

# Continuing large-scale global trade and illegal trade of highly hazardous chemicals

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Pollution caused by anthropogenic chemicals contributes to interlinked planetary crises, together with climate change and biodiversity loss. One of the key treaties adopted to regulate the transboundary movements of hazardous chemicals is the Rotterdam Convention, which created a framework for countries to better handle the international trade of certain hazardous chemicals. To date, research examining the effectiveness of the Convention has been scarce. Here we analysed 66,156 trade records from the United Nations Comtrade database using a workflow that comprehensively addresses data-quality issues in the database. We found that for 46 listed chemicals, at least 64.5 megatonnes were traded in 2004–2019, and illegal trade was prevalent, reaching at least 25,324 trade records and 25.7 megatonnes. For over 70% of the listed chemicals, the Convention has played a positive role, but large-scale trade of some well-known chemicals such as tetraethyl and tetramethyl lead continues. Concerted efforts are warranted to improve how highly hazardous chemicals are traded globally, including enhancing enforcement of the Convention, addressing illegal trade and swiftly listing problematic chemicals (for example, chrysotile asbestos) in the Convention.

While providing desired functionalities and convenience, many anthropogenic chemicals are causing substantial adverse impacts on human health and ecosystems<sup>1–4</sup>. For example, exposure to lead and occupational exposure to 12 well-known carcinogens, out of roughly 350,000 chemical substances registered for use on the global market<sup>5</sup>, were estimated to have caused over 1.2 million premature deaths and loss of about 30 million disability-adjusted life years in 2019. This is nearly the same as the estimated global health burden caused by secondhand smoke<sup>6</sup>. Similarly, chemical pollution has been identified as one of the five major drivers of global biodiversity loss<sup>7</sup>. Together with climate change and biodiversity loss, chemical pollution is now recognized as a planetary crisis that has “put the well-being of current and future generations at unacceptable risk”<sup>4</sup>.

Many countries and regions have established frameworks to manage chemicals produced or consumed in their jurisdictions<sup>5</sup>.

However, the effectiveness of this approach is limited because chemicals manufactured or consumed in one country may enter another via ever-intensified global trade of resources, chemicals, products and wastes, and/or via wind and water currents<sup>8–11</sup>. Also, many other countries have yet to establish their own frameworks<sup>1,8</sup>.

Designed to complement national/regional frameworks, several global treaties have been established to address specific aspects of transboundary movement of hazardous chemicals<sup>12–15</sup>, with a key one being the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade<sup>16</sup>. It entered into force in 2004; its parties are the European Union (EU) and 164 countries as of February 2023<sup>16</sup>.

The Convention introduces the “prior informed consent” (PIC) procedure. This procedure is not designed to ban or restrict any chemicals but to help countries make decisions on their imports and to

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promote shared responsibilities and cooperative efforts on informed trade of the listed chemicals by both exporting and importing countries<sup>12,17,18</sup>. More specifically, for each listed chemical, all parties are required to make an informed decision as to whether they will allow future import of the chemical, known as import responses. All exporting parties are informed about the import responses and required to ensure that exports of the listed chemicals do not occur contrary to the import responses<sup>8</sup>. In other words, it is illegal to export the listed chemicals to a party that has decided not to further import them. Should any importing party fail to transmit an import response, other parties shall still not export listed chemicals to this party unless explicit consent to the import has been sought and received by the exporter. In addition, when the import decision made by a party is 'not to consent to import', the party shall also stop its domestic production and imports from non-parties<sup>8,9</sup>. The Convention regularly assesses and lists new chemicals. As of February 2023, 54 highly hazardous chemicals and groups are subject to the PIC procedure, including pesticides and pesticide formulations, industrial chemicals, and chemicals for both uses<sup>16</sup>. Furthermore, for export of a chemical not listed under the Convention but banned or restricted by a party itself, the party shall provide an export notification to the importing party. It should be noted that the Convention did not have a compliance mechanism (including no provisions on illegal traffic) until 2020. The new compliance mechanism works through a Compliance Committee with its first work programme decided in June 2022, and outcomes are yet to be seen<sup>19</sup>.

Currently, the Convention does not have a formal mechanism to evaluate its effectiveness but largely relies on parties' submissions on measurable impacts. However, only a limited number of parties and observer organizations have put forward submissions<sup>16</sup>. Informally, Núñez-Rocha and Martínez-Zarzoso studied the Convention's effectiveness by analysing a set of trade data in 1995–2012 based on the BACI database originated from the United Nations (UN) Comtrade database<sup>20</sup>. However, this study has two limitations: the dataset covered only 88 countries, and more importantly, while the initial asymmetric import and export data were reconciled using the mirror technique in the BACI database<sup>21</sup>, erroneous trade records (for example, due to overinvoicing and underinvoicing) were not identified and excluded from the analysis. The latter is critical, with potentially drastic impacts on the analysis outcomes, but has often been neglected in trade analyses based on the UN Comtrade database (for example, on plastics<sup>22</sup>).

This study therefore aims to capture an up-to-date, accurate, comprehensive overview of the global trade of highly hazardous chemicals listed under the Convention from 2004, when it entered into force, to 2019. The analysis includes the current state of geographical patterns and illegal trade, taking into account the continuous listing of chemicals and ratification of countries (Supplementary Tables 1 and 2). In total, 46 listed chemicals or groups are included for analysis, while the other 8 are excluded due to a lack of dedicated Harmonized System (HS) codes for the trade classification and records; for more details on the chemicals, see Supplementary Tables 3 and 4 and Methods. For individual chemicals, the starting time of analysis depends on the time when the dedicated HS code was assigned.

We first develop and use a workflow of analysing 79,194 trade records in total from the UN Comtrade database to understand the global trade. To address known data-quality issues in the database<sup>23</sup>, this workflow integrates an outlier analysis using clustering and statistical methods to identify erroneous trade records and a subsequent mirror analysis to reconcile asymmetric bilateral transactions, leading to 66,156 records after data treatment. Some previous studies conducted additional data treatment techniques such as extrapolating missing values by using estimated unit price<sup>23,24</sup> and applying weighted-average methods or statistical treatment for a mirror analysis<sup>21,25,26</sup>. These additional techniques are not applied in this study, because we wanted to keep as much of the raw data from the UN Comtrade database as

possible and to avoid more arbitrary estimations and uncertainties/errors that these techniques may introduce to the datasets.

We then look into 'illegal trade', but only those flows among parties to the Convention. In other words, a trade is determined as illegal only when both trade countries are parties to the Convention and when the trade occurs after the importing country has explicitly provided the import response of not allowing such import.

By taking these conservative approaches, this study provides a minimum scenario of the global trade and illegal trade of 46 highly hazardous chemicals listed under the Convention. On the basis of the global overview, we shed light on the impacts of the Convention on the global trade of hazardous chemicals and provide insights on potential areas for improvement.

## Results

### Continuing large-scale global trade of hazardous chemicals

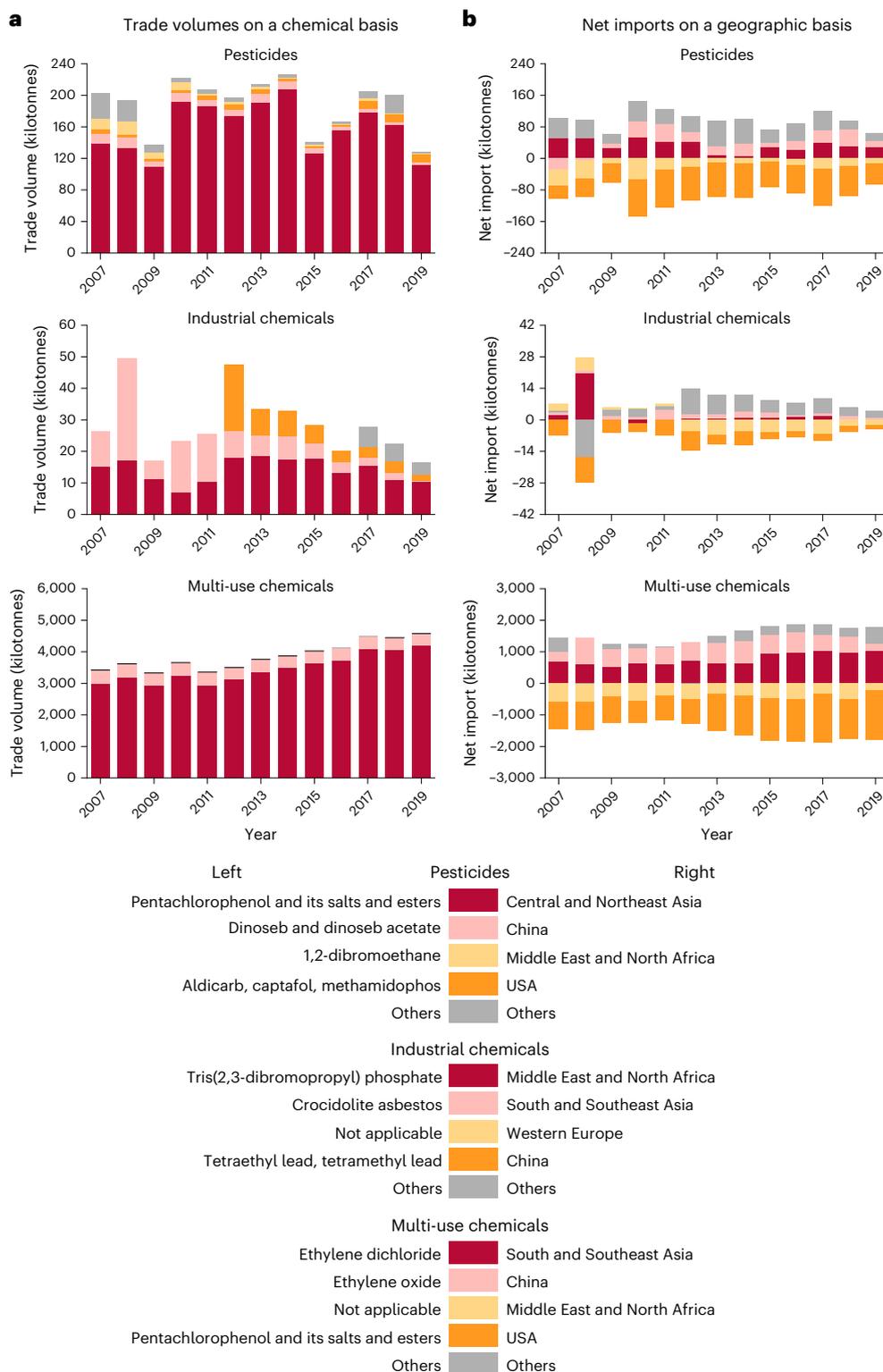
The cumulative global trade of the 46 listed chemicals among all countries (including non-parties to the Convention) reached 64.5 megatonnes in 2004–2019, contributed mainly by ethylene dichloride (55.3 megatonnes) and ethylene oxide (6.3 megatonnes). The highly hazardous pesticides and formulations had lower trade volumes (2.4 megatonnes), dominated by pentachlorophenol and its salts and esters. This echoes the previous understanding that transboundary movements of highly hazardous chemicals still widely take place despite the PIC procedure<sup>12</sup>. It is an especially pressing problem for developing countries and countries with economies in transition<sup>8</sup>; for examples, see the net importing countries in Fig. 1. The influences from the recent addition of new chemicals and parties can be neglected, since only three countries ratified and six chemicals were added after 2015, with very low trade volumes (0.11 megatonnes).

Over the period, the total annual trade has been constantly ascending, mainly due to ethylene dichloride (Fig. 1a). Individually, the trade of many chemicals has seen a slight decrease in recent years (Extended Data Figs. 1 and 2). However, to our surprise, some well-known, largely banned legacy chemicals (Fig. 2) are still being traded in substantial amounts on the global markets.

Tetraethyl and tetramethyl lead are known as notorious anti-knock additives in gasoline, mainly for vehicles. Owing to their harm to people of all ages with no known safe levels, they have been banned since the 1990s–2000s in most countries<sup>27</sup>. By 2011, leaded gasoline was used in only a few countries such as Algeria, Iraq and Yemen, and in July 2021, the UN Environment Programme announced the final termination around the globe<sup>28</sup>. The trade volume in 2019 was ten times lower than that in 2012 (Fig. 2). Surprisingly, however, several thousand tonnes were still traded in 2019. This is probably due to their continued use in fuel for aircraft, farm equipments and high-performance competition vehicles<sup>29,30</sup>.

