention with respect to EUE as human and ecological exposure to such chemicals may lead to detrimental impacts, further underlining the environmental and social injustices which underlie international trade.

International trade has led to an EUE, whereby the populations enjoying the benefits of consuming goods containing chemicals are off-loading a share of the burden of the risk associated with the exposure to such chemicals to human and wildlife populations in regions that are net-exporters of manufactured goods and net-importers of waste. The overall goal of this study is to demonstrate the possibility to quantify the EUE present in such interregional trade using polybrominated diphenyl ethers (PBDEs) as an illustrative example. PBDEs are a class of chemicals commonly used as fire retardants in consumer products such as electronics, carpets, foam cushions, building materials, and textiles. Since PBDEs are not chemically bound to the polymers to which they are added, a fraction of these chemicals may escape during the lifecycle stages of chemical production, product manufacturing, use, and waste disposal (Domingo 2012). As PBDEs are highly resistant to biotic and abiotic degradation, they are capable of undergoing LRET and bioaccumulating in human and animal tissues (Harrad *et al* 2010, Law 2010, Law *et al* 2014). Experimental studies on laboratory animals and observational studies on humans suggest that exposure to PBDEs is likely to cause thyroid homeostasis disruption, neurodevelopmental deficits, reproductive changes, and cancer (McDonald 2002, Alonso *et al* 2010, Bellés *et al* 2010, Kim *et al* 2013, Reverte *et al* 2014, Linares *et al* 2015).

Here we identify the major trade routes and lifecycle stages contributing to EUE for PBDEs by quantifying the historically cumulative PBDEs emissions embodied in the trade of chemicals, products and waste. In doing so, this work uncovers the key drivers of a region's trade-induced chemical emissions and its associated environmental costs.

2. Methods

2.1. Overview of the modeling strategy

Simulations are done with a global-scale dynamic substance flow analysis model 'Chemicals in Products-Comprehensive Anthropospheric Fate Estimation' (CiP-CAFE). Supplied with data on the annual production of chemicals and international trade of chemical-containing products and waste, CiP-CAFE quantifies time-variant flows and stocks of CiPs during production, use and waste disposal stages within and between each of seven interconnected world regions (Li and Wania 2016). Table 1 and figure 2(b) introduce these regions and the labels we use to refer to them.

In this paper, we use CiP-CAFE to quantify the transboundary movement of PBDEs embodied in the trade of neat PBDEs (technical PBDE mixtures and formulations), PBDE-containing products (electronics, foam and carpet, construction, transportation, and textiles), and PBDE-containing waste (mainly electronic waste) between the seven regions of CiP-CAFE between 2000 and 2020. CiP-CAFE quantifies the emissions of six individual PBDEs congeners (BDEs 28, 47, 99, 153, 183, and 209) occurring during chemical production (E_P), product manufacturing (E_M), product use (E_U), and waste disposal (E_W) (figure 1). The simulations on CiP-CAFE are the same as in Abbasi *et al* (2019) and we refer to this earlier study for details on the methodology applied in the calculation of emissions. Here we only provide details on the methodology used to the quantification of trade-embodied emissions. The goal is to appraise the extent to which interregional trade has contributed to EUE in the form of toxic chemical emissions.

In order to quantify the EUE present in interregional trade, we estimate the following export

Table 1. The seven world regions as defined in the global substance flow analysis model CiP-CAFE (Li and Wania 2016).

	Description
R_1	Mainland China
R_2	Developed economies in the Asia-Pacific region (Japan, South Korea, Australia, New Zealand)
R_3	Rest of Asia (incl. India, middle East, Indochina, Indonesia)
R_4	Russia and Eastern Europe (incl. Armenia, Azerbaijan, Georgia)
R_5	Western Europe
R_6	North America (Canada, USA)
R_7	Central America, South America, and Africa (incl. Mexico)

fractions f_X by collecting and curating publicly-available trade statistics: (a) the fractions of the PBDEs (neat chemical and formulations) produced within region i that are exported to the six other regions j ($f_{\mathrm{P}i\to j}$); (b) the fractions of the products containing PBDEs produced within region i that are exported to the six other regions j ($f_{\mathrm{M}i\to j}$); and (c) the fractions of the waste containing PBDEs processed within region i that are imported from the six other regions j ($f_{\mathrm{W}j\to i}$).

