The world-wide waste web

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The world-wide waste web

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Globally, 7-10 billion tonnes of waste are produced annually[1,2], including 300-500 million tonnes of hazardous wastes (HW)–explosive, flammable, toxic, corrosive, and infective ones[3,4]. About 10%[5] of these HW are traded through a *world-wide waste web* (W4). The volume of HW traded through the W4 in the last 30 years has grown by 500%[6] and will continue to grow[7], creating serious legal[8], economic[6], environmental[9] and health[10] problems at global scale. Here we investigate the tip of the iceberg of the W4 by studying networks of 108 categories of wastes traded among 163 countries in the period 2003-2009. Although, most of the HW were traded between developed nations, a disproportionate asymmetry existed in the flow of waste from developed to developing countries. Using a dynamical model we simulate how waste congestion propagates through the W4. We identify 32 countries with poor environmental performance which are at high risk of waste congestion. Therefore, they are a threat of improper handling and disposal of HW. We found contamination by heavy metals (HM), by volatile organic compounds (VOC) and/or by persistent organic pollutants (POP), which were used as chemical fingerprints (CF) of the improper handling of HW in 94% of these countries.

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It is frequently claimed that the global trade of HW is mainly a waste flow from developed to developing countries[5,11]. From an economic perspective waste trade may offer benefits to both types of countries[9]. Developed countries would benefit from cheaper disposal costs in developing nations and avoiding increasing resistance to HW disposal facilities in their countries. Developing countries would gain access to cheap raw materials by recycling wastes, rocketing production and employment. This would be a win-win situation if it were not because many of the importer nations are highly indebted countries with very poor track records of waste management and environmental performance[8]. Additionally, as revealed by several high profile cases[12], the situation is aggravated by illegal HW trafficking to, and dumping in, developing countries[13].

To address the problems of HW, UN created in 1989 the Basel Convention (BC) on the Control of Transboundary Movement of Hazardous Wastes and their Disposal[14]. In its more than 30 years, BC has revealed the difficulties to obtain accurate information regarding the magnitude and direction of global HW flows[5,15]. The information recorded by the BC on waste trade is incomplete, inaccurate and does not contain information on illegal trade. However, it constitutes the most reliable information for building a map of the W4, which is vital to understand how the flows of HW are organized at global and local scales. This analysis is necessary for efficiently managing the transboundary HW trade and implementing more effective measures for its better management and control.

Here we rely on data reported by 163 countries on their trade of 108 categories of HW during the years 2003-2009. This data is the most complete information about transboundary waste trade at the BC database. By merging these categories into seven classes of waste we study the trade networks that account for the legal flow of HW in the world. First, we analyze the global characteristics of these networks with emphasis on the North-South flow of HW. By considering the relation between the simulated risk of waste congestion and countries' environmental performance, we analyze the potential risks of improper handling and disposal of HW by individual nations. Finally, we identify "chemical fingerprints" that reveal the impact of improper handling and disposal of HW on the environment and human health on 32 countries identified at high risk.

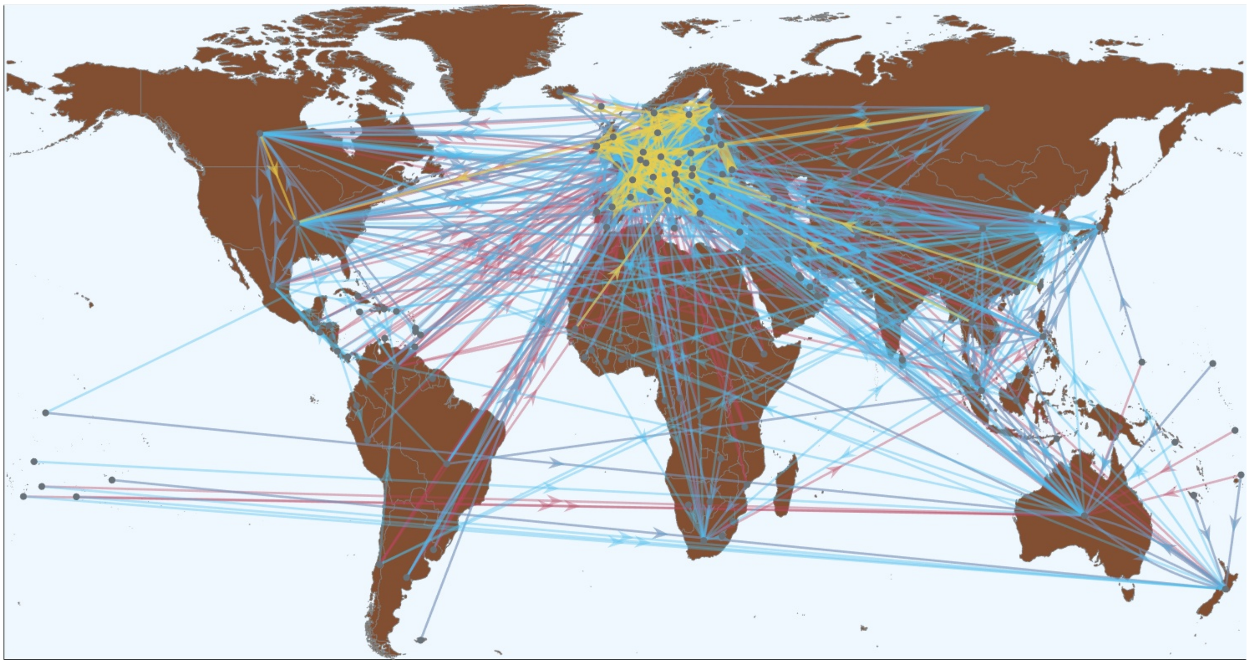

FIG. 1. **The world-wide waste web**. Superposition of the W4 networks of types I (blue edges), type II (red edges) and type III (yellow edges) of waste, where the nodes represent the countries which traded the corresponding waste in the years 2003-2009. The direction of the edges indicates the flow from exporter to importer as reported at the BC database.

GLOBAL ANALYSIS OF W4

During 2003-2009, the total traffic of wastes reported by the BC around the world was of 1,112,539,300 metric tonnes. Time-aggregated weighted-directed networks of seven types of waste grouping together 108 BC categories were created as described in Methods. The distribution of wastes by the different types considered here (see Methods) is very unequal with a large concentration on the wastes of types I-III. These three types of wastes account for 99.9997% of the total weight of wastes traded in the period of study. We then focus here on these three types and the rest are considered in the SI. Waste of type II accounts for 53.8% of the total volume of wastes traded world-wide in the period of study, followed by type I (36%) and type III (10.1%). For the period 2003-2009 most of the international trade of type I-III wastes took place between developed nations. They accounted for 99.88% (type I), 98.85% (type II) and more than 99.99% (type III) of the total volume of waste traded in that period. A closer inspection of the W4 (see Fig. 1) reveals a large unbalance in the directionality of the HW trades between developed, developing and least developed countries. Developed nations exported to developing and least developed ones 1,008,600 and 14,151 tonnes of wastes of type II more than what they imported from such nations, respectively. Even for the case of household wastes (type III) developed nations exported 1,961 tonnes more than what they imported from developing nations. The exports and imports of types I-III display skewed distributions, indicating the existence of a relatively small number of exporters/importers which concentrate most of the volume and number of connections in the W4.

LOCAL ANALYSIS OF W4

Weighted degrees reveal that the major exporters of types I-III are Ukraine, Poland and Russia, as well as Netherlands and Belgium (type I), USA and Italy (type II) and Netherlands and France (type III). The major importers are Belarus and Germany (types I-III), plus Netherlands and Belgium (type I), USA and Belgium (type II) and Monaco and Sweden (Type III). The weighted in- and out-closeness centrality identify countries closer to the rest in the major flows of HW trade. For type I the out-closeness identifies Cyprus, Libya, Egypt, Jordan, Greece and Israel as the most central countries, clearly pointing the North-South flow of HW (Fig. Extended Data 1). For type II, they are Malaysia, Tonga, Cook Islands, New Zealand and Niue, which points to the trans-pacific trade (Fig. Extended Data 2).