Tributyltin compounds (TBTs) became infamous for their use as biocides in anti-fouling paints. Owing to high toxicity to marine organisms, they have been banned internationally in anti-fouling systems on ships since 2008<sup>31</sup>. They also are persistent in the environment, can accumulate in biota and are immunotoxic, causing reduced resistance to infection, and they have an estimated no-observed-adverse-effect level of 0.025 mg per kg body weight per day<sup>27</sup>. They were listed under the Rotterdam Convention as non-agricultural pesticides in 2009 and as industrial chemicals in 2017<sup>16</sup>. Despite these international efforts, the global trade of TBTs has taken place at a constant pace of over 4.5 kilotonnes per annum since 2012. This could be partially caused by continued, illegal uses in anti-fouling systems on ships, which is in line with recent field measurements on coastal sites in many regions where fresh inputs of banned TBTs have been reported<sup>32–34</sup>. This could also partially result from other continued widespread uses such as material and wood preservatives or as a slimicide<sup>35</sup>.

Tris(2,3-dibromopropyl) phosphate, an organophosphorus flame retardant, has been phased out from textiles that may have skin contact

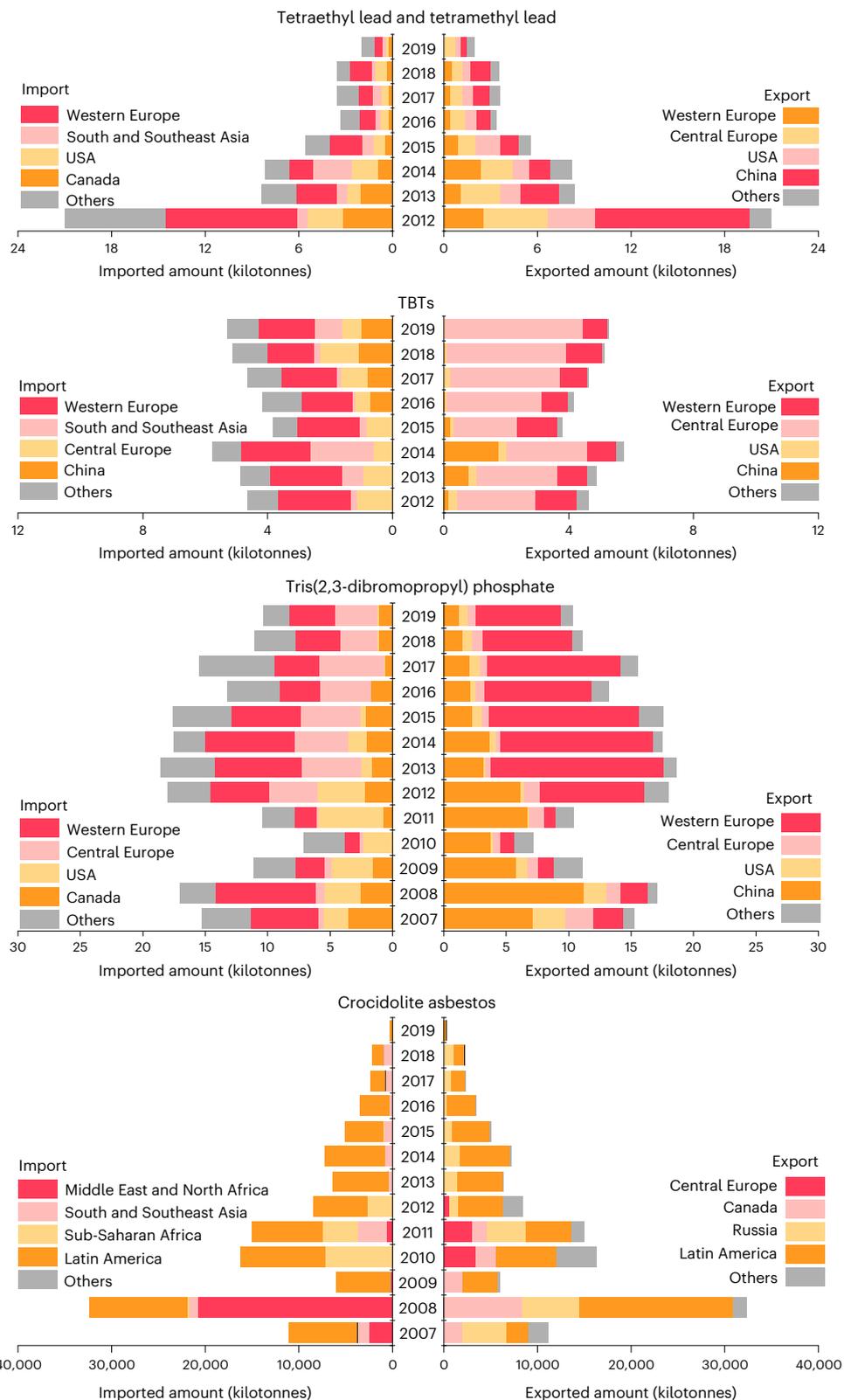


**Fig. 1 | Time trends of the global trade of the 46 highly hazardous chemicals analysed in this study among all countries. a, b,** Trade volumes by chemical (a) and net imports by geographic region (b) of highly hazardous chemicals. Net import = import – export. Note that only the top four (or three) chemicals or regions/countries are shown; others are all grouped into ‘others’. The data

between 2004 and 2006 are not shown here because large parts of the global trade of the listed chemicals during this period were not recorded (or were separately recorded) in the UN Comtrade database, but they are included in the estimated total global trade reported in the main text.

since the 1970s due to its suspected carcinogenicity to humans<sup>36</sup>. However, an average volume of 14 kilotonnes was still traded annually between 2007 and 2019. Ongoing uses in, for example, automobiles

and aircraft interior parts, polystyrene foam, acrylic carpets and sheets, polyvinyl and phenolic resins, and styrene–butadiene rubber may explain these continuous trade flows to some extent.

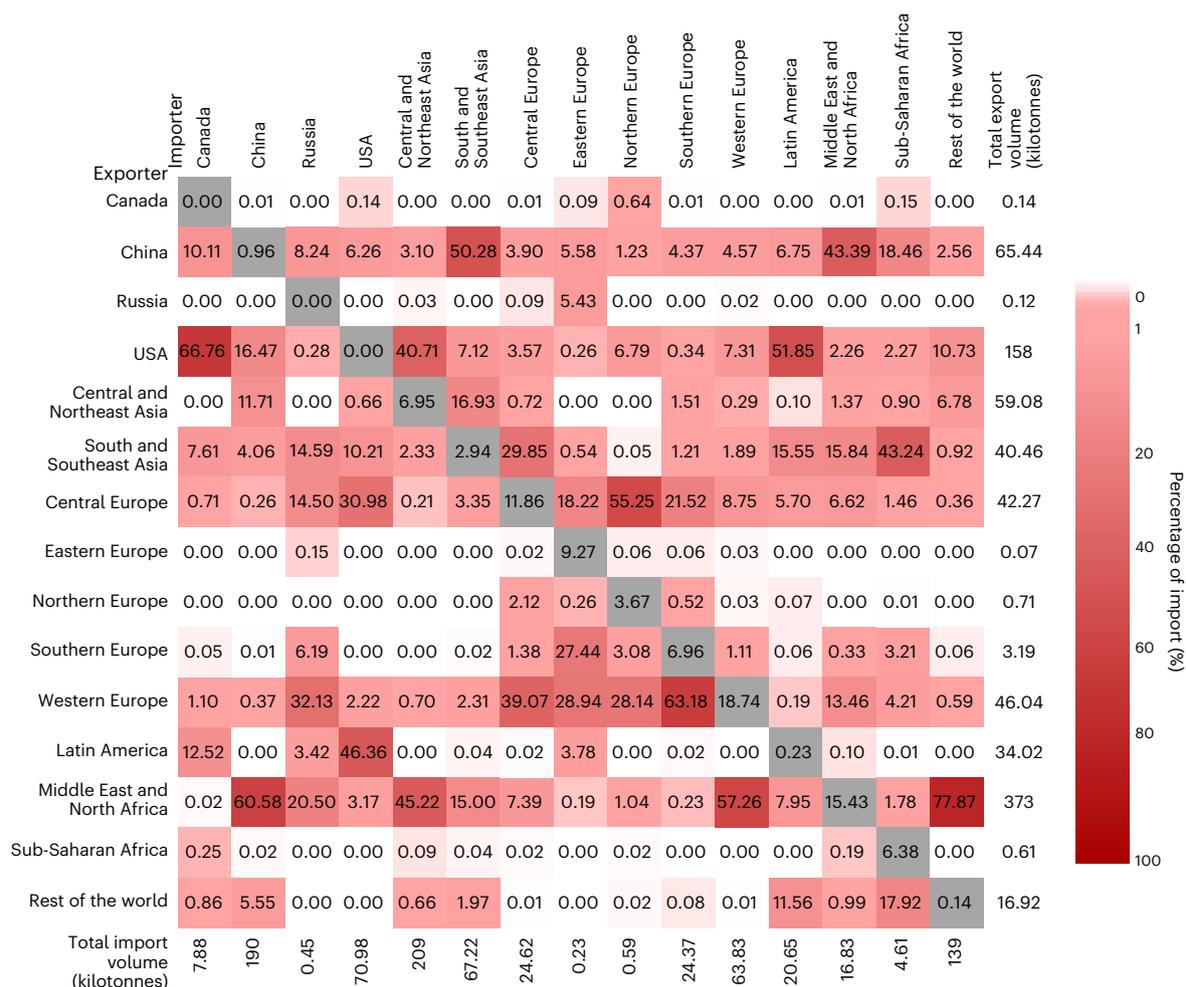


**Fig. 2 | Time trends of the import and export quantities of four examples of well-known highly hazardous chemicals listed under the Rotterdam Convention.** Note that only the top four regions/countries are shown; others are

all grouped into 'others'. The starting year on the y axis for each chemical is the year when the chemical started being recorded with the dedicated HS code in the UN Comtrade database.

The trade of these three highly hazardous chemicals or groups is mainly attributed to the USA, Western Europe, Central Europe, Canada (import) and China (export). Future work may focus on understanding

and addressing the supply and/or demand of these chemicals in these regions or countries to minimize the trade and thus the ongoing releases and potential threats to the environment and human health<sup>37</sup>.



**Fig. 3 | Global trade of highly hazardous pesticides among all countries in the 15 regions in 2015–2019.** Each cell represents the respective import percentage, with the sum of the cells in each column equalling 100%. The grey cells show the import within the defined regions (including the trade within China among mainland, Hong Kong and Macao).

‘Asbestos’ is the generic term for six fibrous silicate minerals that have been commonly used for building settings such as cement sheeting, brake lining and electrical millboard<sup>1</sup>. Although all six varieties of asbestos are proven carcinogenic, only five have been listed under the Rotterdam Convention since 2004. Chrysotile asbestos, which accounts for 90–95% of the global asbestos production, is still being debated for listing (since 2006)<sup>1</sup>. Currently, the same HS code is assigned for actinolite, anthophyllite, amosite, chrysotile and tremolite, while crocidolite has its own HS code. The crocidolite trade shows a clear declining tendency (for example, about 0.3 kilotonnes in 2019, which is 2% of the trade volume in 2010; Fig. 2), implying a positive impact of listing under the Convention. By contrast, a relatively constant trend after 2013 (an annual trade of around 1 megatonnes; Extended Data Fig. 2) was observed for the other five varieties, with chrysotile being dominant, which further calls for the long-awaited listing of chrysotile under the Convention.