We then calculate emissions embodied in trade by multiplying the CiP-CAFE-estimated emission rates with the corresponding export and import fractions. This yields three different types of emissions: (a) the emissions in region i caused by the export of chemicals to region j ($E_{\mathrm{P}i\to j} = E_{\mathrm{P}i}\, f_{\mathrm{P}i\to j}$); (b) the emissions in region i caused by the export of products to region j ($E_{\mathrm{M}i\to j} = E_{\mathrm{M}i}\, f_{\mathrm{M}i\to j}$); and (c) the emissions in region i caused by the import of waste from region j ($E_{\mathrm{W}j\to i} = E_{\mathrm{W}i}\, f_{\mathrm{W}j\to i}$). The results are expressed as three multiregional input-output (MRIO) tables (table S1 available online at stacks.iop.org/ERL/17/044054/mmedia illustrates the MRIO table for the trade in chemicals and products and table S2 illustrates that for the trade in waste). Please note the difference between the trade in chemicals and products (where import leads to an 'off-loading' of emissions to the exporting region) and the trade in waste (where export leads to an 'off-loading' of emissions to the importing region). The terms $E_{\mathrm{P}i\to j}$, $E_{\mathrm{M}i\to j}$, and $E_{\mathrm{W}j\to i}$ are summed over the period from 2000 to 2020. Overall, emissions in region i driven by consumption in region j, i.e. the 'emissions embodied in trade', can be calculated as:

$$E_{j\to i} = E_{\mathrm{P}i} f_{\mathrm{P}i\to j} + E_{\mathrm{M}i} f_{\mathrm{M}i\to j} + E_{\mathrm{W}i} f_{\mathrm{W}j\to i}.$$

Thus, summing the entries in the three MRIO tables for trade in chemicals, products and waste, we obtain a fourth MRIO table with the total emissions embodied in interregional trade.

2.2. Retrieval of trade statistics

While CiP-CAFE considers the respective total chemical flows entering and departing from a region due to trade in chemicals, products and waste, it does not directly trace trade flows specifically from one region i to another region j. In this work, we obtain international trade information from the United Nations COMTRADE database (www.comtrade.un.org) in order to estimate the export fractions for the trade in chemicals and the trade in products containing PBDEs (UN COMTRADE nd). We collect data from the year 2000–2020 for all countries concerning import and export trade values (measured in US dollars) of Harmonized Systems codes 29 (organic chemicals), 57 (carpets, surrogate for emissions from the 'foam and carpet' category defined by Abbasi *et al* 2019), 59 (textiles, surrogate for emissions from the 'textiles' category), 85 (electronic equipment and electronics, surrogate for emissions from the 'electronics' category), 87 (vehicles, surrogate for emissions from the 'transportation' category), and 94 (furniture and mattresses, surrogate for emissions from the 'construction' category). Commodities with the other codes are used as proxies for the trade flows of the five categories of PBDE-containing products. In the absence of compound-or category-specific data on the trade in PBDEs or flame retardants, code 29 (organic chemicals) is used as a proxy for the trade flows of PBDE chemicals (neat and in formulations). This rests on the assumption that PBDEs are traded internationally similarly to other organic chemicals.

We first organize individual countries into their respective regions and calculate the total import and exports of each commodity (in units of US dollars) of each region. Assuming a uniform cost of commodities across countries, we calculate the export fraction $f_{\mathrm{M}i\to j}$ for each commodity by taking the average between the export of a given commodity x from region i to region j (reported by region i) and the import of x from region i to region j (reported by region j). The imports and exports between countries within the same CiP-CAFE region are omitted as we are concerned only with interregional trade. The interregional import/export fraction matrices for each of the commodities can be found in the supporting information (tables S7–S13).

Transboundary waste flows are often illicit (Bisschop 2012, Breivik *et al* 2014). For instance, an estimated 82.6% of e-waste disposal was undocumented in 2019 (Forti *et al* 2020). As such, the UN COMTRADE database is not able to offer sufficiently accurate estimates of interregional waste trade flows, as the estimates reported mostly include only legal waste trades (the estimates are still incomplete even for legal waste trades) (Lepawsky and McNabb 2010). In addition, since there are no currently available data on the trade flow of waste products containing PBDEs