There is a potential trade-off between waste congestion (WC) and countries environmental performance (EP). Thus, we introduce the Potential Environmental Impact of Waste Congestion (PEIWC) (see Methods). In Fig. 2(a) we illustrate a typical PEIWC. Ideally, those countries with poor EP should manage low volumes of HW. They should appear at the top-left corner of the PEIWC. Those countries with good EP and low levels of HW congestion should appear in the low-right corner of the PEIWC. The central zone represents a "tolerance" zone, where countries manage wastes according to their capacities and their environmental responsibilities. However, there are countries with poor EP that may congest very quickly of waste. They are located over the tolerance zone and represent countries with high risk of improper handling and disposal of wastes (HRIHDW). We use a fractional susceptible-saturated model (see Methods) to estimate the relative times at which a country may congest of a given type of waste. In Fig. 2(b-d) we illustrate the PEIWC for wastes

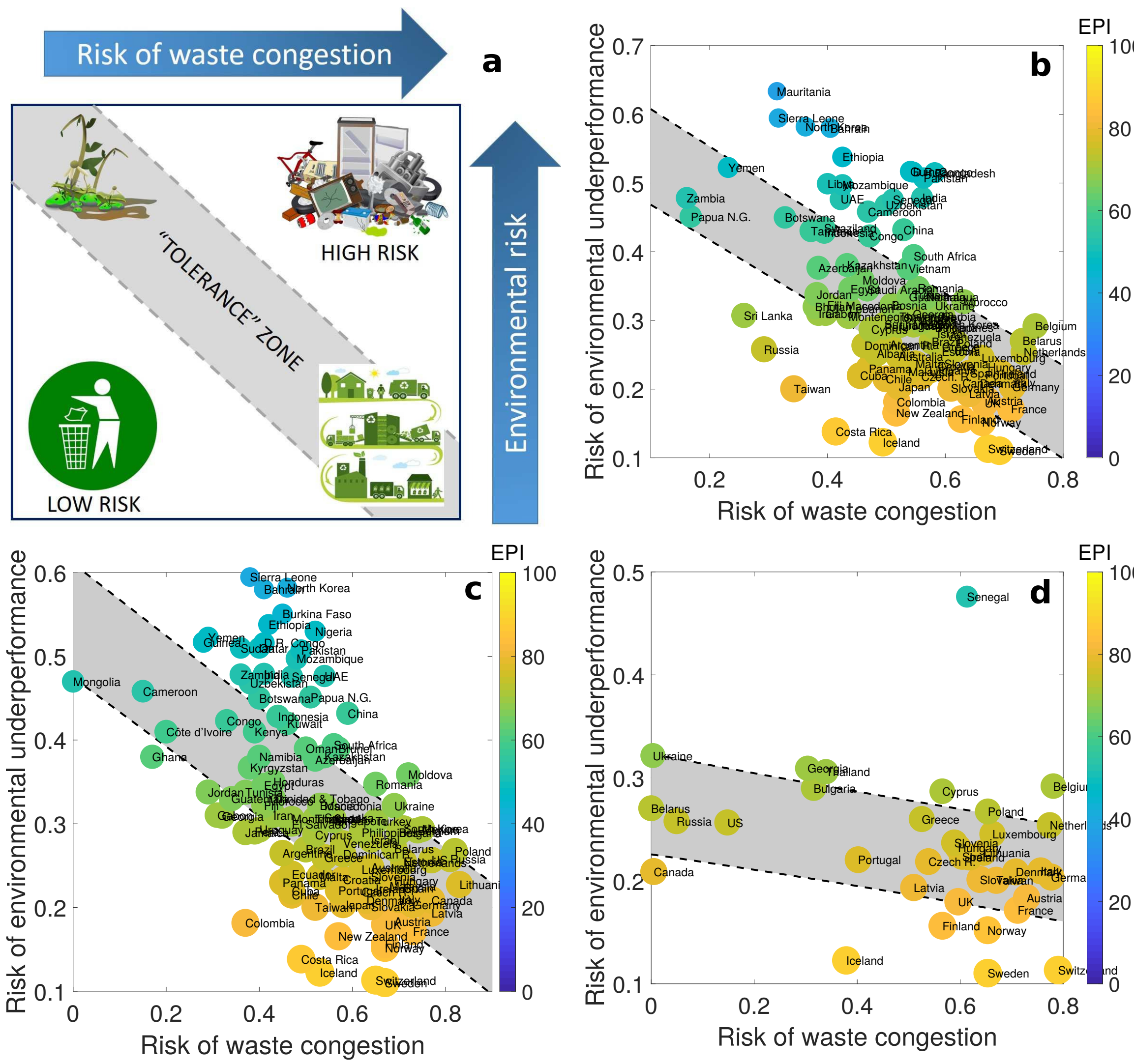

FIG. 2. **Potential Environmental Impact of Waste Congestion (PEIWC)**. Plot of the risk of waste congestion versus the environmental performance (a) indicating the central region of "tolerance" where countries process waste with relatively low environmental and human health impacts. The tolerance zone is defined here by the upper and lower 50% prediction bounds for response values associated with the linear regression trend between the two risk indices. Countries over the tolerance zone are at high risk of improper handling and disposal of wastes (HRIHDW). They are countries pressed to manage more waste than what their environmental performances indicate that they can manage. (b)-(d) Illustration of the PEIWC for wastes of types I-III, respectively. The risks of waste congestion are calculated from the simulated dynamics using a fractional susceptible-congested model described in Methods. The index of risk of environmental underperformance is obtained from the of Yale University environmental performance index (EPI). Nodes representing countries are colored by their EPIs.

of types I-III. We identified 32 countries at HRIHDW: 16 from Africa, 8 from Asia, 4 from Middle East and 4 from Europe. On the safer side of the PEIWC we find Costa Rica, Iceland, New Zealand, Switzerland, Sweden, Finland, Norway and Colombia.

We also study waste-aggregated W4 networks for every year in the 2003-2009 period. Temporal trends of the waste congestion and environmental underperformance risks were built for 19 of the 32 countries at HRIHDW (Fig. Extended Data 3). Only three countries display a tendency to improve both risk indices, while 10 showed simultaneous detriment of both from 2003 to 2009.

CHEMICAL FINGERPRINTS OF W4

We have found that wastes of types I-III may leave environmental and/or human health chemical fingerprints (CF) in one or more of the following categories: (i) heavy metals (HM)[16], (ii) volatile organic compounds (VOC)[17,18], and persistent organic pollutants (POP)[19]. In Fig. 3 we illustrate the connections between the BC wastes Y1-Y47, their CFs and the 32 countries at HRIHDW.

Heavy metals

Wastes are one of the main anthropogenic sources of HM in the environment[16,20], with electrical and electronic waste (e-waste) alone containing 56 metals[21]. We focus on 8 HM ubiquitous in wastes of different kinds. Lead (Pb), cadmium (Cd), nickel (Ni), mercury (Hg), chromium (Cr), zinc (Zn), copper (Cu) and arsenic (As), appear in wastes from pesticides, medicines, paints, dyes, catalysts, batteries, electronic devices, industrial sludge, printing products, incineration of household wastes, among others[16,20](see SI). In total, there are 25 countries at HRIHDW in which wastes are expected to leave CFs in the form of HM. These HM are identified as pollutants directly or indirectly related to wastes in 23 out of the 25 countries at HRIHDW. For instance, the death of 18 children in Senegal[22]has been linked to high levels of Pb in children living in surrounding areas used for recycling of used lead-acid batteries. Higher than expected hair levels of Pb, Cd, and Hg have been claimed as a potential cause of childhood iron deficiency anemia in Uzbekistan[23]. Learning disorder has been associated with high levels of Pb, Cd, As, Ni, and Cu in children of UAE[24]. In