### Complex geographical distributions of the global trade

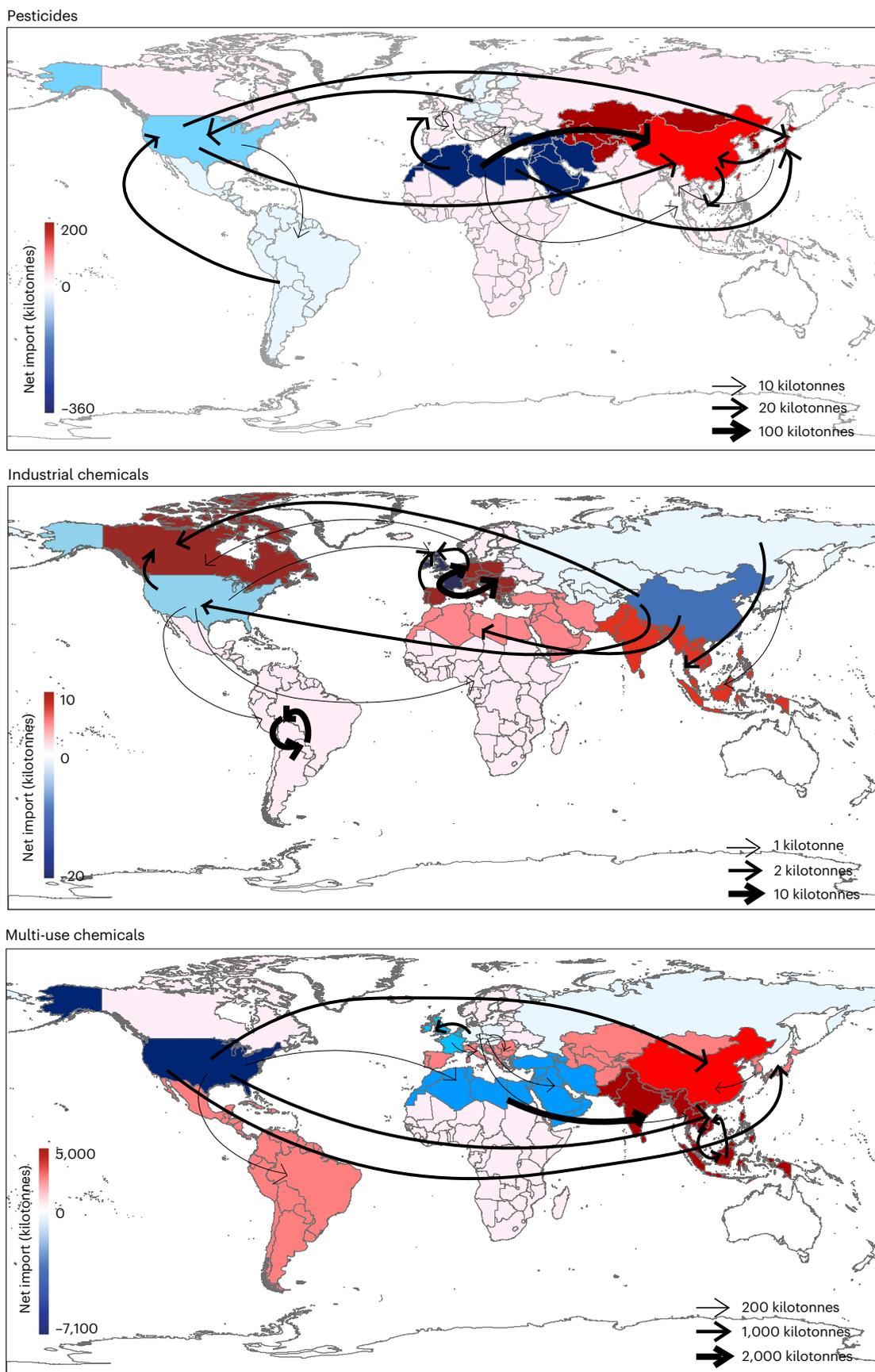
An analysis of trade relationships among all countries in the 15 defined regions in 2015–2019 found that most of Asia were the major importers of pesticides and multi-use chemicals, while the USA and Middle East were the major exporters of these two types of chemical (Figs. 1b, 3 and 4 and Extended Data Figs. 3 and 4). For instance, biocide pentachlorophenol and its salts and esters and the insecticide 1,2-dibromoethane

were both mainly exported from Israel and Jordan to Asian countries (Supplementary Fig. 1). Central and Western Europe were not only major importers but also big exporters of industrial and multi-use chemicals. Germany was the biggest exporter of TBTs—mainly imported by other Western European countries (for example, Belgium and the UK), China and the USA—and also various pesticides and ethylene oxide (Supplementary Figs. 1–3). More detailed origin–destination pairs and the percentage of regional contributions for individual chemicals are provided in Supplementary Figs. 1–7 and Supplementary Text 1.

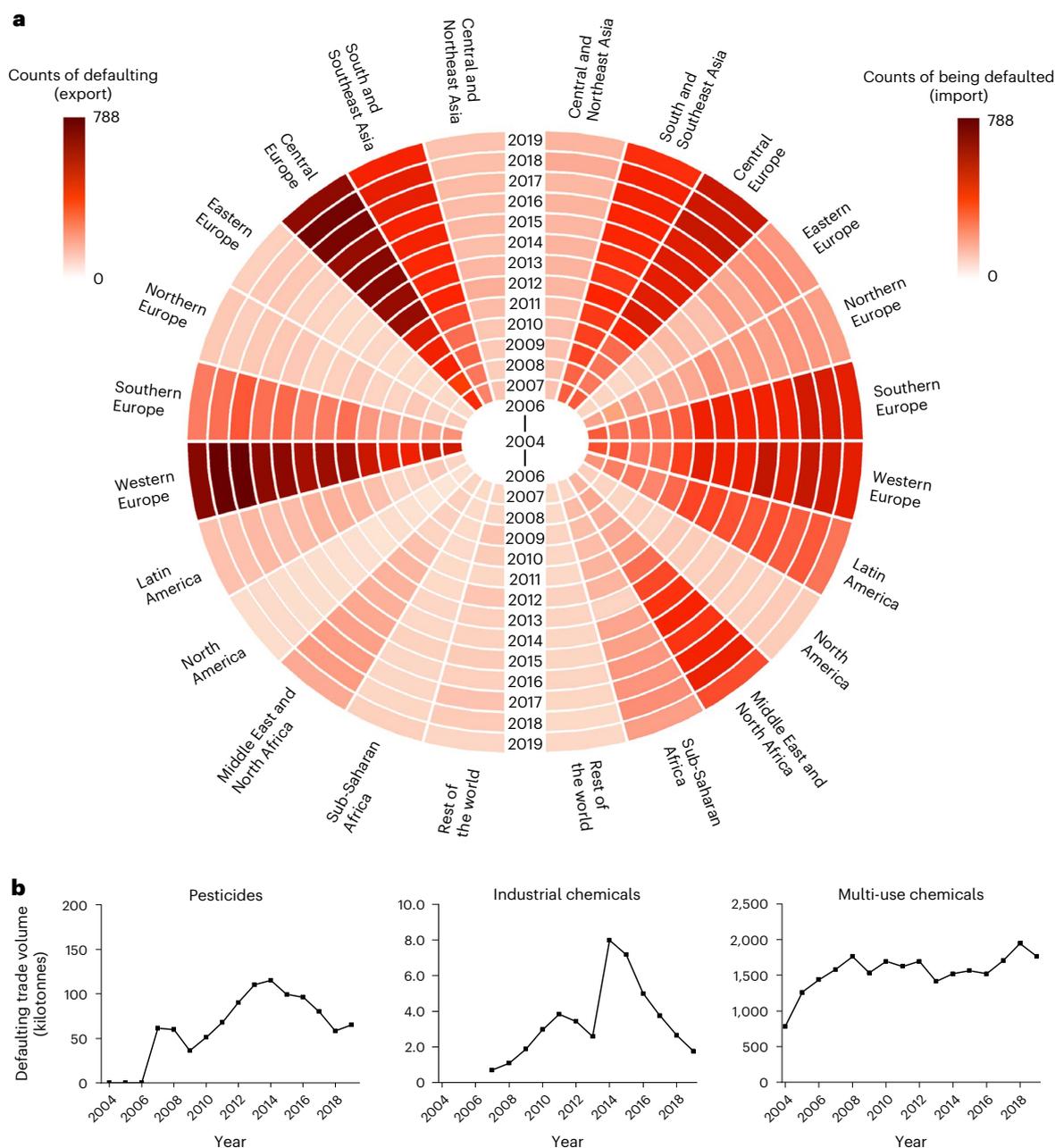
As one major source of international trade, the USA exported about 158 kilotonnes of the listed pesticides and 7 megatonnes of the listed multi-use chemicals (mainly ethylene dichloride) to Asian countries in 2015–2019. Meanwhile, it also imported 71 kilotonnes of pesticides from Central Europe and Latin America and several kilotonnes of multi-use chemicals (mainly ethylene dichloride). Detailed global trade flows related to specific countries or regions (China, the USA, the EU, Canada and Russia) are presented in Supplementary Fig. 8 and discussed in Supplementary Text 2. No consistent patterns of trade among OECD and non-OECD countries were observed across all three types of listed chemical (Supplementary Figs. 9 and 10 and Supplementary Text 3).

### Prevalent illegal trade of hazardous chemicals

As stated above, under the Rotterdam Convention, if a party confirms their import response as ‘no consent’ for the import of a chemical, then



**Fig. 4 | Global transfer of the listed highly hazardous chemicals.** The map of global transfer with net imports of the 46 highly hazardous chemicals in the 15 regions in 2015–2019. Credit: basemap, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences.



**Fig. 5 | Defaulting summary of the listed highly hazardous chemicals analysed in this study. a,** Defaulting counts of the trade for exporting parties and counts of being defaulted for importing parties. **b,** Time trends of defaulting trade volume. Note that the defaulting analysis was performed only for the listed chemicals having their own HS codes in the 12 defined regions (excluding

the non-party USA and with China, Russia and Canada grouped into their corresponding regions) in 2004–2019. If one hazardous chemical with no import consent registered is imported or exported once by a given party country, it is counted as 1. Note that the counts of defaulting between 2004 and 2006 are not shown here because the grids are too small to be distinguished.

trade of the chemical from an exporting party shall not take place. Trade of the listed chemicals among parties despite the import response of ‘no consent’ is considered illegal—that is, defaulting on the party’s legal obligations under the Convention. The defaulting counts of exporting the listed chemicals in individual regions between 2004 and 2019 are visualized in Fig. 5a. The counts of being defaulted are also presented for importers; these are probably due to domestic reasons such as weak awareness of chemical risks and inadequate customs supervision.

Surprisingly, as shown in Fig. 5a, the defaulting phenomenon was prevalent all over the world, especially in Central, Western and Southern Europe, South and Southeast Asia, and the Middle East. In total, 25,328 of the total 48,342 records with HS codes for specific individual

chemicals were on default, which accounted for 40% of the total trade volume (that is, 25.7 of 64.5 megatonnes), underlining the insufficient effectiveness of the Convention.

This does not mean that the remaining 23,014 trade records were all legal. In fact, the defaulting problem was even worse than we present here, since those HS codes containing more than one chemical are excluded from our defaulting analysis.

Furthermore, given that the USA is not a party to the Convention, its export to a party with an import response of ‘no consent’ is not counted in our illegal-trade analysis (more elaborations are provided in the Discussion). Our separate analysis shows that about 122 kilotonnes of the listed pesticides and 3,989 kilotonnes of the listed multi-use

chemicals were traded from the USA to parties to the Convention with import responses of 'no consent' (Supplementary Figs. 11–13). The legal status of these trades, subject to the domestic legislation of the importing countries, is not analysed here but may be an interesting area for future research.

The defaulting counts are seemingly on the rise over time. Several reasons, or a combination of them, may have contributed to this observation, including (1) defaults were on the rise, (2) more submissions of trade information from each country or region took place over time, and (3) specific HS codes were only recently assigned to some of the listed hazardous chemicals, leading to more records in the UN Comtrade database in recent years, and the early use of non-specific HS codes hampers identifying illegal trade of the chemicals in the data from early years.

The time series of defaulting trade volume show a decreasing trend after 2014 for pesticides and industrial chemicals but keep a high value (over 1.5 megatonnes) for multi-use chemicals (Fig. 5b). Closer monitoring and investigation of the defaulting phenomena over time in future studies is warranted. The detailed interregional relationships and global transfer of illegal trade are shown in Extended Data Fig. 5 and Supplementary Figs. 11–13.