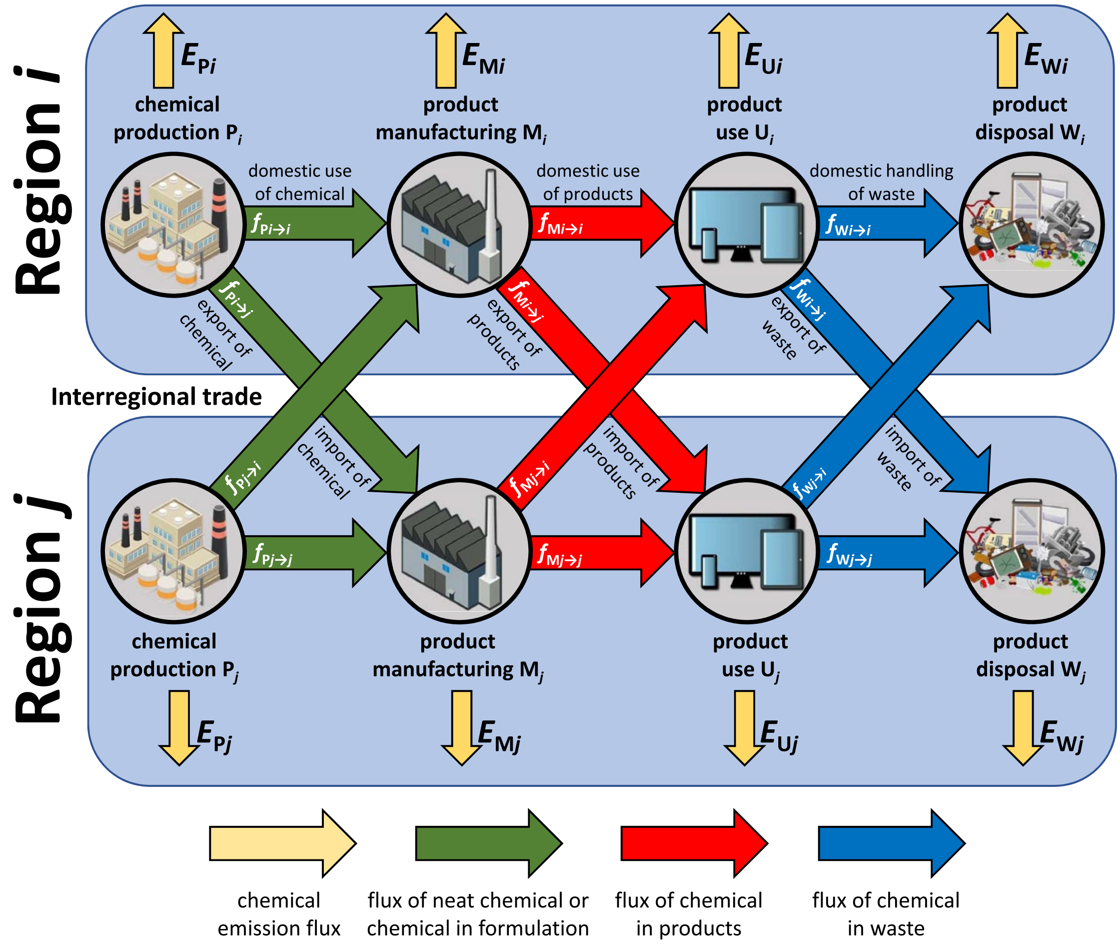

Figure 1. Conceptual display of the emissions embodied in the trade of chemical, products and waste between two regions *i* and *j*.

other than e-waste, we limit our calculation of interregional import fractions of waste to e-waste alone. While it is quite likely that there are other PBDE-containing wastes (e.g. flame retarded textile waste), omitting those from our analysis is justified because the exported fractions tend to be small for waste other than e-waste (<5% versus 10%–32% for e-waste) and because their disposal leads generally to lower PBDE emissions than disposal of e-waste. We use international e-waste trade flow data by Breivik *et al* (2014) to calculate the import fractions for waste ($f_{Wj\to i}$), while acknowledging that these estimates are highly uncertain, incomplete and likely biased low. Overall, data in Breivik *et al* (2014) show that Regions 1, 3, and 7 are solely waste-importing regions, while Regions 2, 4, 5, and 6 are solely waste-exporting regions.

3. Results

3.1. PBDE emissions embodied in global trade

The annual global PBDE emissions (sum of six congeners) arising from chemical production, product manufacturing, and waste disposal varied during 2000–2020 (figure S1). PBDE emissions caused by chemical production and product manufacturing have been declining over the 20 years. Globally, over the 20 years, PBDE emissions caused by the production of chemicals totaled 76 tonnes, while emissions caused by the manufacturing of products totaled 10 tonnes. Emissions caused by waste disposal were highest, totaling ∼1000 tonnes, and saw an increase in the first decade (2000 until 2009) followed by a decline in the second decade (2009–2020), reflecting the gradual depletion of the waste stock after the phase-out of PBDEs before the 2010s. A fuller account of the temporal variations of the global emissions of PBDEs can be found in Abbasi *et al* (2019). The central aspects of the analysis presented here, namely the regions bearing and offloading emissions and the relative importance of the emissions embodied in the trade of chemicals, products and wastes did not undergo major changes in the 20 years under consideration. Therefore, the results are only presented aggregated over this time period.