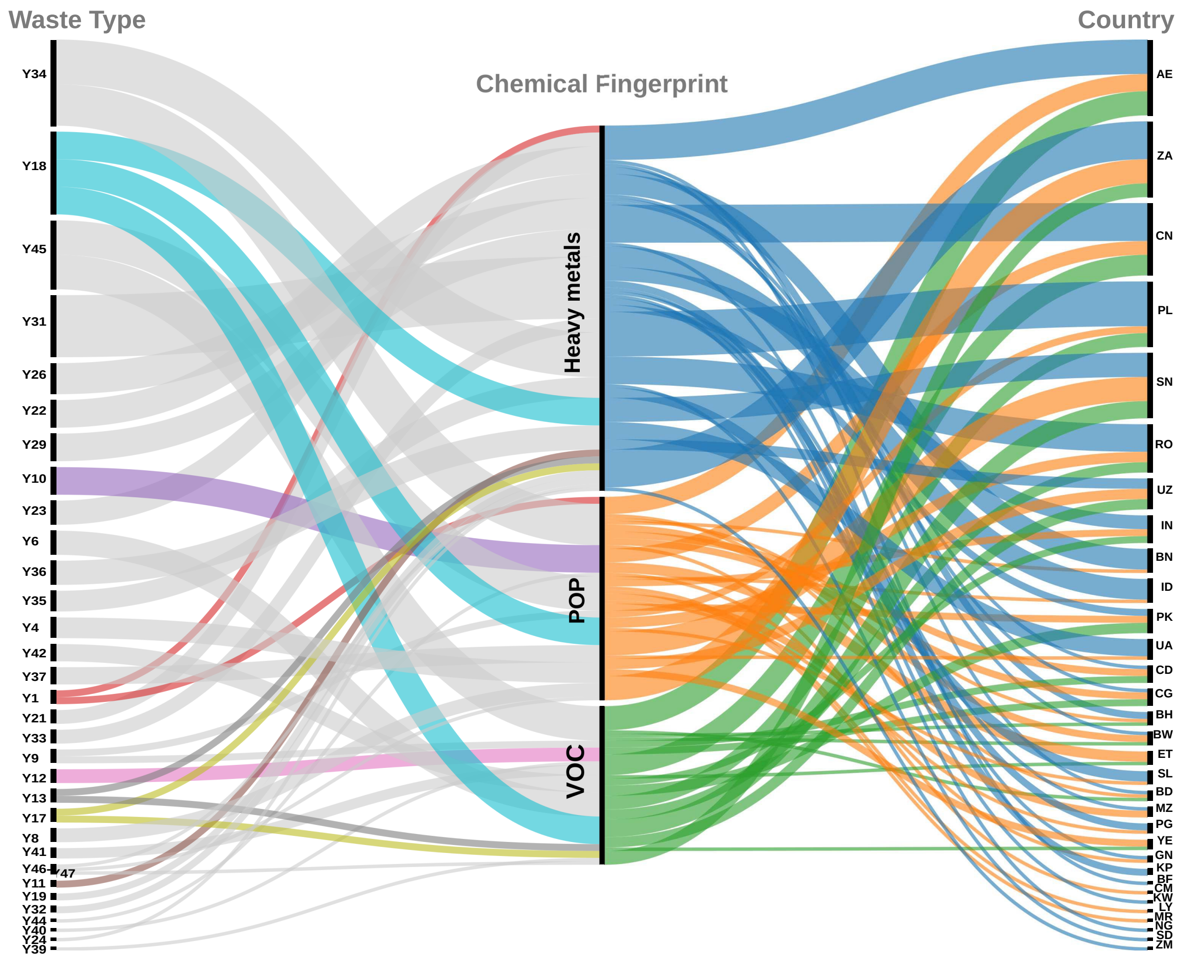

FIG. 3. **Chemical fingerprints of waste**. The three classes of chemical fingerprints left by BC categories of waste Y1-Y47 in the 32 countries at high risk of improper handling and disposal of wastes (HRIHDW). Waste types are described in the SI. Countries are represented by their ISO 3166-1 alpha-2 code.

Indonesia, high levels of Pb, As, Cd and Hg in hair of children living close to places where e-waste is dumped, or (formally or informally) processed, has been associated with their deficits in attention and executive function[25]. In China[26], levels of Pb in mother-infant pairs were found to be five times higher in regions known for the high concentration of e-waste disposal/processing than in control. It was related to the higher rates of adverse birth outcomes observed in Guiyu–where 70% of global e-waste ends up[27]–related to control. In the same region children are reported to have significantly higher levels of Pb, Cr, and Ni, which have been linked to low mean IQ, and decreased forced vital capacity[26]. Cd, Pb, Zn, Cu, Ni, As, and Cr were also found at higher levels in hairs of residents and dismantling workers in Longtang and Taizhou relative to control locations[26]. The levels of dermal exposure of these HM in workers of Indian e-waste recycling sites is 192.6 (Cr), 78.1 (Cu), 30.9 (Pb) and 37.3 (Zn) times higher than those for people not exposed to e-waste[28].

Volatile Organic Compounds

VOC are ubiquitous organic pollutants affecting atmospheric chemistry and human health[17]. VOC can be released from wastes containing solvents, paints, cleaners, degreasers, refrigerants, dyes, varnishes and household wastes, from processing of e-wastes, plastics and waste incineration[17,18]. We identify benzene (B), toluene (T), ethylbenzene (E) and o-, m-, and p-xylenes (X) as potential CF of Y1-Y47 waste[17,18,29,30]. Toluene is the only BTEX which has significant non-traffic sources, with important contributions from previously mentioned sources. Indeed, when the T/B ratio is over two it indicates the existence of sources beyond vehicular traffic[31].

We identified 16 countries at HRIHDW which potentially have an impact in the emission of VOC from wastes. For instance, several VOC have been identified in an e-waste dismantling town in Guangdong province of China, including alkanes, BTEX, and organohalogen[29]. The T/B ratio found here was 3.15, which clearly correlates with emissions of VOC occurring during pyrolisis of e-waste[29]. T/B ratio of 9.36 is reported for Guangzhou[32], which is the capital city of Guangdong. In the city of Dakar, Senegal, both at the urban district and at a semirural district, T/B ratios were 4.51 and 5.32[33]. Senegal is a country at HRIHDW for types I, II and III. In Senegal there has been continuous problems with the collection of household waste[34], which have been responsible for public health problems (dermatosis, diarrhea, conjunctivitis and malaria)[35]. Other high risk countries also have high values of T/B ratio reported at different locations: South Africa (4.87, 5.67, 21.3), India (3.67, 6.66, 8.97), Bangladesh (6.85), Ethiopia (4.25), Belgium (3.8, 4.38), and Poland (2.29, 2.96) (see SI for references).

Persistent Organic Pollutants

POP are chemicals with high resistance to degradation in the environment, high accumulation in human/animal tissues and transmission through food chains[19]. As POP indicators we consider here polychlorinated biphenyls (PCB)[36] and polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs)[37]. In total these CFs are related to 12 BC waste categories with impact in 26 countries at HRIHDW.

PCB are intentionally produced due to their many industrial applications. They are related to neurodevelopment effects in infants, cancer and immunotoxic effects in humans[36]. Vast amounts of PCB are stored in some of the countries at HRIHDW (Fig. Extended Data 4)[38]. For instance, in Sierra Leone there are 103,372 tonnes of oil having PCB. Contamination by high levels of PCB has been found about 400 km off parts of the coast of Sierra Leone[39]. In Mozambique 240,571 tonnes of oil suspected to have PCB are reported. Pollution by particulate and vapor samples containing PCB was detected in three sites in KwaZulu-Natal Province, South Africa[40], which is close to Mozambique border. PCBs are also found in four fish species from Lake Koka, Ethiopia[41]. In China high PCB concentrations have been reported in sediments from Pearl River and its estuary[42,43]. In Dalian Bay and Songhua River the pollution by PCB is directly related to PCB equipment storage locations[42]. In the Bengal coast of Bangladesh PCB contamination is linked to the past and on-going use of PCB-containing equipment[44]. Indeed, all 209 congeners of PCBs were found in 48 seafood samples collected from the coastal area of Bangladesh, with severe health risk for coastal residents[45]. Additionally, in three European countries at HRIHDW, Poland, Ukraine and Romania, there are 253,000 (second in Europe after Russia), 103,102 (third in Europe) and 6,869 equipments, respectively, that contains or might contain PCB[38].

On the other hand, PCDD/Fs are known to be extremely toxic in animals/humans[37]. Consequently, their release to the environment are presented as toxic equivalent (TEQ) (see Fig. Extended Data 5)[46]. In D. R. Congo alone PCDD/Fs amount to 300,412 g/TEQ/a (grams per toxic equivalent per year)[47]. It is followed by China (10,232), India (8,658), Indonesia (7,352) and Nigeria (5,340). The mean TEQ of PCDD/Fs in 73 countries, excluding those found here at HRIHDW, is 428.13[46].