Much of the illegal trade has occurred across borders with poor controls<sup>8</sup>. As reported by the UN Environment Programme, Brazil and its neighbouring countries are hotspots of illegal traders of pesticides<sup>8</sup>; this was found to also be the case for industrial chemicals in this study (accounting for over 60% of the identified illegal trade volume of industrial chemicals).

Even for developed countries, controlling and supervising the illegal trade can be challenging. In 2014, the EU enforced the PIC Regulation as means to implement the Rotterdam Convention within the EU, which supervises both the export to non-EU countries and the import into the EU<sup>8,38</sup>. This has allowed for more detailed analysis of the defaulting situation in the EU (Extended Data Fig. 6). Interestingly, the data available under the EU PIC Regulation point out even worse export defaulting problems by the EU member states, with 4,601 more counts of defaulting reported under the EU PIC Regulation than what can be seen from our analysis of the UN Comtrade database above. This discrepancy encouragingly indicates more stringent reporting within the EU than that under the Rotterdam Convention and according to the UN Comtrade database; however, the PIC Regulation did not stop illegal trade.

Furthermore, some chemicals analysed are also listed under the Stockholm Convention on Persistent Organic Pollutants (Supplementary Table 5), which also entered into force in 2004 with broader legal obligations than those under the Rotterdam Convention<sup>39</sup>. Surprisingly, some of the highly hazardous pesticides such as aldrin, chlordane, heptachlor and dieldrin, which have been listed under the Stockholm Convention since 2004 for global elimination without any exceptions<sup>16</sup>, were still being traded (albeit at low volumes). In addition, imports by Italy, Hungary, Slovenia and Spain have been the main registered trades of endosulfan (mainly used for pest control in crop production such as cotton and tobacco<sup>40</sup>) since 2017, but these EU member states have not requested any exemptions under the Stockholm Convention and should be covered by EU trade and use rules<sup>40</sup>.

Pentachlorophenol and its salts and esters were added to the Stockholm Convention in 2015 for global elimination, except for production and use for utility poles and cross-arms that shall be easily identified by labelling or other means throughout their life cycles<sup>41</sup>. Only Mexico registered for the exception, noting that 99.98% of its 6.8 kilotonnes of annual production were exported to the USA; this exception expired in December 2021<sup>42</sup>. However, large exports from Israel, Jordan and the USA to Asian countries (for example, China, South Korea, Thailand and Japan) were reported, over twice the amount of the reported exports from Mexico to the USA. This indicates some misconduct or limitations in the registration and supervision of production

and trade of pentachlorophenol and its salts and esters under the Stockholm Convention.

### Error analysis and reconciling of global trade data

Data quality can be an often-overlooked bottleneck when using the UN Comtrade database, as the accuracy of individual data entries depends on the reporting country<sup>23,43</sup>. Importantly, erroneous reporting of trade volumes (for example, due to overinvoicing, underinvoicing or mislabelling<sup>8,11,44</sup>) has been observed. For instance, as the major producer of perfluorooctane sulfonic acid (PFOS) and its salts in the past decade or two, China had a total production capacity of less than 250 tonnes per year<sup>37</sup>, but the export record of ammonium PFOS from Kuwait in 2018 was about 10.5 kilotonnes, which cannot be true. Similarly, odd peaks appeared in the trade of several other chemicals such as alachlor, endosulfan, and tetraethyl and tetramethyl lead (Extended Data Figs. 1 and 2). Another key issue is that the corresponding import and export records often do not match with each other for one reason or another<sup>43</sup>, including missing trade records from some countries or regions.

Using our integrated workflow of processing and analysing trade data from the UN Comtrade database, we identified 13,038 probably erroneous import/export records (out of 79,194 original records), representing 1.2% of the original total trade volume (Supplementary Tables 6 and 7). The distribution of these probably erroneous data is presented in Extended Data Fig. 7, mainly attributed to alachlor, ethylene dichloride, ethylene oxide, and pentachlorophenol and its salts and esters. Geographically, they were largely reported by South and Southeast Asia, Central and Western Europe, the USA, and the Middle East. In addition, our analysis found that nearly 10,000 trade records (out of 66,156 records after treatment by the error analysis) were missing, particularly for exports; these missing records were then filled in using mirror analysis.

## Discussion

### A minimum scenario of global trade and illegal trade

Encouragingly, over 70% of the highly hazardous chemicals listed under the Rotterdam Convention show a decreasing trend in global trade (Extended Data Figs. 1 and 2), reflecting some positive impacts of the Convention. Meanwhile, an increasing trend can still be observed for other chemicals such as ethylene dichloride and TBTs. In addition, illegal trades that violate the import responses submitted by parties to the Convention are globally prevalent. Among them, some countries export chemicals that are banned or restricted in their own territories to other countries<sup>8</sup>. Others allow temporary registration of pesticides for testing purposes with no quantity limits and no developed control systems, which might promote more consumption and further encourage their import, as noted elsewhere<sup>8</sup>.

It should be further noted that the analysis of 'illegal trade' in this study could not consider two important types of illegal trade. First, strictly speaking, when a country makes an import decision of 'no consent', the country shall stop imports from non-parties as well. However, this process is done through domestic legislation without public reporting requirements under the Rotterdam Convention. As it is a formidable task to compile domestic legislation around the world, this type of illegal trade between parties and non-parties to the Convention could not be identified in this study. Second, in addition to trade with records, illegal trade can occur in the form of smuggling, mislabelling or black markets. Such illegal trade of mercury has been demonstrated to exist widely, especially in Asia and Central and South America<sup>11,45,46</sup>, raising concerns and calling for more effective enforcement of the Minamata Convention. Currently, information on this type of illegal trade remains sparse for most chemicals<sup>8</sup>. Here we used a conservative approach, without accounting for illegal trade between parties and non-parties or for illegal smuggling. The actual global trade of highly hazardous chemicals, especially illegal trade, is even larger.

## Tackling the global trade of highly hazardous chemicals

Hence, while the Rotterdam Convention is playing a positive role, more concerted efforts are still needed to address the continuous, large global trade of highly hazardous chemicals to protect human health and the environment, particularly the prevalent illegal trade. We highlight the following several aspects in the global, regional and national contexts for consideration.

At the global level, the Rotterdam Convention's geographical coverage needs to be expanded by inviting and encouraging non-parties to ratify the Convention towards universal membership, along with three additional actions to strengthen the Convention's implementation. First, learning from the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, parties to the Rotterdam Convention may be required to strengthen the supervision of either export out of or import into their countries by ascertaining compliance with corresponding import responses. Some penalty strategies, such as imposing criminal penalties on all persons involved in illegal trade, might be useful to ensure effectiveness, as further discussed in ref. 8.

Second, further efforts are needed to enable swifter listing of chemicals under the Rotterdam Convention such as well-known chrysotile asbestos and paraquat. Recently, multiple parties have proposed to modify the Convention to address those chemicals that have been recommended by the Convention's Chemicals Review Committee for listing but have not been listed under the Convention due to a lack of unanimous agreement<sup>47</sup>. This amendment proposal brings in new perspectives of possible solutions by allowing those countries in the position to take concerted action to address such chemicals; it thus should be supported and further developed by parties to the Convention.

Third, while our workflow enables better processing and analysis of trade data, data availability, quality and accessibility need to be further improved to allow for better monitoring and understanding the global trade flows of highly hazardous chemicals over time, including understanding and addressing the causes of erroneous reporting. This will also help a better understanding of smuggling, false declaration and the black market; of cases when a party does not publicly announce its import response; and of the global trade of other commodities such as plastic wastes, which is critical for implementing the Basel Convention and monitoring its effectiveness.

At the regional and national levels, the roles of developed countries in reducing their exports of highly hazardous chemicals to less-developed ones, particularly illegal trade, need to be strengthened. Ongoing large usage of highly hazardous chemicals in Asian and Latin American countries also calls for further measures at both domestic and regional levels (for details on uses, see Supplementary Table 1). In addition, as used in the Stockholm and Basel Conventions, regional centres might be an option for strengthening intercountry cooperation<sup>10,48</sup>. Synergies and coordination with other international treaties to facilitate more harmonized policymaking should also be noted, as addressed by Selin<sup>48</sup>.

Furthermore, national policies need to understand and address the lock-in of hazardous chemicals<sup>37</sup>, increase awareness of hazardous chemicals, promote safer alternatives, encourage collaborations among stakeholders, improve customs capacities, and impose warnings on the consequences of illegal trade<sup>8,10</sup>. It is time to take urgent action on the global trade of highly hazardous chemicals, particularly illegal ones.

## Methods

### Chemical scope of the study

The chemicals included in this study are the highly hazardous chemicals listed under the Rotterdam Convention with dedicated HS codes according to the Harmonized Commodity Description and Coding Systems, an international nomenclature system for product classification. By 2019, 52 chemicals or groups were listed under the Convention.

They were classified into three categories based on their uses (Supplementary Table 3)—that is, pesticides, industrial chemicals and multi-use chemicals (for both pesticidal and industrial uses). Several chemicals (such as carbofuran, toxaphene, trichlorfon and short-chain chlorinated paraffins) had no corresponding dedicated HS codes assigned yet and were therefore excluded from the trade analysis. The assigned HS codes of some chemicals included a broad group of chemicals—for example, the code 2909.30 includes aromatic ethers and their halogenated, sulphonated, nitrated or nitrosated derivatives rather than only tetra- to hepta-bromodiphenyl ether, and 2903.99 includes a large range of halogenated derivatives of aromatic hydrocarbons rather than only octa- or deca-brominated biphenyls. As such, they were not suitable to accurately pinpoint trade flows of the chemicals of interest in this study and were excluded from the analysis. Hence, a total of 46 chemicals or groups listed under the Rotterdam Convention were included in the trade analysis. Asbestos with the HS code 2524.90 was separately considered since chrysotile (one of the asbestos varieties under the same HS code) was not yet listed under the Rotterdam Convention.

### Global historical trade data

The global trade data were retrieved from the UN Comtrade database, which is the largest data pool of international trade flow and is continuously updated (<https://comtrade.un.org/data>). Since 1962, over 170 countries/regions have reported their trade statistics to the UN Statistics Division, detailed by quantity, value (in US dollars) and partner countries/regions. The trade data in the Comtrade database are organized by HS codes.

The HS was established by the UN in 1988 and has undergone several changes over time. For the same product, different HS versions (that is, 2002, 2007, 2012, 2017 and 2019; Supplementary Table 3) since the date of entry into force of the Rotterdam Convention were considered.

In this study, the global trade analysis of highly hazardous chemicals listed under the Convention covered the data from 2004 to 2019. The data before 2004 were not included, since many of the chemicals listed under the Convention did not have their own HS code assigned before 2004 and their trade was separately recorded in the UN Comtrade database only later on. All registered trade of all chemicals (including newly listed ones; Supplementary Table 1) from all countries (Supplementary Table 2) over time was integrated.

The trade data recorded in the UN Comtrade database include not only import/export data but also re-import/re-export data (for example, exported goods may be returned to the countries of origin without further processing if they have the following problems: being defective, being defaulted on payments or cancelled by the importer, being imposed an import barrier by the importer, or being worthwhile to bring back in the context of demand or prices in the countries of origin<sup>49</sup>). Between 2004 and 2019, re-imports and re-exports contributed to 0.058% and 0.064% of all global imports and exports, respectively, which were close to the lower end of the percentages estimated for the trade of plastic waste (0.02–9.3%) by UNEP<sup>27</sup>. In this study, these re-imports/re-exports were subtracted from the global trade data.

Considering the geographical categories from the UN and the World Bank as well as the important roles of specific countries including China, the USA, Russia and Canada, countries around the world were divided into 15 countries or regions to facilitate the analysis of trade flows between these countries or regions, as illustrated in Extended Data Fig. 8 and Supplementary Table 8. For example, while the EU member states follow the same trade rules within the EU, they were divided into different regions such as Central, Western and Southern Europe in the analysis, considering their different environmental conditions (which may affect pesticide uses) and economic development status (which may affect industrial chemical uses).