Figure 2(a) shows the acquiring (red) and offloading (blue) of embodied total PBDE emissions for each of the seven regions between 2000 and 2020. No single region acts as both a major importer and exporter of emissions; i.e. a region is either mostly

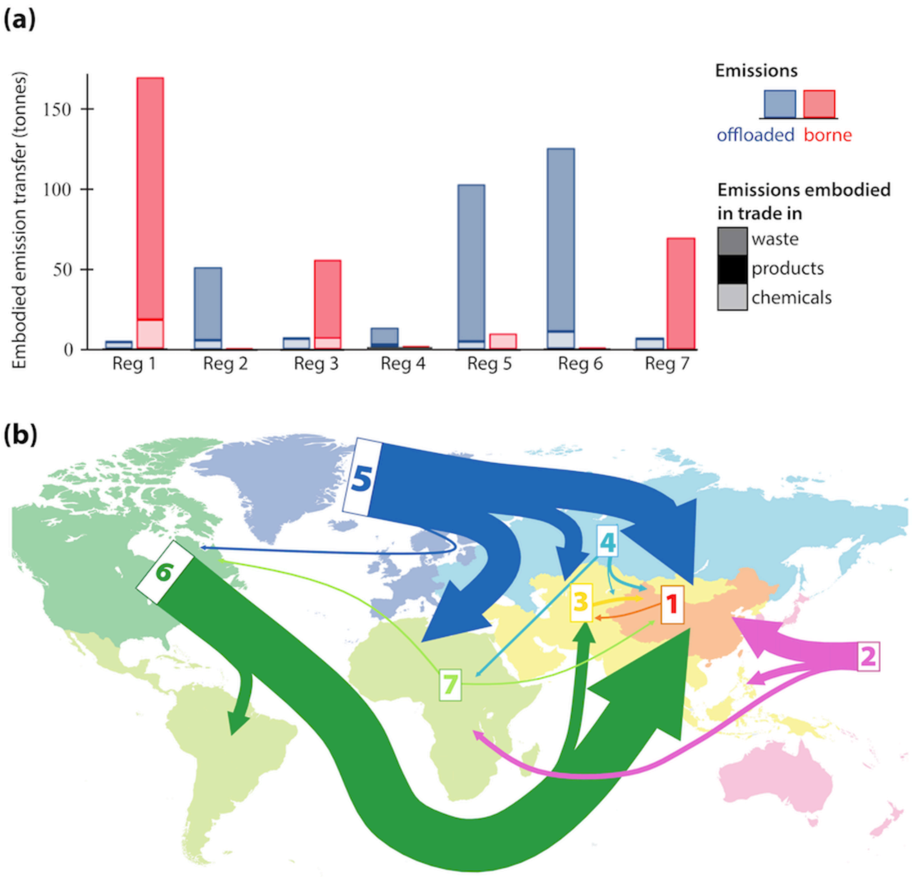

Figure 2. (a) Comparison of the emission transfers (tonnes), aggregated from 2000–2020 in the seven geographic regions in the CiP-CAFE model (see table 1 for definition) and (b) illustration of the flows of the trade embodied emissions between those regions.

an importer of embodied emissions or an exporter. Three of the regions are net importers of embodied PBDE emissions, namely mainland China (R_1, 173.8 tonnes), Central and South America and Africa (R_7, 71.3 tonnes), and the rest of Asia (R_3, 56.2 tonnes). Most, if not all, developed economies are net exporters of embodied PBDE emissions, most notably Western Europe (R_5, 127.0 tonnes), North America (R_6, 105.5 tonnes), and developed economies in the Asia-Pacific region (R_2, 51.9 tonnes) (figure 2(b)).

The different life cycle stages make very different contributions to the embodied emissions (figure 2(a)). From the global perspective, the emissions of PBDEs embodied in the trade in waste are estimated to constitute most of the embodied emissions globally (88%), whereas the production of traded PBDEs contributes another 11%. The emissions embodied in the manufacturing of traded products make a contribution of less than 1%. However, on a regional scale, there are exceptions to this pattern. For example, we estimate that the minor embodied emissions borne by North America (R_6) arise mostly from the manufacturing of PBDEs exported to other regions. On the other hand, China (R_1), the rest of Asia (R_3) and Africa and South America (R_7) off-load some embodied emissions by importing PBDEs made elsewhere.