CONCLUSIONS

The W4 in the period 2003-2009 shows a disproportionately asymmetric trade of HW. These flows mainly from the developed to the developing world, placed several third-world countries at HRIHDW. The current work reveals the urgent necessity of substantial in-

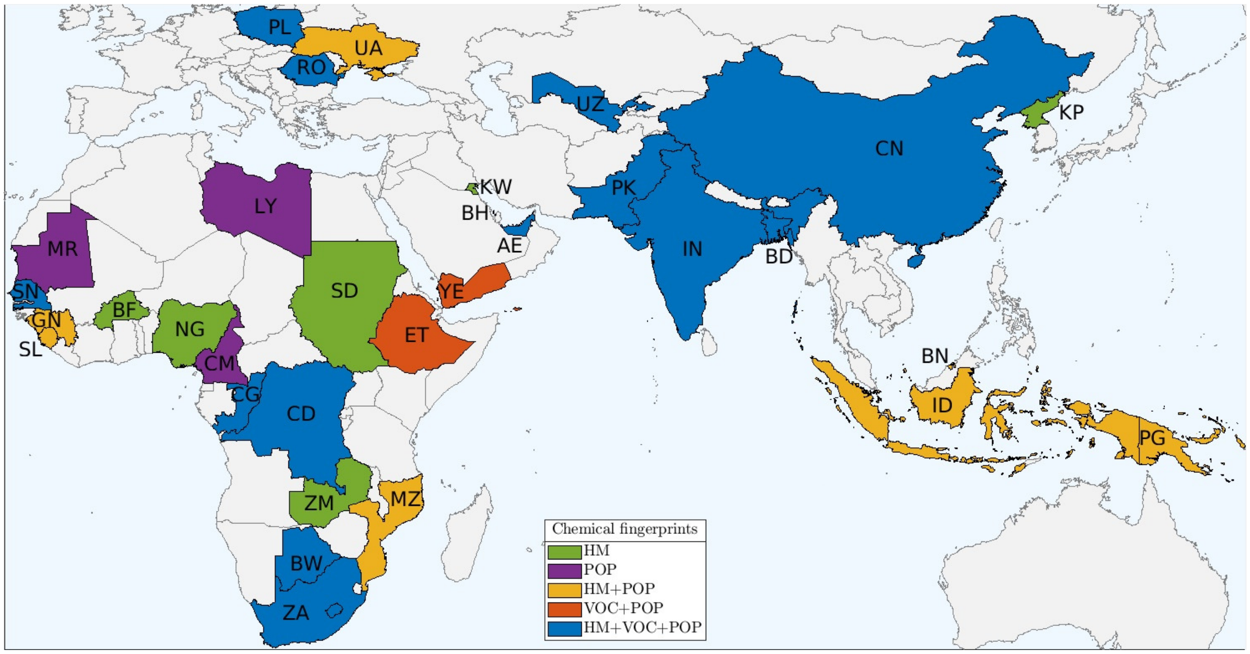

FIG. 4. **High risk of improper handling and disposal of wastes**. Illustration of the 32 countries at HRIHDW of types I-III wastes and the chemical fingerprints left by these HW in their environment and/or human health. Countries with impact of heavy metals (HM) (green), persistent organic pollutants (POP) (purple), HM and POP (yellow), volatile organic compounds (VOC) and POP (red), HM and VOC and POP (blue) are illustrated.

vestment in waste management in those countries at HRIHDW. It also paves the way to understand further rechannels of the HW through the W4 due to "import bans" policies in major importers, like the one impossed in 2017 by China[48]. It also will allow to understand the potential waste congestion problems arising from the COVID-19 pandemic and from emerging sources of e-waste[49,50].

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METHODS

Data collection

We extract the data used to build W4 networks from BC Online Reporting Database[51,52]. It contains summarized compendiums where individual national reports are altogether condensed into single Excel files per year, with the explicit and quantitative information of associated parties: destination, import, origin and transit. We extract from these files the information about countries/territories of exports and imports, transaction amounts in metric tons (tonnes), waste classification codes, characteristics and type of waste streams. While the on-line repository of surveys range from years 2001-2019, the quantitative digest of commercial waste transactions are only available from 2003 to 2009[52]. Code names of countries, and special territories like those that has no total political sovereignty, are considered by using the standard ISO 3166-1 alpha-2[53]. We do not include the countries of transit due to its scarcity in the reports, and because of the lack of information about the temporary order of the landings. We also excluded the existing self-export (a country that exports to itself). We manually curated the database for errors in the country/territories names, e.g., due to typos or possible transcription errors, as well as for the use of nonofficial country codes such as EIRE instead of IE for Ireland. The BC reports may also combine formal ISO alpha-2 codes with others codes that have become obsolete and sometimes with codes of another standards like transitory codes or international postal union codes. Reports may pointing out to a state party that currently is dissolved or split into two new ones, e.g., Serbia and Montenegro. In the case of waste categories we also exclude those for which their codes do not coincide with the ones defined by the BC, such as 11b, AN8, Y48.

Waste types

We consider 108 categories of wastes according to BC classification, which are then grouped into seven types of waste designated by Type I-VII. The classification of wastes used in this work are based on the Annexes I, II and VII of the BC[51]. No wastes in categories B of the BC are included in this work as they are not reported by countries in the database of the Convention[52].

Type I considers, for instance, Y1: Clinical wastes from medical care in hospitals, medical centers of clinics, Y2: Wastes from the production and preparation of pharmaceutical products, up to Y18: Residues arising from industrial waste disposal operations (see pp 46 of Ref [54]). The **Type II** of wastes used in this work associates the second subdivision of the Annex I, Y-codes Y19-Y45. In general, wastes containing 27 chemical constituents, i.e., Y19: Metal carbonyls, Y20: Beryllium compounds, up to Y45: Organohalogen compounds. The **type III** of wastes discussed here accounts for the Annex II of the BC classification. Y46: Wastes collected from households, and Y47: Residues arising from the incineration of household wastes. A complete list is provided in the SI.

The remaining four types of wastes recover the four subclassification of the Annex VIII[51]. Specifically, **Type IV** links with the Metal and Metal-Bearing Wastes. It accounts for A-list items grouped from A1010-A1090 and A1100-A1190, e.g., A1010: Metal wastes and waste consisting of alloys of Antimony, Arsenic, Cadmium, Selenium, among others; up to A1190: Waste metal cables coated or insulated with plastics containing or contaminated with coal tar, PCB11, lead, cadmium, other organohalogen compounds (see pp 66 of Ref [54]). **Type V** relates Inorganic constituents containing metal and organic material. (cathode-ray glasses, liquid inorganic fluorines, catalysts, gypsum, dust-fibres of asbestos, coal-fired power plant fly-ash). Its A-items ranges from A2010-A2060. **Type VI** associates Organic constituents containing metal and inorganic material. (Petroleum coke and bitumen, mineral oils, leaded anti-knock sludge, thermal fluids, resin, latex, plastiticizers, glues, adhesives, nitrocellulose, phenols, ethers, leather wastes, (un)halogenated residues, aliphatic halogenated hydrocarbons, vinyl chlorides), accounting for A-items: A3010-A3090, A3100-A3190 and A3200. Finally, **Type VII** are Wastes which may contain either inorganic or organic constituents (Some pharmaceutical products, clinical-medical-nursing-dental-veterinary wastes from patients and researches, biocides-phytopharmaceutical, pesticides, herbicides outdated, wood chemicals, (in)organic cyanides, oils-hydrocarbons-water mixtures, inks, dyes, pigments, paints, lacquers, varnish, of explosive nature, industrial pollution control devices, for cleaning of industrial off-gases, peroxides, outdated chemicals, from research or teaching activities, spent activated carbon, to name a few). It accounts for the groups A4010-A4090, and A4100-A4160.

W4 construction

We construct a weighted directed network for each of the types of waste analyzed. In every network the nodes correspond to the countries/territories reporting the given type of waste in the period 2003-2009. It is frequent in the BC database that a country i reports the export (import) of an amount q_{ij} to (from) j, which includes several BC waste categories. If all the BC categories belong to the same waste type, then we simply use that amount as the weight of the link (i, j). However, it happens sometimes these BC categories belong to several waste types. Let us consider two BC categories C_1 and C_2, e.g., Y1 and Y19. Then, C_1 belongs to one waste type, e.g., type I, and C_2 to another, e.g., type II. In this case we have to split the quantity q_{ij} in the weights of the links between i and j for the two types of wastes. We then proceed as follows. We obtain the weight of the link (i, j) for the waste of type k as

$$w_{ij}^{k} = \frac{q_{ij} \cdot \phi_k}{\Phi} \ , \tag{1}$$

where ϕ_k is the average of the amounts of waste of type k traded between every pair of countries during the corresponding year, and $\Phi = \sum_k \phi_k$ where the summation is carried out for all types of waste involved in the quantity q_{ij}.