## Error analysis

The accuracy of data in the UN Comtrade database relies on the reporting countries<sup>45</sup>. In this study, outliers of the unit price were searched for to identify probably erroneous trade data, since the database has better supervision of market values than volumes. In other words, the over-reporting or under-reporting of trade volumes could be reflected by abnormally low or high unit prices, respectively. There are several methods commonly used for outlier analysis, such as the quartile method, *k*-means clustering and isolation forest<sup>50–52</sup>. Due to the data characteristics of unit price in this study (that is, no typical statistical patterns such as normal distribution, and lack of a big training dataset for machine learning), a combination of statistical (that is, quartile) and clustering analyses (that is, *k*-means clustering) was applied to identify the probably erroneous data.

Briefly, the database of unit prices was classified into different categories by doing variance analysis in SPSS v.22.0 (<https://www.ibm.com/support/pages/spss-statistics-220-available-download>) for inter-annual data. The unit price within each category was then quartered to find the lower outliers—that is, the higher outliers of trade volumes (over-reporting). The higher outliers of unit price (that is, the lower outliers of trade volumes or under-reporting) were identified by quartering the reciprocals of the unit price instead. In parallel, a *k*-means clustering analysis that groups the data according to the distance between a pair of objects was performed by using Python programming<sup>53</sup> (Python 3.9.9; <https://www.python.org/downloads/>), aiming to make a clustering of unit prices. The outliers of unit price picked out by the quartile method were then compared with the classification results realized by the *k*-means clustering method. If the lower outliers fell in the first half of the clusters where they overlapped, to be conservative, the data before this cluster were regarded as the final outliers—that is, the probably erroneous data. If the lower outliers fell in the second half, the data within and before this cluster were regarded as the final probably erroneous data. The higher outliers were treated in the opposite way. The detailed flow chart is shown in Extended Data Fig. 9. The reliability of our workflow was validated by analysing the identification of those odd records registered in the UN Comtrade database.

For PFOS and its salts, even after eliminating the probably erroneous data, there were still some large amounts traded annually since 2017, at the level of several thousand tonnes and mostly within Europe. This cannot be true for the reason described above. The remaining error is largely caused by the fact that after 2017 when PFOS and its salts started to be regulated under the Rotterdam Convention, only a limited number of trade records were reported. Therefore, PFOS and its salts were excluded from our final trade calculation.

## Data reconciling by mirror analysis

In principle, each bilateral trade flow should have the same value for import and export. However, this is not always the case in the UN Comtrade database. For instance, the imports of crocidolite asbestos from Brazil and Russia by the United Arab Emirates were recorded as 13.0 and 4.9 kilotonnes in 2008, respectively, but no corresponding exports were reported by Brazil or Russia. To get a consistent import-and-export database, we reconciled the trade data (after removing all probably erroneous data) by using mirror analysis (Extended Data Fig. 10). The processing logic is as follows: (1) when only the import or only the export record exists, fill the missing one by using the available one; and (2) when both import and export data exist and one number is higher, replace the lower one with the higher one. Finally, a combined and unified database was obtained where the import and export data are equal for further analysis<sup>53</sup>.

## Analysis of defaulting under the Rotterdam Convention

Article 10 of the Rotterdam Convention states the obligation of parties to make decisions on the import of the listed chemicals. The database of import responses submitted by the parties includes the time when

they began to ban the import of certain listed chemicals (<http://www.pic.int/Procedures/ImportResponses/Database/tabid/1370/language/en-US/Default.aspx>). Therein, if a trade record between two parties to the Convention existed in the UN Comtrade database after the import-ban year by the importing party, the exporting party was considered as the defaulting party that did not strictly administer the Convention according to Article 11. The importing party in this case was considered as being defaulted. The defaulting counts for exporters (or counts of being defaulted for importers) were then counted as 1 when one listed chemical with an import response of ‘no consent’ was traded once by a given party.

The EU PIC Regulation, operating since March 2014, implements the Convention within the EU and supervises both importers and exporters. In principle, the EU member states should report the information about their imports and exports, including substance names, destination countries and quantities (<https://echa.europa.eu/regulations/prior-informed-consent/annual-reporting-on-pic-exports-and-imports>). We further assessed the defaulting status by comparing the records in the PIC Regulation and the UN Comtrade database—that is, whether or not the trades between EU member states and other parties to the Convention registered in the UN Comtrade database appeared in the reported list of the PIC Regulation in the context of both reported countries and quantities. For one chemical reported under the PIC Regulation, since the origin and destination countries submitted contain more than one country, it is impossible to unscramble the specific bilateral transaction line among them. Thus, a trade from the UN Comtrade database with either side of bilateral countries that did not appear in the reports under the PIC Regulation was treated as a defaulting trade. For transactions that appeared in both the UN Comtrade database and the reports of the PIC Regulation, if the registered quantities in the former database were higher than the ones in the latter reports, the corresponding transactions were considered to be defaulting. In other words, the defaulting counts identified here were minimums, and the actual defaulting situation was worse.

The individual chemicals included in the default counting were those having their own HS codes, since it was not possible to trace back a default trade for one specific chemical using an HS code that contains more than one chemical. In addition, the analysis was based on the mirrored data after the error analysis, which represented the occurrence of trades more accurately.

## Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

## Data availability

All original data are publicly available online. The HS codes of the listed highly hazardous chemicals are available at <https://www.wcoomd.org/en/topics/nomenclature.aspx>. The trade data were retrieved from the UN Comtrade database and are available at <https://comtrade.un.org/data/>. The data after treatment for the final trade analysis are available in the Zenodo repository at <https://doi.org/10.5281/zenodo.7943211>. The ratification status of parties and import responses are available at <http://www.pic.int/>.

## Code availability

Python scripts (Python v.3.9.9) were used for the error analysis and mirror analysis in this study. The codes are available in the Zenodo repository at <https://doi.org/10.5281/zenodo.7943211>.

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## Author contributions

H.Z. and Z.W. led the project, conceptualized the study and supervised the work. T.W. collected the data, performed the calculations and did the visualization and programming. H.Z., Z.W. and Z.-L.W. were involved in writing and reviewing the manuscript.

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## Competing interests

The authors declare no competing interests.

## Additional information

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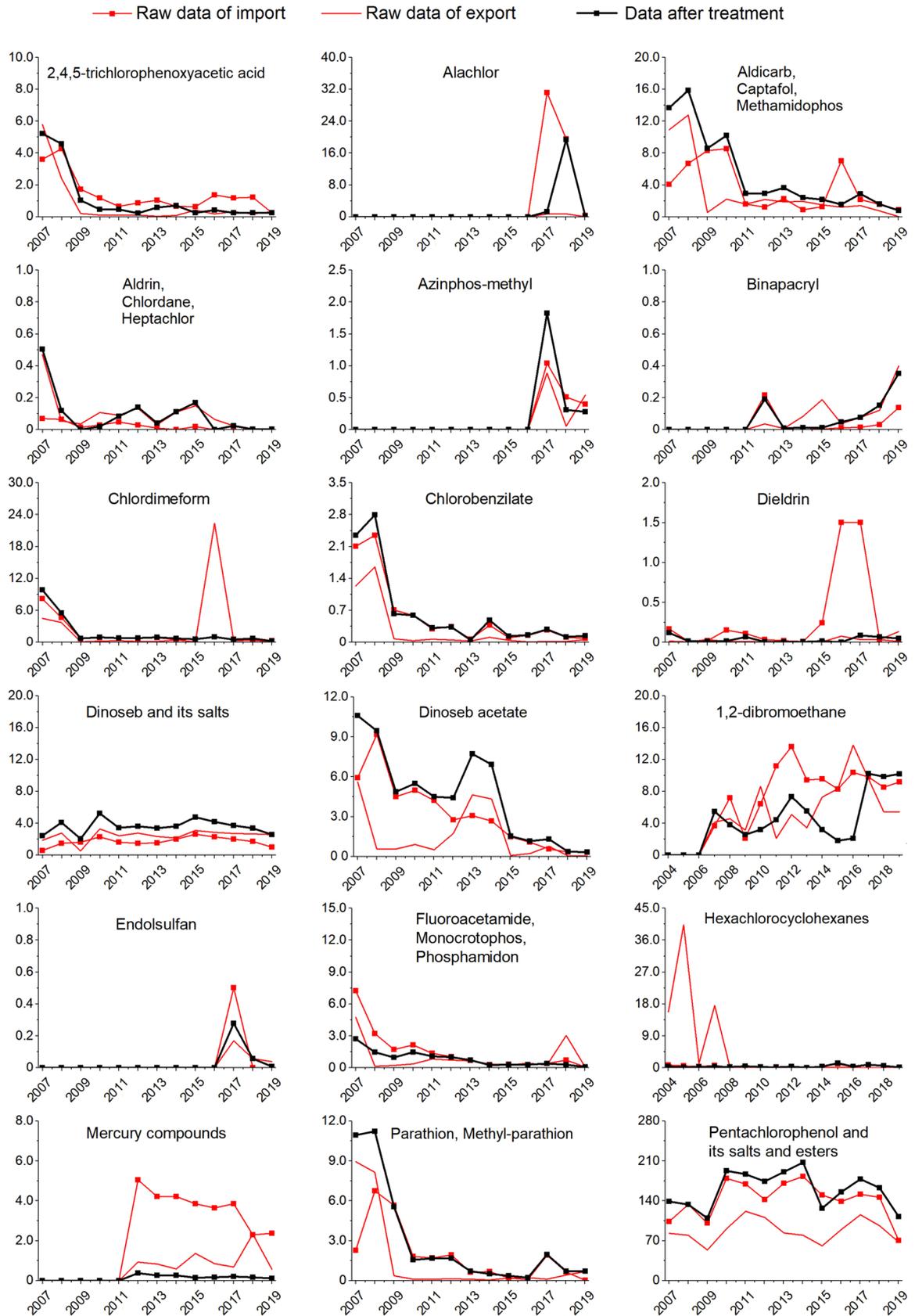
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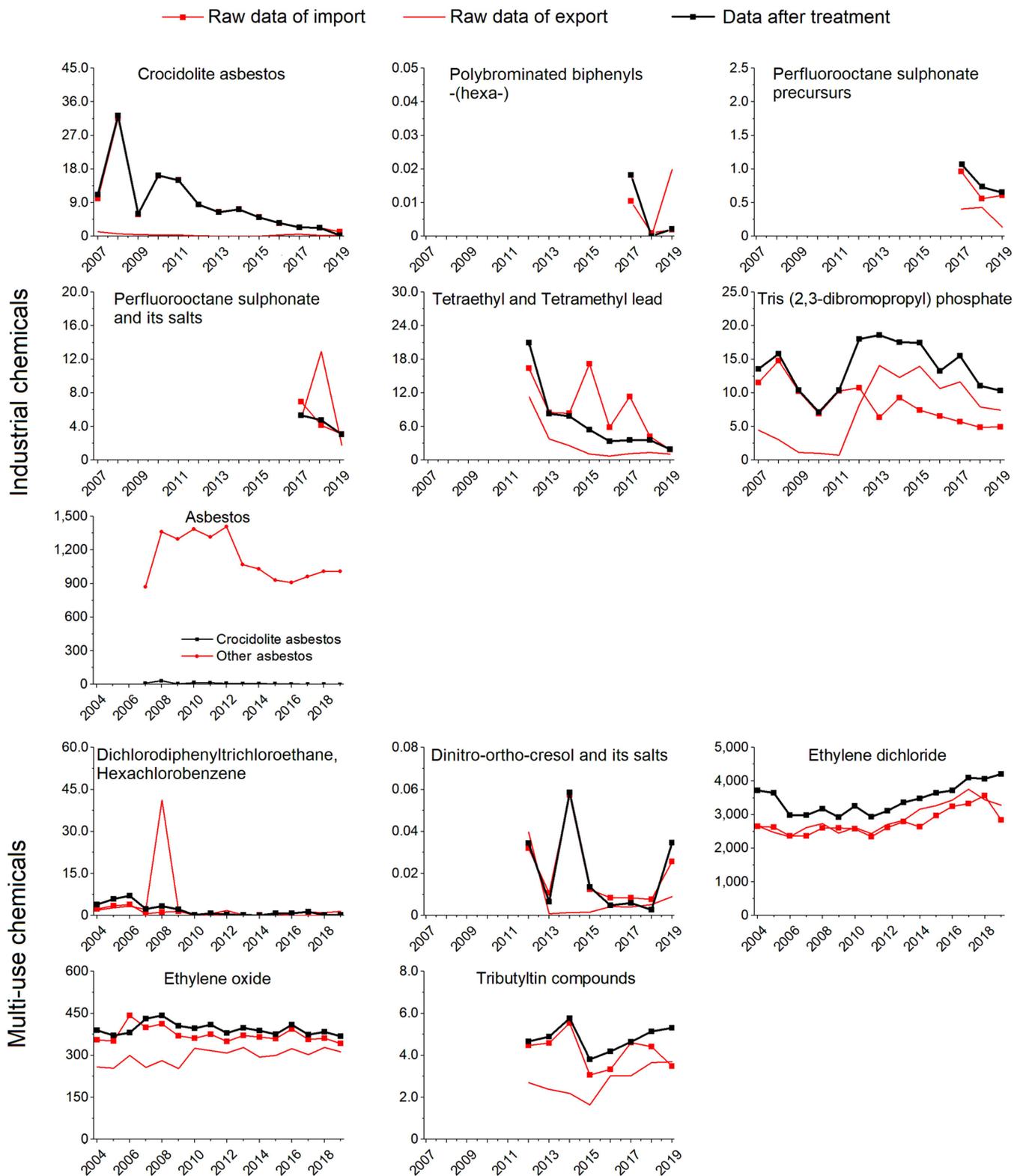
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Unit: kilotonnes