3.2. Interregional exchange of trade-embodied PBDE emissions

Region-to-region trade embodied PBDE emissions associated with chemical production, product manufacturing, and waste disposal are displayed in figures 3(a)–(c), with the corresponding MRIO tables given in tables S3 to S5 in the supporting information. Figure 3(d) displays the sum of the embodied emissions from these trade activities (for numeric results, see table S6). Figure 3 informs us of the regions that do or do not participate in the import/export of PBDE emissions in each of the lifecycle stages. For instance, figure 3(a) shows that R_2, R_4, R_5, and R_7 do not produce PBDE neat chemicals for export to other regions, and figure 3(c) shows that R_1, R_3, and R_7 are solely waste-importing regions, while R_2, R_4, R_5, and R_6 are solely waste-exporting regions.

Figure 3 helps identify the trade routes which give rise to the most embodied emissions, consequently EUE. For instance, figure 3(a) shows that the major trade routes responsible for emissions embodied in chemical production are mainland China's (R_1) exports to the rest of Asia (R_3) (5.3 tonnes) and Western Europe (R_5) (4.1 tonnes), and North America's (R_6) exports to Western Europe (R_5) (3.7 tonnes). That is, the production of PBDEs in R_1 and R_6

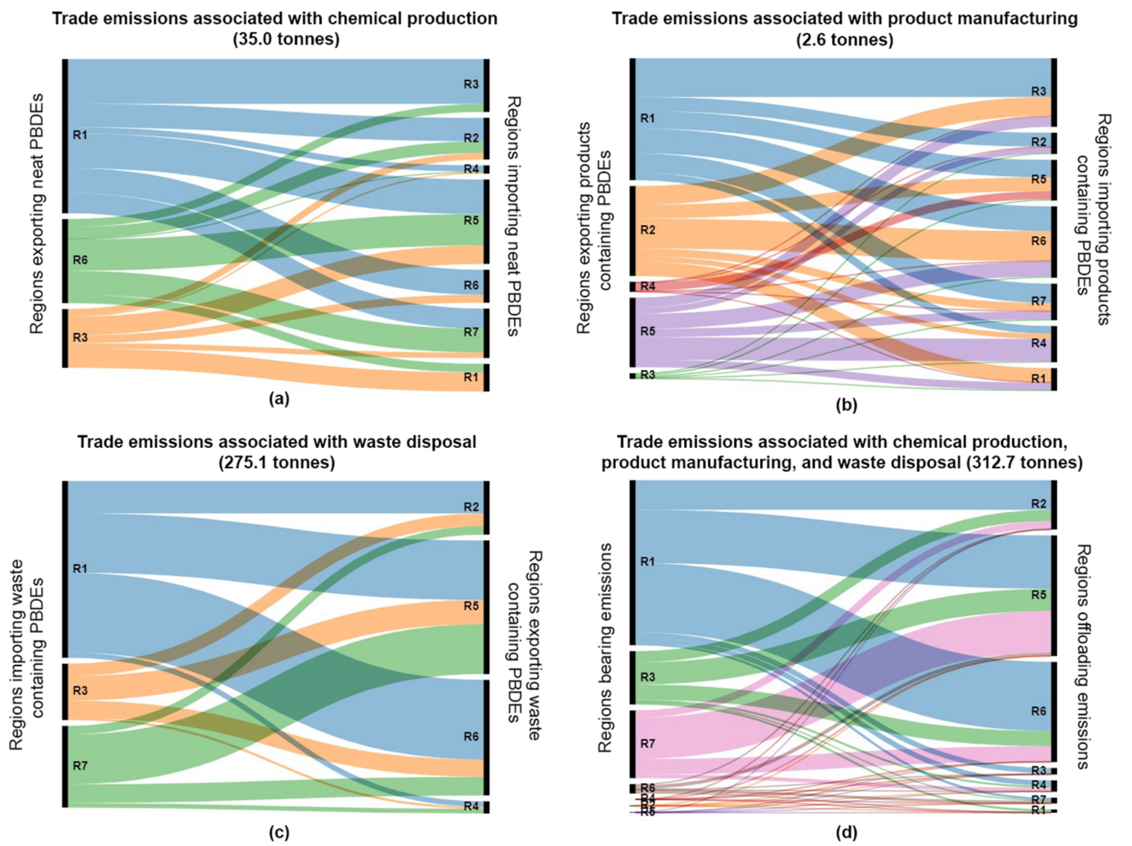

Figure 3. Diagram illustrating the flow and magnitude of PBDE emission transfers associated with the interregional trade in neat PBDEs (a), in products containing PBDEs (b), and waste containing PBDEs (c), and the sum of those trade flows (d). Left and right-hand columns represent the regions bearing and off-loading the emissions embodied in the trades, respectively. The world regions represented by RX are defined in table 1 and displayed in figure 2(b). Please note that the width of the bars cannot be compared between the four different panels, as the emissions embodied in the trade of waste (c) are much larger than those in embodied in the trade of chemicals (a) and especially products (b). The columns on the left-hand side of figures 3(a) and (b) represent the exporting regions, while for figure 3(c) they represent the importing regions. The height of each of the black columns graphically represents the magnitude of the emissions exported/imported relative to other regions on the same side.