In any case we can obtain two different weights for a pair of countries based on the data reported at BC from "Export" and "Import" reports. Then we can have the following two different cases: (a) that the amount $E(i, j)$ reported by country i as exported to country j coincides with the amount $I(j, i)$ reported by j as imported from i; (b) that $E(i, j) \neq I(j, i)$. In the case (a) we simply add a directed arc from i to j with the weight $E(i, j) = I(j, i)$. In the case (b) we assume that i exports $\max[E(i, j), I(j, i)]$ to j. We designate by $\tilde{A} = \tilde{A}(G)$ the adjacency matrix of the network G. Notice that $\tilde{A}$ is not necessarily symmetric because $\tilde{A}_{ij} = \max[E(i, j), I(j, i)]$ is not necessarily the same as $\tilde{A}_{ji} = \max[E(j, i), I(i, j)]$. Here we normalize the adjacency matrices by: $A = \tilde{A}/\sum_{i,j} \tilde{A}_{ij}$.

Network parameters of the W4 networks

Because the W4 networks are weighted and directed we consider here the distributions of their in- and out-degrees. The weighed in-degree of the node i is the sum of the weights of all links pointing to i. The weighed out-degree of that node is the sum of the weights of all links leaving that node. For each kind of degrees we tested 17 types of distributions[55]: beta, Birnbaum-Saunders, exponential, extreme value, gamma, generalized extreme value, generalized Pareto, inverse Gaussian, logistic, log-logistic, lognormal, Nakagami, normal, Rayleigh, Rician, t-location-scale, and Weibull. To test the goodness of fit we used[56,57]: negative of the log likelihood, Bayesian information criterion, Akaike information criterion (AIC), and AIC with a correction for finite sample sizes. The results are given in the Supplementary Information.

We also studied several centrality measures, apart from the in- and out-degrees, of the individual countries in the weighted-directed networks of the W4[58]. The weighted betweenness centrality of a given node k is obtained as

$$BC\left(k\right) = \sum_{i \neq j \neq k} \frac{\rho_{ikj}}{\rho_{ij}}, \tag{2}$$

where ρ_{ikj} is the number of weighted directed shortest paths from i to j that pass through node k, and ρ_{ij} st is the total number of weighted directed shortest paths from from i to j.

We also calculated the in- and out-closeness centrality, which are defined as the inverse sum of the shortest-path distance from a node to all other nodes in the weighed directed network. If not all nodes are reachable, then the centrality of node i is:

$$CC_t\left(k\right) = \frac{\eta_k}{n-1} \frac{1}{\sum_j d_{kj}}, \tag{3}$$

where $t = \{o, i\}$ for out- and in- types, respectively, η_i is the number of reachable nodes from node i (not counting i), n is the number of nodes, and d_{ij} is the weighted shortest-path distances from node i to j. If no nodes are reachable from node i, then CC_i is zero. For the in-closeness, the distance measure is from all nodes to node i.

Susceptible-congestion dynamics

We model waste congestion propagation as a contagion process in which at a given time t, a country i is susceptible to get congested of wastes or it is actually congested. The rate at which a congestion at a given country is transmitted to another is given by β. The capacity of a link between two countries to carry wastes is accounted for the corresponding entry of the weighted adjacency matrix. We use here relative link capacities by dividing every entry of the adjacency matrix by the sum of all entries of the given matrix, such as the link weights are bounded between zero and one. Finally, we assume the realistic scenario in which wastes at a given country are not "exported" immediately to another, but that they can have a variable "residence time" at given countries. To account for such variable (and unknown) residence times of wastes at given countries we use Caputo time-fractional derivatives in the model[59] . We detail the models below.

Before proceeding we should clarify some specific characteristics that are present in the W4 that influence the HW congestion of a given country. The obvious situation is that a country with poor capacities for waste management get congested because others export large amounts of waste to it. This could be for instance the case of China, where an estimate of 70% of the world's e-waste ends up in Guiyu, in Guangdong Province where no more than 25% is recycled in formal recycling centers. However, more tricky is to detect cases where a given country has already large amounts of a given type of waste, which it needs to export, possibly because it cannot cope with it with its actual capacities. This is the case of household waste in Senegal, where the lack of infrastructures and collection system makes the problem insurmountable by local authorities. Senegal exported more than 15,000 tonnes of household waste to Italy in 2009. To differentiate both situations we will designate them as (i) congestion at arrival, for the case where congestion can be produced by importing large amounts of a given type of waste; and (ii) congestion at departure, for the case where congestion can be produced due to the existence of large amounts of waste in a country, which are then exported to another.

For a given W4 network G we consider the following two dynamical process accounting for the congestion of waste trade among countries. Let $s_i\left(t\right)$ be the "surprise" that a country i is not congested at time t, namely $s_i\left(t\right) := -\log(1-x_i\left(t\right))$, where $x_i\left(t\right)$ is the probability that the country i is congested of a given type of waste at time t following Lee et al.[60]. Let

$$D_t^{\alpha} f\left(t\right) := \frac{1}{\Gamma\left(\kappa-\alpha\right)} \int_0^t \frac{f^{(\kappa)}\left(\tau\right) d\tau}{\left(t-\tau\right)^{\alpha+1-\kappa}},$$

be the Caputo time-fractional derivative of the function $f\left(t\right)$ where $0 < \alpha \leq 1$ and $\kappa = \lceil \alpha \rceil$[61]. Let $s_A(t)$ and $s_D(t)$ be the vectors of "surprises" for individual countries in a given W4 network. Then, let $x\left(t\right) = x_0$, we have

i) Congestion at arrival

$$D_t^\alpha s_A(t) = \beta_A^\alpha A x\,(t), \tag{4}$$

ii) Congestion at departure

$$D_t^\alpha s_D(t) = \beta_D^\alpha A^T x\,(t), \tag{5}$$

where A^T is the transpose of A. The solution of these fractional-time congestion propagation models is given by (see Supplementary Information for details)[59]:

$$s_\ell\,(t) = \left(\frac{1-\gamma}{\gamma}\right) E_{\alpha,1}\left(t^\alpha \beta_\ell^\alpha \gamma B\right) \vec{1} - \left(\frac{1-\gamma}{\gamma} + \log\gamma\right) \vec{1}, \tag{6}$$

where $\ell = A, D,\ B = \left\{A, A^T\right\},\ E_{\alpha,1}\Big(\zeta B\Big),\ \zeta = t^\alpha \beta_\ell^\alpha \gamma$ is the Mittag-Leffler matrix function of B, $\gamma = 1 - x_0$ with $x_0 = \frac{c}{n}$ where $c \in \mathbb{R}^+$, and n the number of nodes in the network[62]. Here we consider the same rate for both processes, i.e., $\beta_A = \beta_D$. In the simulations we use $\alpha = 0.75$, $\beta = 0.01$, and $c = 0.005$.

As a way of quantifying how easy a country get congested by a given waste we use the time at which 50% of the total congestion is reached. Let us designate by $\hat{t}_i$ this time. Then, $\hat{t}_i$ is the time t at which $s_\ell\,(t) = 0.5$.

Let us consider a trade network of three countries where A exports 100 tonnes of waste to B and 120 tonnes to C; B exports 200 tonnes to C, and C exports 50 tonnes to A. As can be seen in Fig. Extended Data 6., the times $\hat{t}_C < \hat{t}_A < \hat{t}_B$ for the congestion at arrival model. This indicates that C is at the highest risk of congestion due to its large imports of waste. However, if we consider the process at departure, $\hat{t}_A < \hat{t}_B < \hat{t}_C$, which indicates the highest risk at node A due to the existence of large amounts of this waste at the node.

Potential Environmental Impact of Waste Congestion

We first define here the risk of waste congestion for a given country as

$$R_i := 1 - \hat{t}_i / \max_j \hat{t}_j, \tag{7}$$

where i represents a given country, $\hat{t}_i$ is the congestion time for the country i either by importing or by exporting wastes of a given type. That is, if $t_{1/2}(i \leftarrow)$ and $t_{1/2}(i \rightarrow)$ are the times at which country i reaches 50% of congestion by importing and exporting a given type of waste, respectively, then $\hat{t}_i = \min\left[t_{1/2}(i \leftarrow), t_{1/2}(i \rightarrow)\right]$. The index R_i is normalized between zero (no risk) and one (maximum risk) of congestion of wastes of a given type.