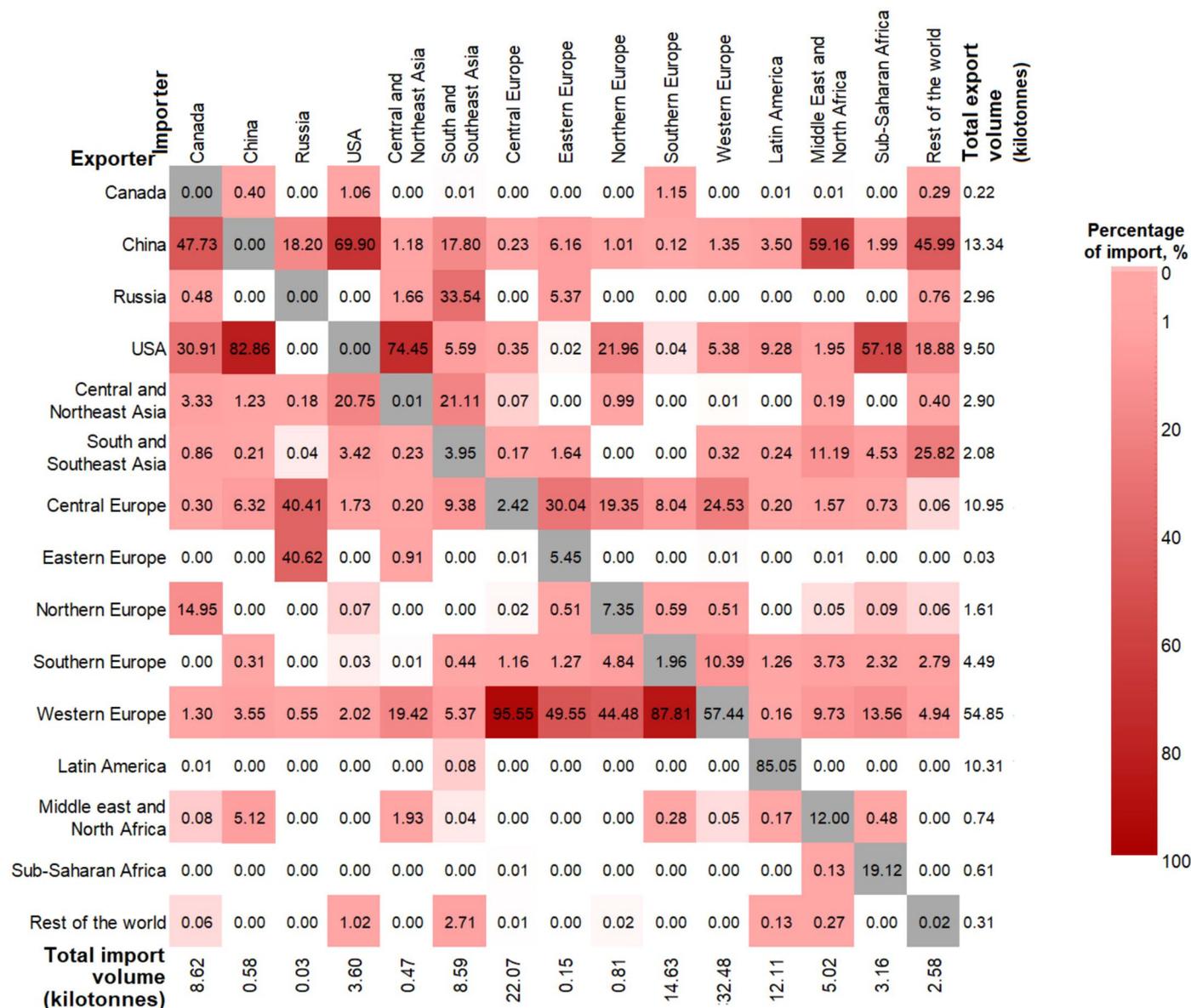


**Extended Data Fig. 1 | Time trends of the listed pesticides.** Time trends of trade quantities of individual pesticides before and after data treatment.

**Unit: kilotonnes**

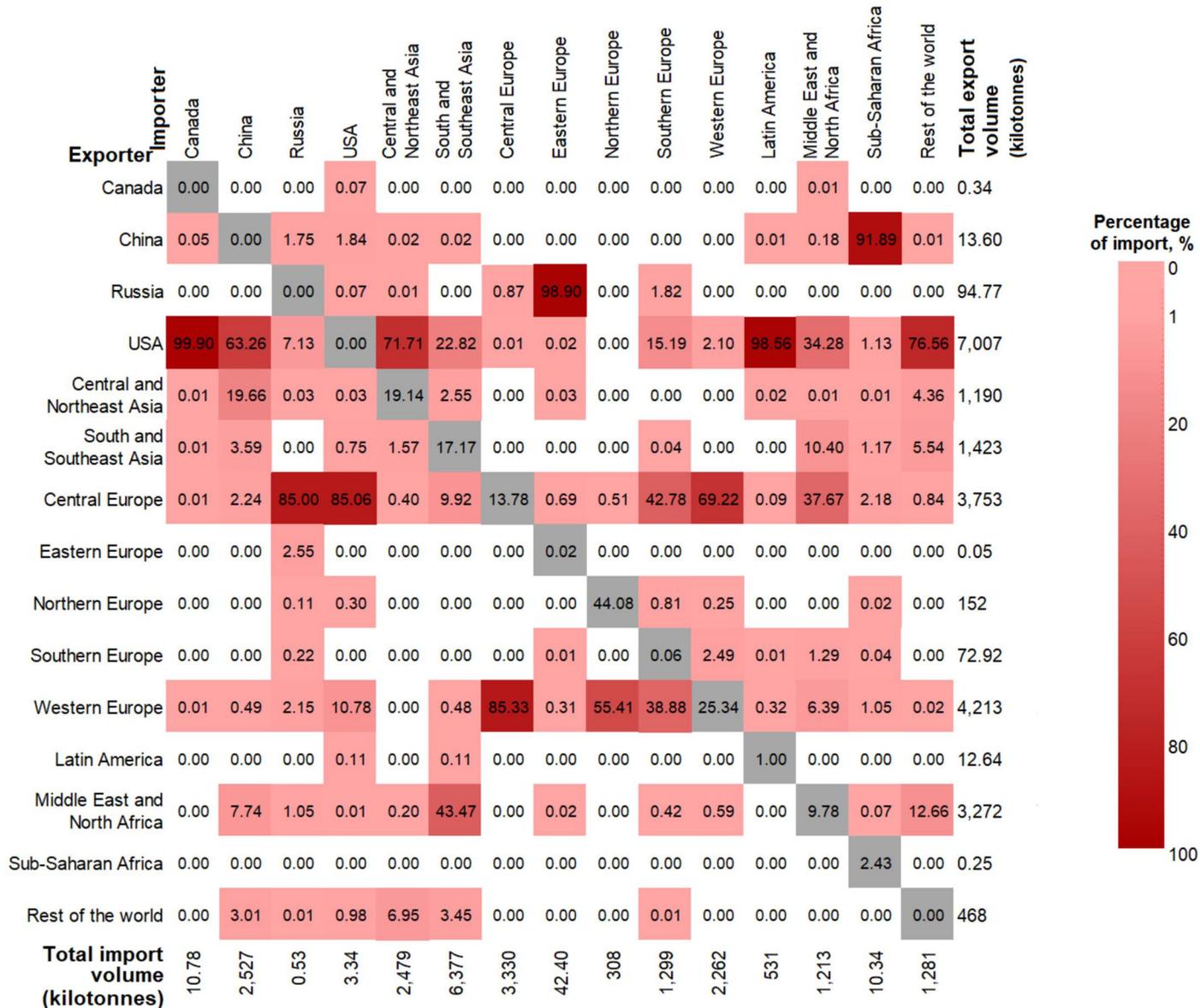


**Extended Data Fig. 2 | Time trends of the listed industrial and multi-use chemicals.** Time trends of trade quantities of individual industrial chemicals and multi-use chemicals before and after data treatment.



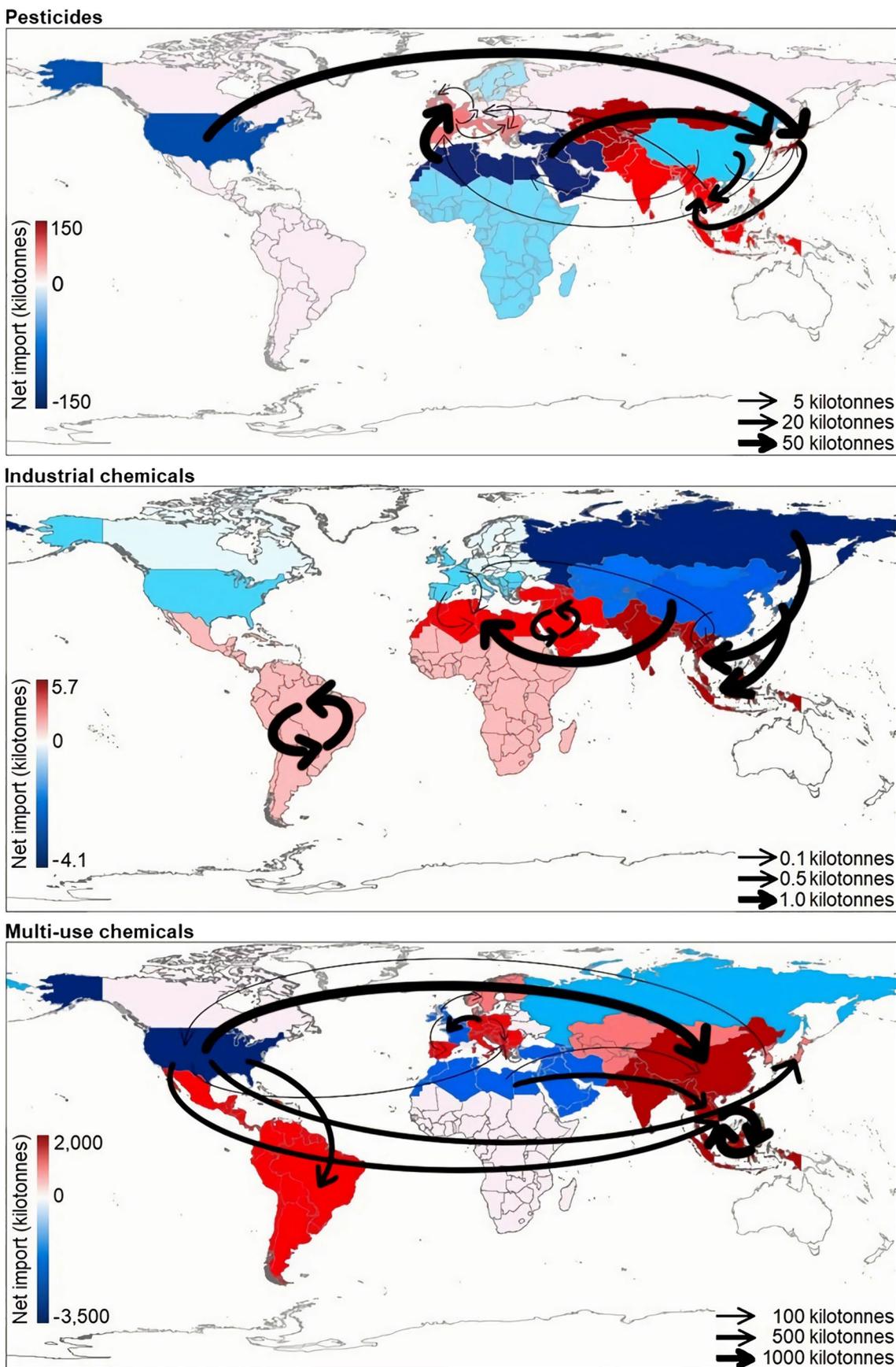
**Extended Data Fig. 3 | Interregional relationships of industrial chemical trade. Global trade of industrial chemicals among 15 regions during 2015–2019.** Each cell represents the respective import percentage, with the sum of the

cells in each column equaling to 100%. The grey cells mean the import within the defined regions (including the trade within China among mainland, Hongkong and Macao).