helps avoid PBDE emissions in R_3 and R_5. For total embodied emissions including chemical production, product manufacturing, and waste disposal, figures 2(b) and 3(d) shows that the major trade routes contributing to EUE are North America (R_6), Western Europe (R_5) and developed economies in the Asia-Pacific region (R_2) off-loading emissions to China (R_1) (73, 56, 31 tonnes, respectively), mostly through the trade in waste. Also significant are the emissions embodied in the trade of waste from Western Europe (R_5) to Africa and South America (R_7) (44 tonnes). Consequently, the regions bearing the most embodied emissions are the regions which import the most waste containing PBDEs from other regions.

3.3. Share of total PBDE emissions in a region embodied in trade

In order to place the trade embodied emissions into context, figure 4(a) plots them as a share of the total PBDE emissions in the seven regions as calculated in Abbasi *et al* (2019). Three regions stand out as having much higher total PBDE emissions, namely R_1, R_3 and R_7. The emissions added through trade (mostly the trade in e-waste) in those regions constitute a notable fraction of the total PBDE emissions, making up ∼18% in the Rest of Asia (R_3) and Africa and South America (R_7) and even dominate emissions in mainland China (60% R_1). The picture is reversed in regions R_2, R_5 and R_6, where total PBDE emissions are not only rather small, but the emissions avoided by interregional trade greatly exceed the total emissions within the regions. We note here the emissions of PBDEs that would have occurred in regions R_2, R_5 and R_6 if they had not exported some of their waste to other regions ('avoided emissions') would likely have been smaller than the white bars in figure 4 suggest. This is because waste disposal practices vary between regions and e-waste disposal practices prevalent in R_2, R_5 and R_6 result in lower PBDE emissions than the more informal disposal practices common in R_1, R_3, and R_7. Keeping this limitation in mind, we estimate that Western Europe (R_5) unloads 96% of the PBDE emissions that it would have to bear if it were not to engage in international trade. Interregional trade conducted by North America (R_6) and developed economies in the Asia-Pacific region (R_2) avoids approximately three quarters of their PBDE emissions. In the case of North America, the