Due to the socio-economic differences between the countries in the world, the use of R_i along could be of little practical value. For instance, for wastes of type I the Netherlands and Burkina Faso have about the same value of R_i, which is near 0.99. For the same type of wastes Ireland and Cte d'Ivoire also have $R_i \approx 0.89$. The situation is similar for waste of type II, where the first pair of countries have $R_i = 1$ and the second pair have $R_i \approx 0.94$. However, while Netherlands and Ireland are among the richest countries in the world with GDP ranging 578-868 billions USD (Netherlands) and 164-236 billions USD (Ireland), the other two countries are among the poorest with GDPs of 4.7-9.4 billions USD (Burkina Faso) and 15-24 billions USD (Cte d'Ivoire) for the period of time considered here. This obviously gives these countries very different capacities for managing a waste congestion, a situation which is well reflected in the environmental track record of each of these countries. The Environmental Performance Index (EPI), published by the Universities of Yale and Columbia[63], quantifies the performance of every country using sixteen indicators reflecting United Nations' Millennium Development Goals. They are accounted for by six well-established policy categories (see Policymakers' Summary at[63]): Environmental Health, Air Quality, Water Resources, Productive Natural Resources, Biodiversity and Habitat, and Sustainable Energy, such that it covers the following two global goals: (1) reducing environmental stresses on human health, and (2) promoting ecosystem vitality and sound natural resource management. Then, while Netherlands and Ireland are among the top environmental performers in the 2003-2009 period with average EPIs larger than 70 out of 100, Burkina Faso and Cte d'Ivoire are the bottom of the list with average EPIs of 45.2 and 55.9, respectively. We can account the risk of environmental underperformance by an index bounded between zero and one as: $U_i = 1 - EPI(i)/100$. PEIWC are defined by plotting the waste congestion risk R_i for a given type of waste versus U_i. For the demarcation of the tolerance zone we use here the following. We obtain the linear regression model that best fit U_i as a linear function of R_i. Then, the tolerance zone is defined by the upper and lower 50% prediction bounds for response values associated with this linear regression trend between the two risk indices. The value of 50% is used here as a very conservative definition of the tolerance zone. Widening this zone too much will make that almost no country is at HRIHDW, which does not reflect the reality. On the contrary, narrowing it to much will simply split countries into two classes, which will make difficult to identify those at the highest risk of environmental underperformance due to waste congestion.

CODE AVAILABILITY

Custom MATLAB code is available on GitHub (https://github.com/JohannHM/Fractional-congestion-Dynamics)

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AUTHOR CONTRIBUTIONS

E.E. designed, directed and wrote the manuscript. J.H.M. contributed with extraction, and curation of data. Both J.H.M and E.E. analyzed the results, performed simulations and computations, draw figures and revised the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

DATA AVAILABILITY

All raw data of the manuscript and its Supplementary Information was obtained directly from the Basel Convention web page (http://archive.basel.int/natreporting/datasrces/index.html). Extracted set of Export and Import networks available in (https://github.com/JohannHM/Fractional-congestion-Dynamics).

ADDITIONAL INFORMATION

Supplementary Information is available for this paper. Correspondence and requests for materials should be addressed to J.H.M and E.E.

566 **EXTENDED DATA**

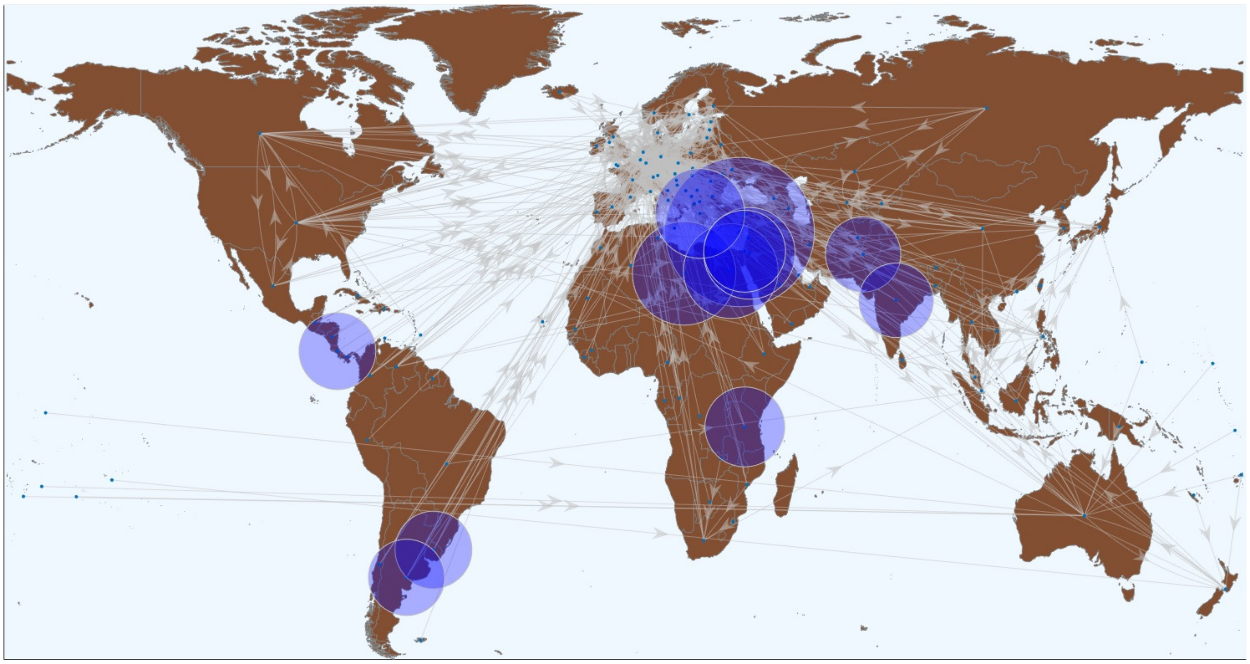

FIG. Extended Data 1. Illustration of the out-closeness of every country in the W4 network of type I waste. The circles have radius proportional to the centrality. Notice that the most central countries are close to the North-South border, particularly between Europe and Africa, pointing out to the traffic between these two continents.

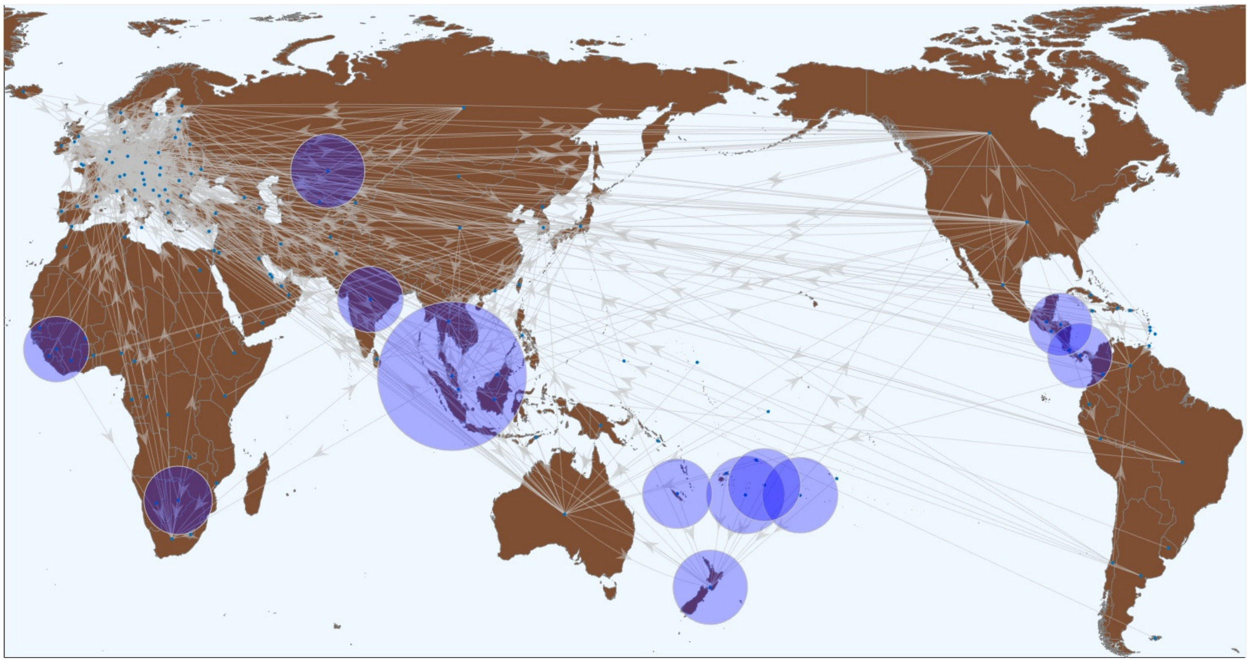

FIG. Extended Data 2. Illustration of the out-closeness of every country in the W4 network of type II waste. The circles have radius proportional to the centrality. Notice that the most central countries are around the Pacific ocean, pointing out to the trans-Pacific traffic of this type of waste.