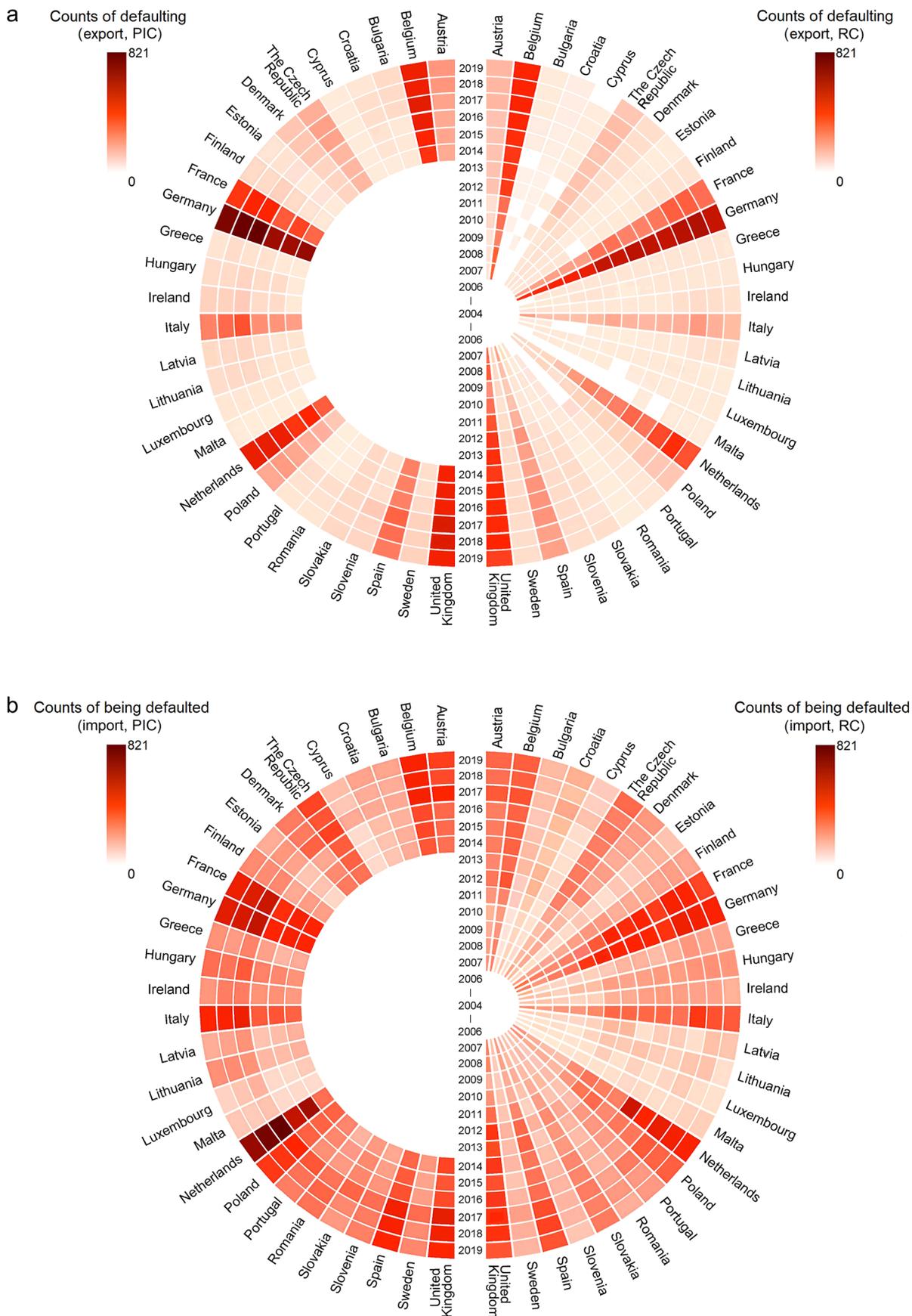


**Extended Data Fig. 4 | Interregional relationships of multi-use chemical trade. Global trade of multi-use chemicals among 15 regions during 2015–2019.** Each cell represents the respective import percentage, with the sum of the

cells in each column equaling to 100%. The grey cells mean the import within the defined regions (including the trade within China among mainland, Hongkong and Macao).

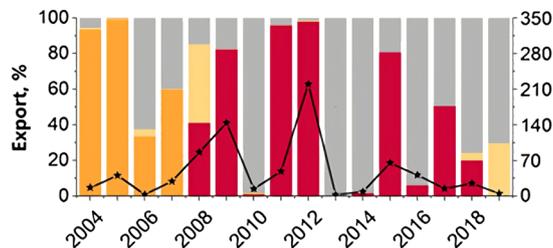
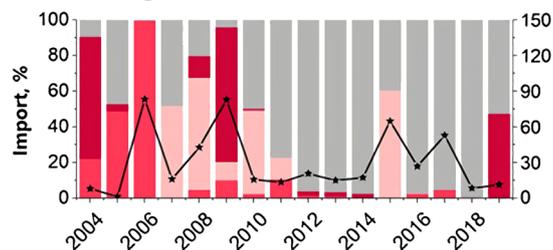


**Extended Data Fig. 5 | The map of global illegal transfer of the listed highly hazardous chemicals.** The map of illegal trade transfer with net imports of listed highly hazardous chemicals among the 15 defined regions during 2015–2019. Credit: basemap, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences.

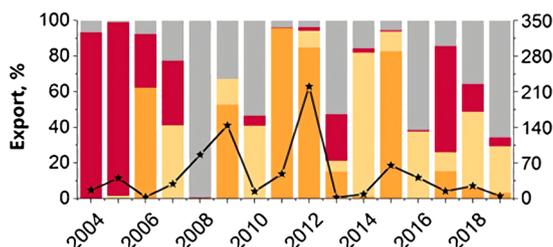
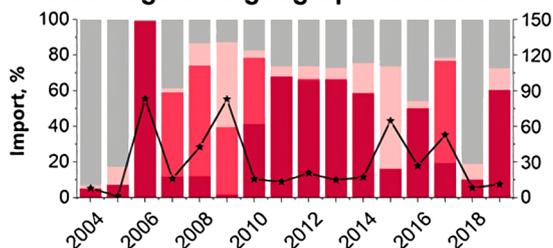


**Extended Data Fig. 6 | Defaulting summary of the listed highly hazardous chemicals. Defaulting summary of the listed highly hazardous chemicals in the EU member states according to the Rotterdam Convention (RC) and the PIC Regulation (PIC). Counts of defaulting for exporting Parties (a) or counts of being defaulted for importing Parties (b).**

**a. Percentage on a chemical basis**

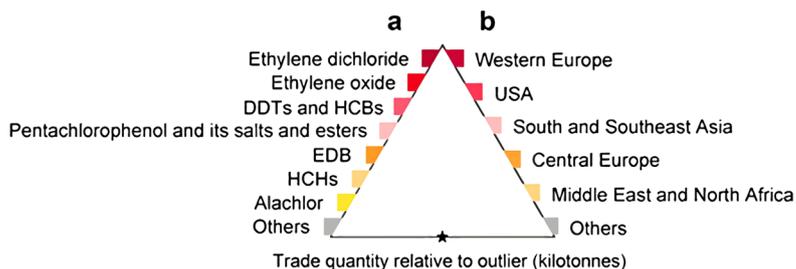
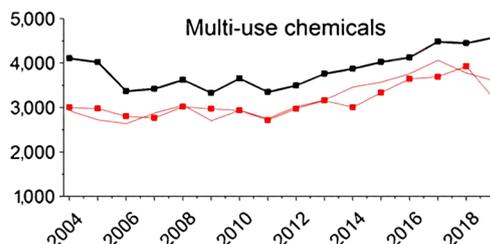
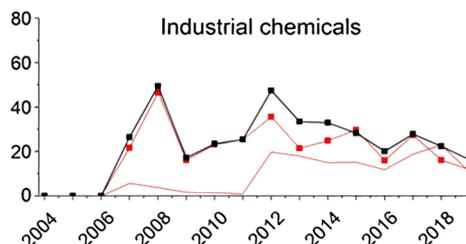
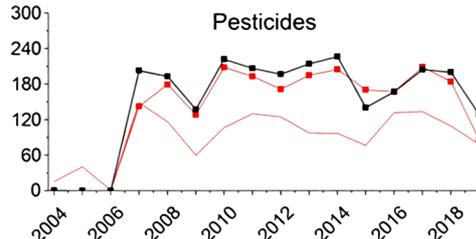