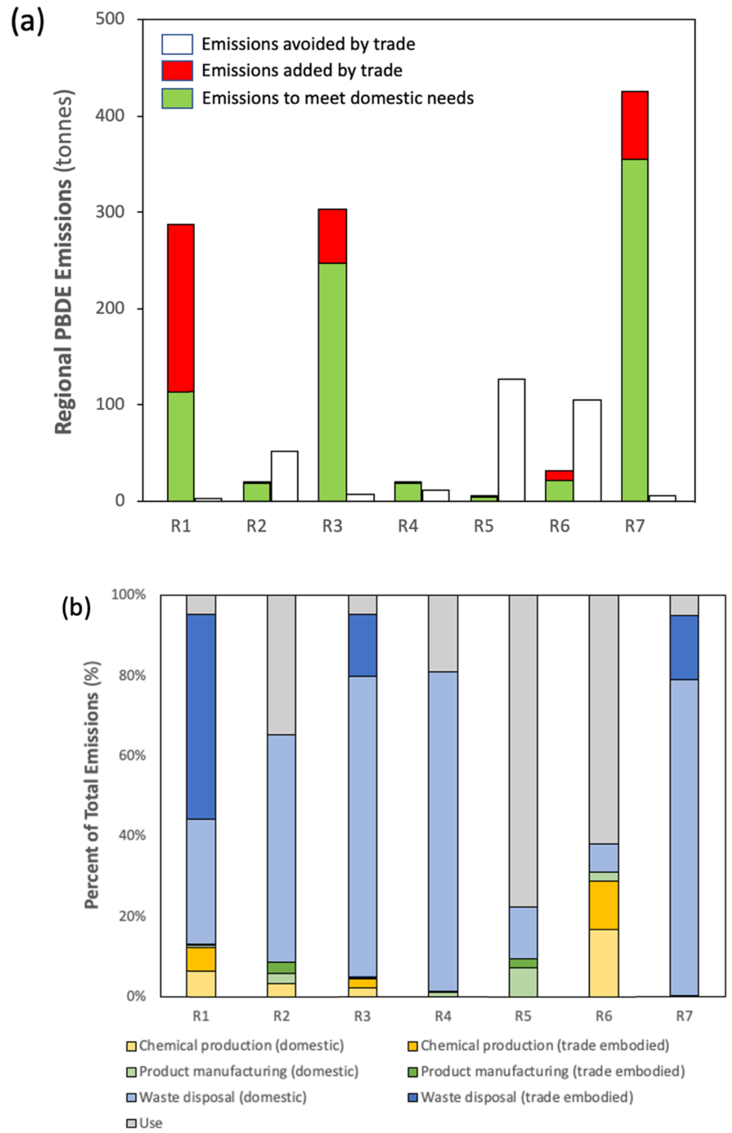

Figure 4. (a) Total PBDE emissions in each region (sum of six congeners, cumulative 2000–2020), with emissions added and avoided as a result of international trade. (b) Relative contribution of different chemical life stages to the PBDE emissions within a region, separating the emissions arising from domestic activities and international trade. The world regions represented by RX are defined in table 1 and displayed in figure 2(b).

emissions added through the production of PBDEs destined for export are much smaller than the emissions avoided through the export of PBDE containing waste.

Because of the different roles different regions play in the global economy, the relative contribution of different activities to the emissions of PBDEs in a region diverges widely (figure 4(b)). Whereas in peripheral and semi-peripheral regions (R_1, R_3, R_7), emissions from waste disposal are by far dominant, the core countries (R_5, R_6) have off-loaded these emissions through the export of waste to such a large extent, that product use is now the dominant chemical life cycle stage to result in PBDE emissions. In Western Europe, more than three quarters of PBDE emissions arise from product use, as this region not only unloads the emissions associated with waste, but also those associated with PBDE production. In North America, this share is somewhat smaller (~60%), because of the production of PBDEs within the region. The overall message is that the core regions have greatly reduced their emissions of PBDEs (figure 4(a)) to the point that only those emissions that cannot be unloaded to other regions remain, because they are associated with the use of products (figure 4(b)).

While all results are presented here as the sum of six PBDE congeners, emissions during all four chemical lifecycle stages are dominated by BDE-209, largely owing to its 20× larger production volume and an order of magnitude higher potential of releases (mainly the informal treatment of e-waste), compared to other congeners (Abbasi et al 2019). The one lifecycle stage, where the more volatile congeners (esp. BDE-47) notably contribute to the emissions is the product use stage.

The quantitative results of the analysis presented here are highly uncertain, because of uncertain input data and assumptions we had to make to infer the trade in PBDEs and in products and wastes containing PBDEs (e.g. the use of proxy data to approximate trade flows of PBDEs). This is particularly the case for the estimates of the emissions embodied in the trade of waste, because reliable data on the source-receptor relationships in the largely illicit trade in relevant e-waste do not exist, in particular over lengthy periods of time as investigated here. Nevertheless, we believe the broad strokes of the uncovered relationships to be robust, such as the transfer of embodied PBDE emissions from developed economies to mainland China and regions in the global South, the dominance of the trade in waste in the embodied PBDE emissions and the importance of PBDE emissions associated with product use in developed economies.

4. Discussion

Our results highlight the considerable PBDE emission transfers in interregional trade. Most strikingly, there are significant disparities between developed regions (Regions 2, 5, 6) and less developed regions (Regions 1, 3, 7) with regard to emission transfers: the developed regions are all net emission off-loaders, while the less developed regions are all net emission bearers. These results provide support for the theory of EUE. Our findings suggest that the inhabitants of core, developed regions off-load the environmental effects of their consumption onto other regions, most significantly through the disposal of waste products. Because of the different waste disposal practices with different emission potential in core versus periphery, this implies not only a transfer of emissions, but also an overall increase in total global emissions (Li and Wania 2016). As such, our work suggests that interregional inequalities are maintained and exacerbated through processes of unequal trade exchanges between developed and less developed regions, highlighting the environmental injustices which underlie global trade.