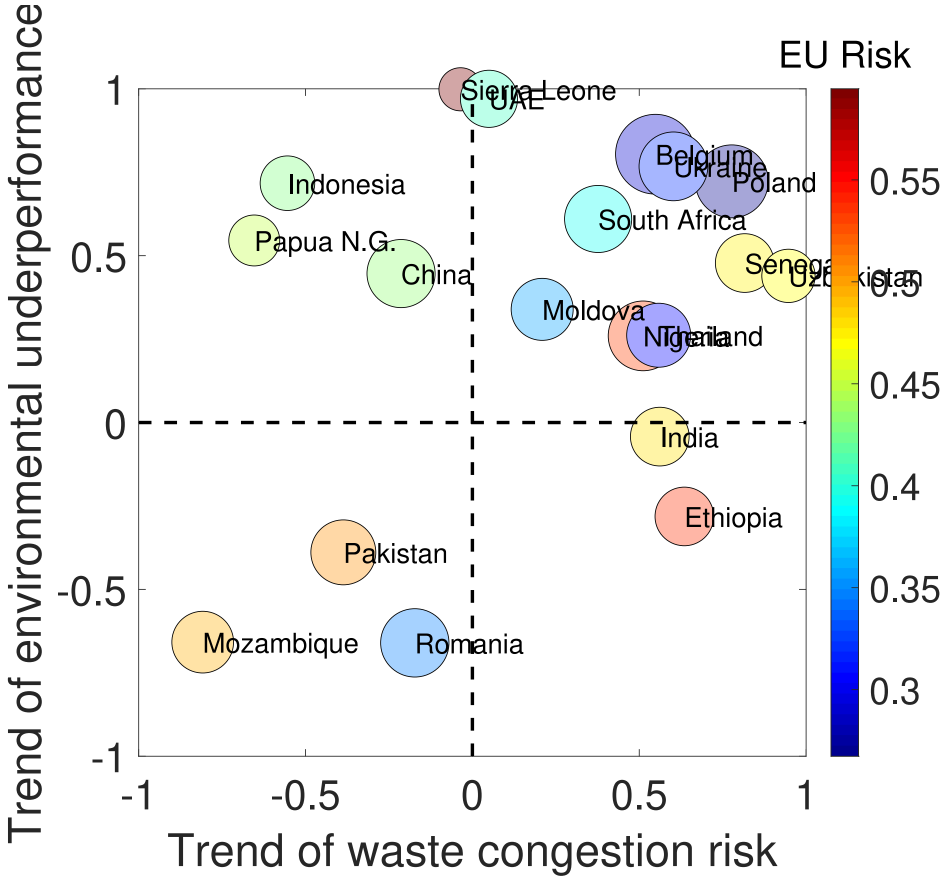

FIG. Extended Data 3. Temporal trend (period 2003-2009) of the waste congestion risk and of the environmental underperformance risk for some countries at HRIHDW. The trend is measured by the Pearson correlation coefficient between the corresponding variable and the years in the period. Bottom-left quarter identifies the countries with a trend to improve both indices. Top-right quarter identified those countries with a trend to deterioration of both indices.

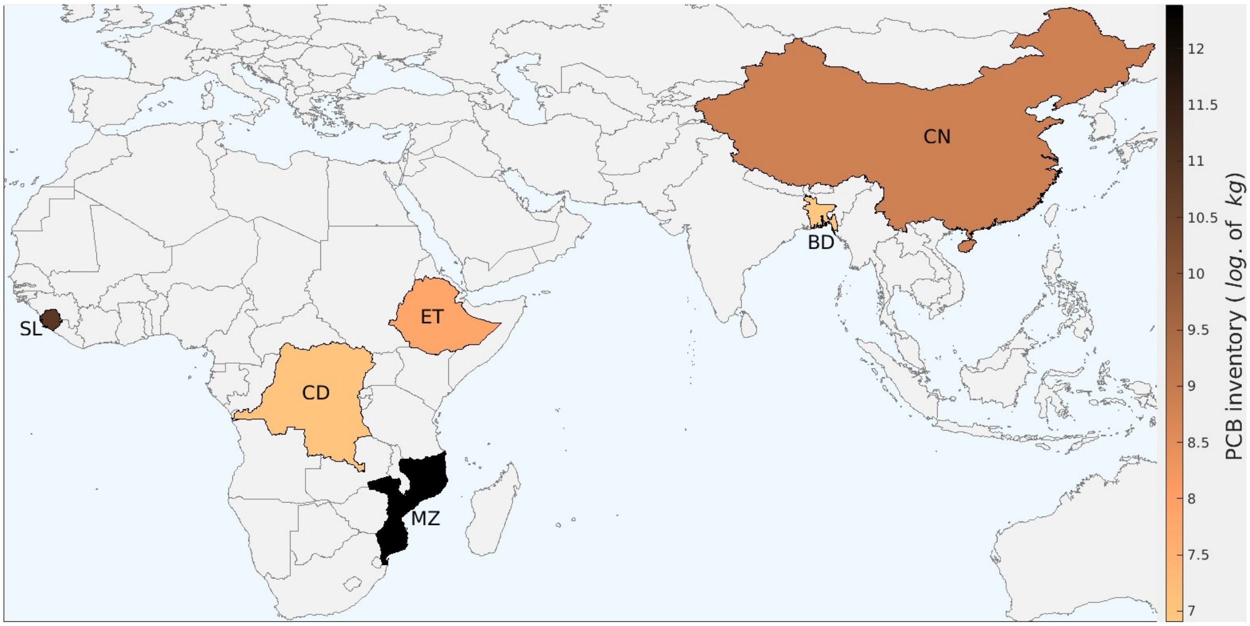

FIG. Extended Data 4. Amounts of PCB stored in some of the countries at HRIHDW identified in this work. The amounts are given in logarithmic scale.

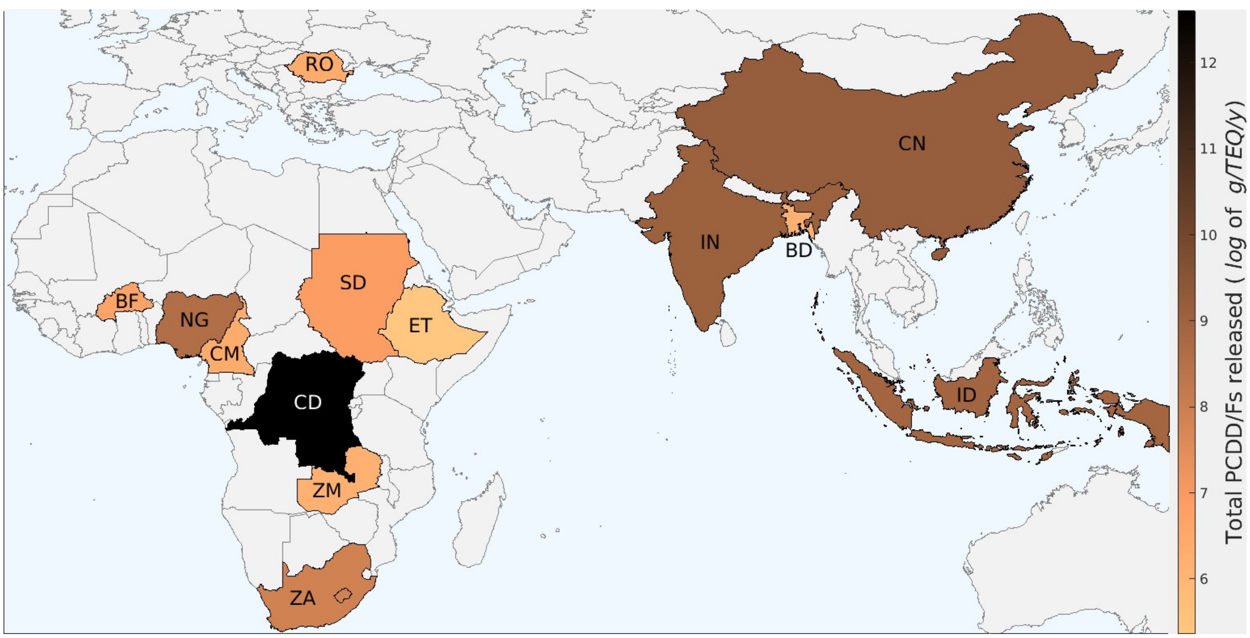

FIG. Extended Data 5. Total amounts of PCDD/Fs released to the environment by some of the countries at HRIHDW identified in this work. The amounts are given in logarithmic scale. The average amount of PCDD/Fs released in the 73 countries not in the list of countries at HRIHDW is 428.1 g/TEQ/y, which in log scale is 6.06.