**b. Percentage on a geographical basis**

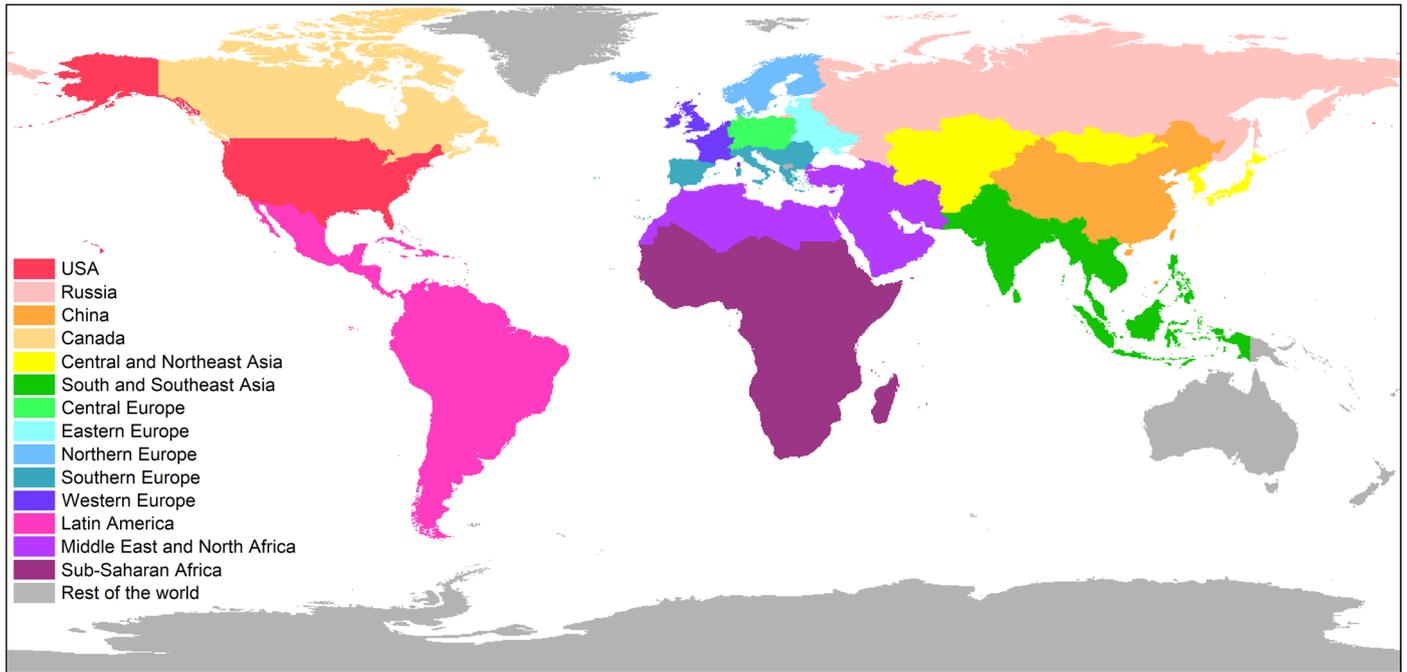


Raw data of import    Raw data of export    Data after treatment

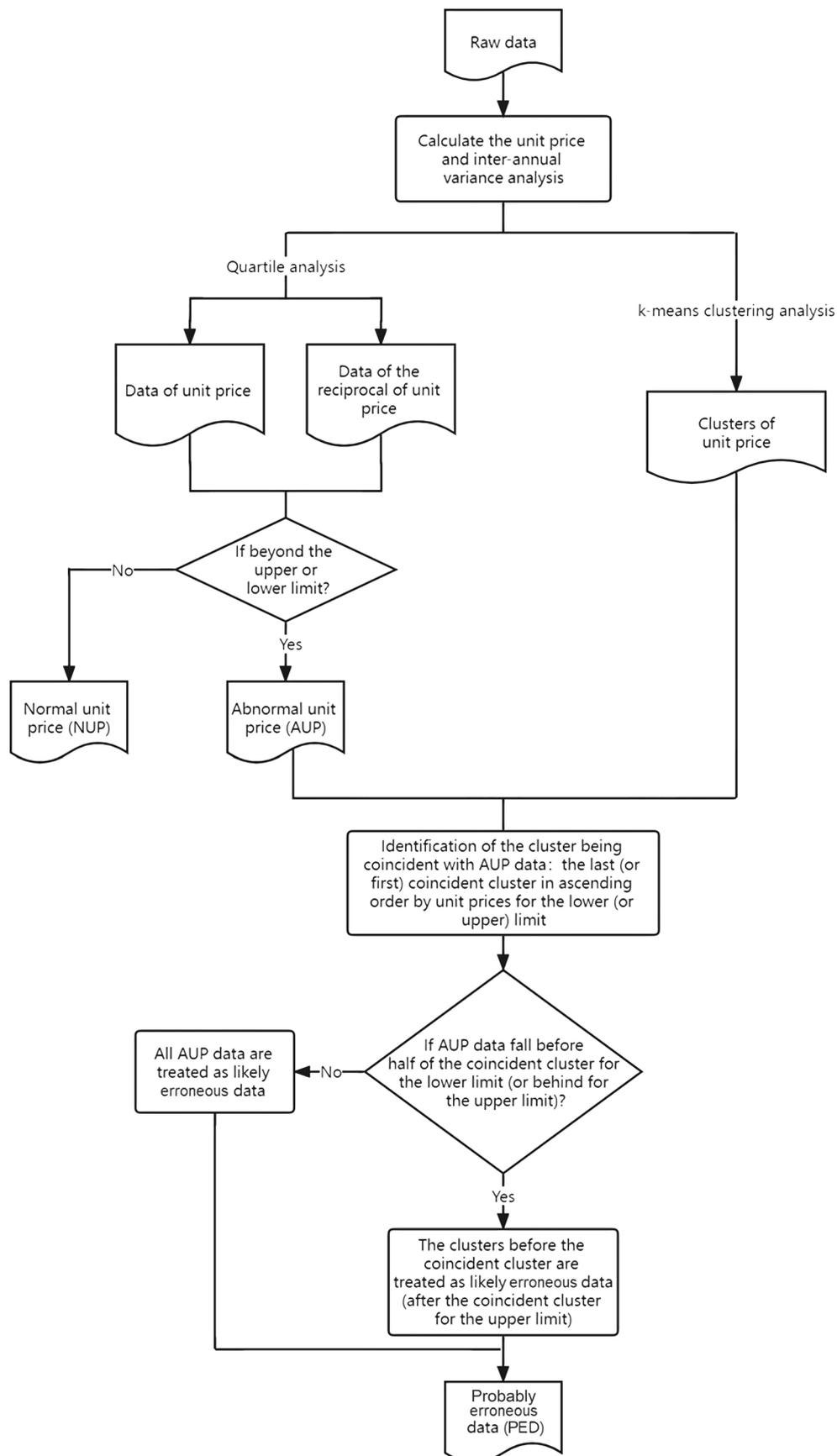
**c. Total volume (kilotonnes)**



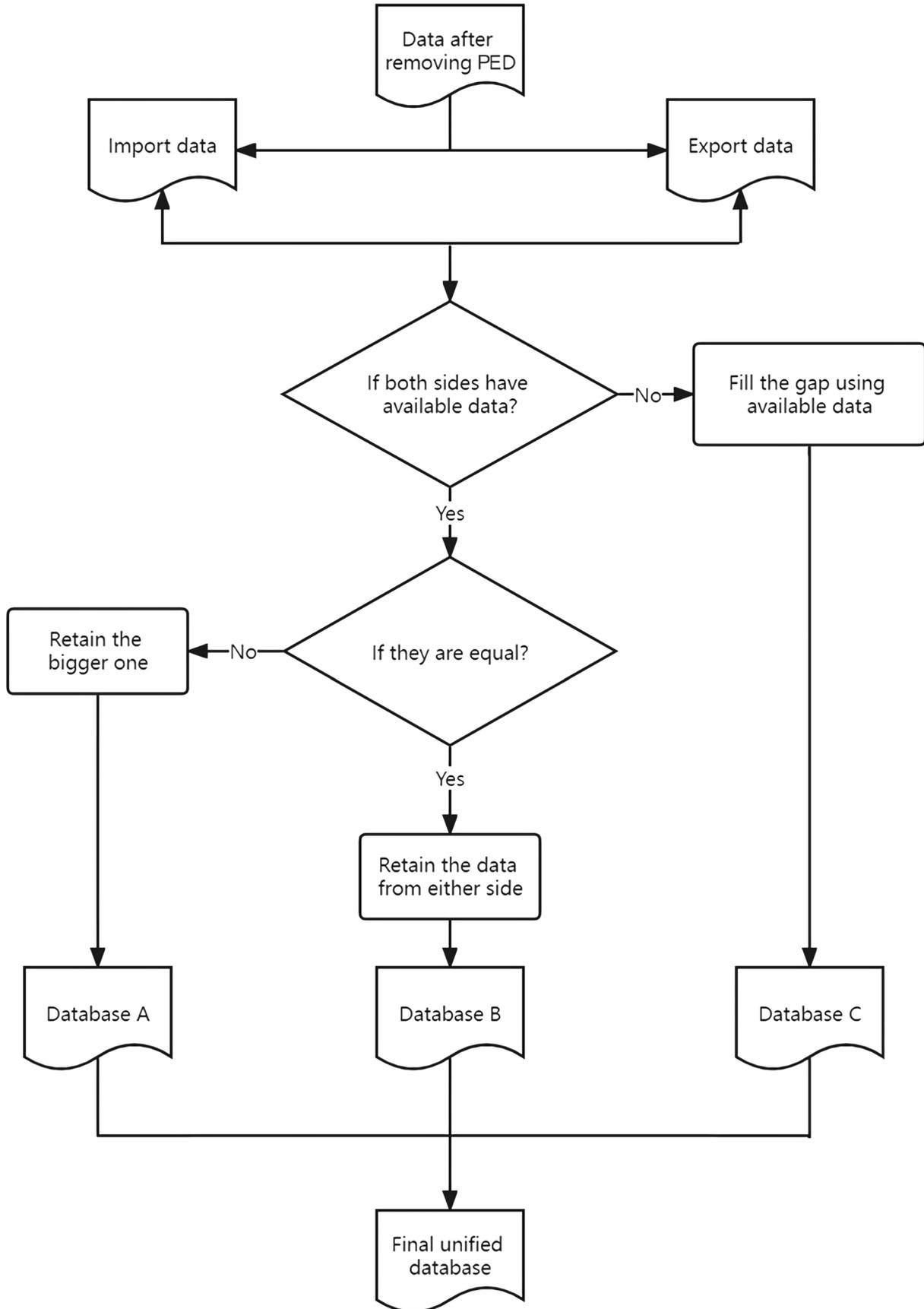
**Extended Data Fig. 7 | Data summary for data treatment. Data summary for error analysis and mirror analysis.** Percentage distribution of likely erroneous data of hazardous chemicals on a chemical basis (a) and a geographical basis (b) and time trends of trade quantities before and after data treatment including error analysis and mirror analysis (c).



**Extended Data Fig. 8 | Illustration of region division.** Illustration of the defined 15 regions. Credit: basemap, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences.



**Extended Data Fig. 9 | Scheme of error analysis.** Flow chart of error analysis of trade quantity.



**Extended Data Fig. 10 | Scheme of mirror analysis.** Flow chart of mirror analysis of trade quantity.

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| <input checked="" type="checkbox"/> | <input type="checkbox"/> For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings   |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes   |
| <input checked="" type="checkbox"/> | <input type="checkbox"/> Estimates of effect sizes (e.g. Cohen's $d$ , Pearson's $r$ ), indicating how they were calculated   |

*Our web collection on [statistics for biologists](#) contains articles on many of the points above.*

### Software and code

Policy information about [availability of computer code](#)

Data collection

Data analysis https://doi.org/10.5281/zenodo.7943211."/>

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

### Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

All original data were publicly available online. The HS codes of the listed highly hazardous chemicals are available at <https://www.wcoomd.org/en/topics/nomenclature.aspx>. The trade data were retrieved from the UN Comtrade database and are available at <https://comtrade.un.org/data/>. The data after treatment

for the final trade analysis are available in the Zenodo repository at <https://doi.org/10.5281/zenodo.7943211>. The ratification status of Parties and import responses are available at <http://www.pic.int/>.

## Human research participants

Policy information about [studies involving human research participants and Sex and Gender in Research](#).

Reporting on sex and gender	<input type="text" value="N/A"/>
Population characteristics	<input type="text" value="N/A"/>
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Ethics oversight	<input type="text" value="N/A"/>

Note that full information on the approval of the study protocol must also be provided in the manuscript.

## Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

Life sciences       Behavioural & social sciences       Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://www.nature.com/documents/nr-reporting-summary-flat.pdf)

## Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	<input type="text" value="This study is to analyse the global trade of the highly hazardous chemicals listed under the Rotterdam Convention and to examine the effectiveness of the Convention. Furthermore, a novel workflow that comprehensively address data-quality issues in the UN Comtrade database is developed to achieve a more accurate estimation of global trade flows."/>
Research sample	<input type="text" value="This study does not involve taking samples."/>
Sampling strategy	<input type="text" value="This study does not involve taking samples."/>
Data collection	<input type="text" value="The trade data used are collected from the UN Comtrade database that is the largest data pool of international trade flow of various products."/>
Timing and spatial scale	<input type="text" value="The time span in this study starts from the inception of the Rotterdam Convention (i.e., 2004) to 2019. The geographical distributions of trade flows are based on the 15 defined regions around the globe."/>
Data exclusions	<input type="text" value="The dataset in the UN Comtrade database contain records that are missing, under-reporting or over-reporting issues. If not treated properly, the analysis of global trade would be largely biased. This study develops a new workflow to identify those likely wrong data, remove them, and reconcile the asymmetric import/export or missing data."/>
Reproducibility	<input type="text" value="All attempts to repeat the final results were successful."/>
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Did the study involve field work?	<input type="checkbox"/> Yes <input checked="" type="checkbox"/> No

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We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

## Materials & experimental systems

- | n/a                                 | Included in the study                                  |
|-------------------------------------|--|
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## Methods

- | n/a                                 | Included in the study                           |
|-------------------------------------|---|
| <input checked="" type="checkbox"/> | <input type="checkbox"/> ChIP-seq               |
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