Since the largest proportion of interregional PBDE emission transfer arises from the waste disposal stage, global efforts aiming to address the issue of the EUE and reduce the health and environmental impacts of PBDEs should focus on tackling the problem of e-waste trade. Since countries in the developed regions often have higher labor costs and more stringent environmental regulations, a large proportion of their wastes are exported to other, often less developed countries (Robinson 2009). For example, it was previously estimated that 50%–80% of e-waste collected in the U.S. for recycling is exported to developing countries; however, since the U.S. has not ratified the Basel Convention, this may not necessarily be illegal (Wang 2007, Kahhat *et al* 2008). This is highlighted in our results, which indicate that the trade route between R_6 (North America) and R_1 (China) embodies the highest amount of PBDE emissions (73 tonnes). Although the Chinese government has banned the import of e-waste since 2002, the illegal import still persists through different channels (Shinkuma and Huong 2009). Mainland China announced in 2017 an unprecedentedly stringent ban on the import of foreign waste including e-waste, which shifted the waste trade hotspots to other regions and also raised the costs of recycling and processing of e-waste in developed countries such as the U.S. (Wen *et al* 2021). Our results highlight the importance of a global coordinated effort to tackle the problem of e-waste trades, and by extension, the issue of EUE.

More relevant than the emissions of toxic chemicals embodied in trade is the exposure of human and wildlife populations arising from these emissions. While quantitative methods linking emissions with exposures exist, that is no trivial task because differences in the emissions arising from different stages of the PBDE life cycle have significant exposure implications (Li *et al* 2020). For example, emissions from product use occur largely in indoor environments and are widely dispersed within a region, whereas emissions from other lifecycle stages occur within industrial settings or to the outdoors and often are spatially constrained. For example, PBDE emissions from end-of-life disposal of products will mostly occur at e-waste dismantling sites and emissions associated with chemical and product manufacturing will be confined to the vicinity of those industrial operations. Product use emissions will mostly lead to low level exposures of the entire population, whereas industrial emissions often are responsible for much higher occupational exposures. Because our analysis suggests that most trade embodied PBDE emissions are associated with waste handling, workers and community members in areas receiving imported e-waste will bear the brunt of the PBDE exposure associated with international trade.

5. Conclusions

In this study, we demonstrated the possibility to quantify the EUE present in the interregional trade in chemicals, products and waste, using the PBDEs as an illustrative example. Similar analyses should be conducted on other chemicals that combine high production volumes, the possibility for population-level exposures and health effects with a presence in, or importance to the making of, internationally traded commodities. Emission characteristics of different chemicals can diverge widely, e.g. with respect to the relative contributions of different life cycle stages to the emissions, so it is conceivable that trade embodied emissions of other toxic substances have very different patterns from those uncovered for the PBDEs in the present study. For example, pesticide use in the production of crops destined for export will also result in the emission of, and exposure to, toxic chemicals embodied in trade (Wesseling *et al* 2001). While there are differences from CiPs, it, too, is likely to lead to substantial EUE, where agricultural communities in peripheral and semi-peripheral economies suffer the exposure to chemicals that are used for the benefit of consumers in core economies.

Our work adds to the growing body of research indicating the existence of EUE in global trade, with poorer countries/regions bearing the environmental burden associated with a significant portion of the consumption of rich countries/regions. The novelty of our contribution lies in the extension of the concept of EUE to the emissions of toxic CiPs and to demonstrate the feasibility of quantifying it through the application of comprehensive and global-scale substance-flow analysis models. The potential long-term risks which harmful and persistent CiPs such as the PBDEs pose to the environment and human health further underlines the magnitude of the injustices underlying global trade.

As we have shown in this study, PBDE emissions associated with chemical production, product manufacturing and waste disposal occur mostly in developing regions with manufacturing economies, whereas emissions associated with product use occur mostly in developed regions with service-dominated economies. This not only leads to much reduced occupational exposure in richer, developed regions, but also lower emissions to the environment and therefore reduced exposure to the general population and to wildlife in those regions. On the other hand, populations in developing regions that are net importers of emissions are suffering increased contaminant exposure (Asante *et al* 2011, Nipen *et al* 2022). Perhaps not by coincidence, the exposure science and contaminant epidemiology communities in core countries are increasingly concerned with exposure arising from product use (Jolliet *et al* 2015, Safford *et al* 2015) (see also figure S2). Future work may thus seek to quantify the effects of human exposure arising from the unequal trade in chemicals, products and waste.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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