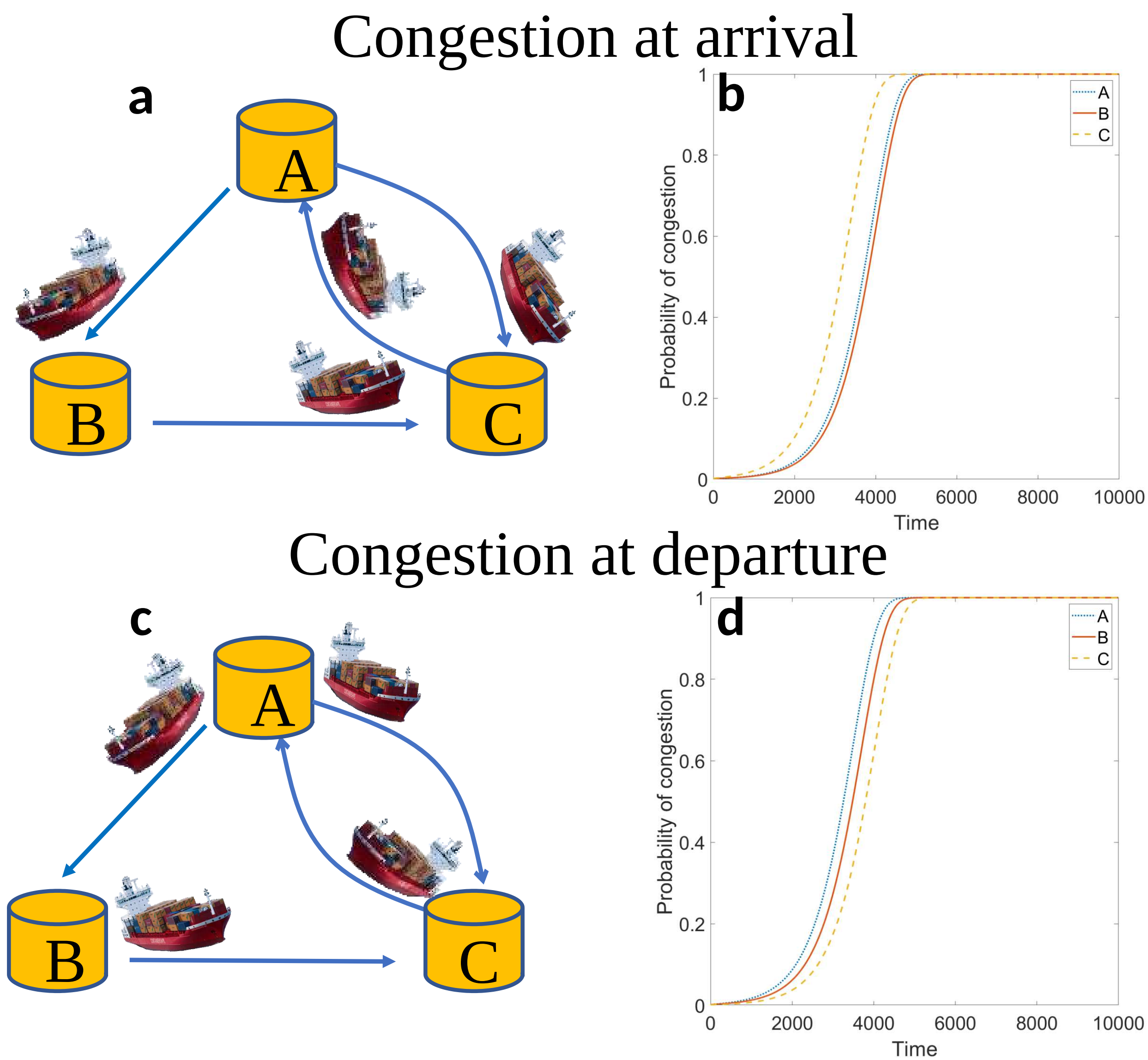

FIG. Extended Data 6. Schematic illustration of the congestion at arrival (**a**) and congestion at departure (**c**) models and the time-evolution of the congestion propagation through the nodes using these models (**b** and **d**). Notice that in the congestion at arrival (panel **b**), node C reaches 50 % of congestion at a earlier time than A and B. In the congestion at departure (panel **d**), node A reaches 50 % of congestion earlier than B and C. Also notice that the ordering of congestion times at departure and arrival are not simply one the reverse of the other.

Figures

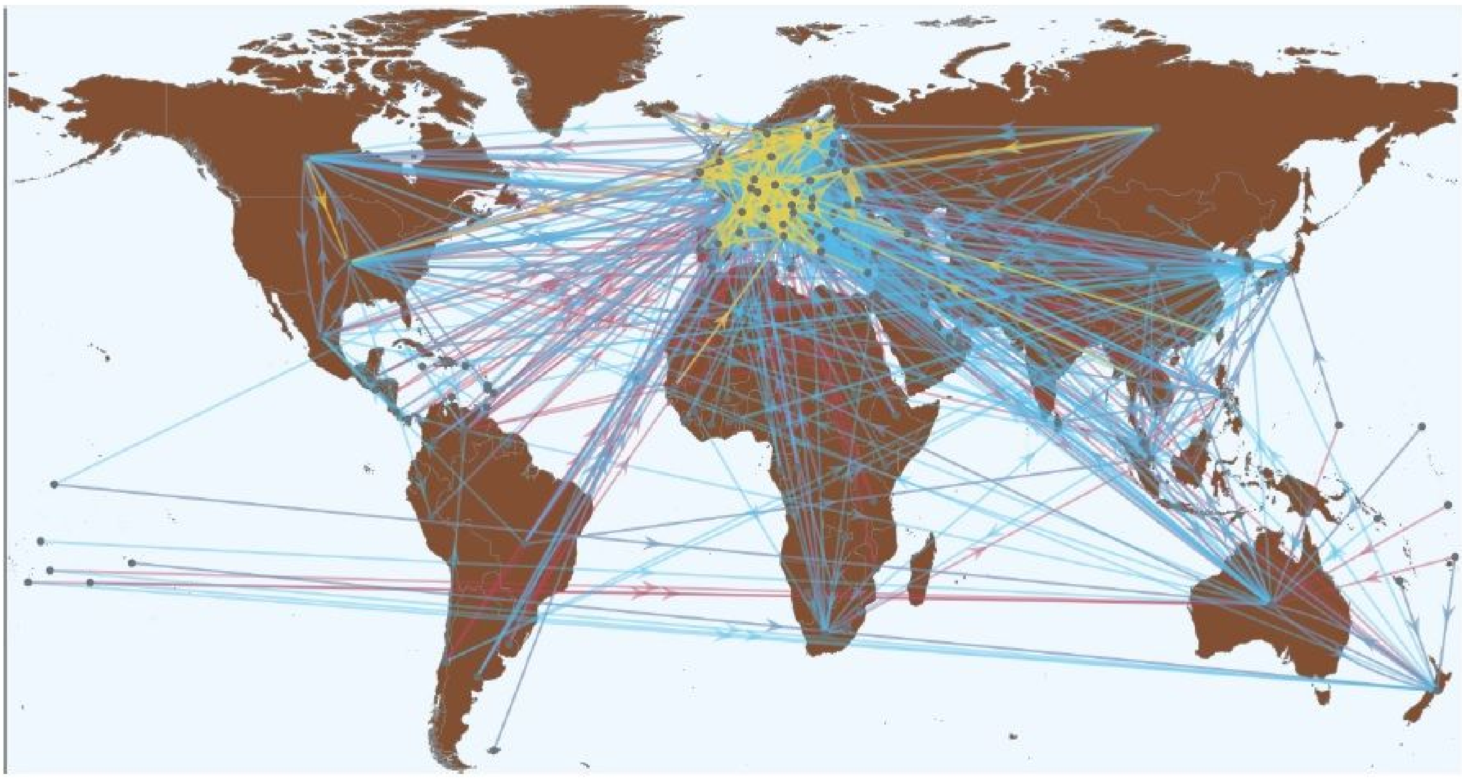

Figure 1

The world-wide waste web. Superposition of the W4 networks of types I (blue edges), type II (red edges) and type III (yellow edges) of waste, where the nodes represent the countries which traded the corresponding waste in the years 2003-2009. The direction of the edges indicates the flow from exporter to importer as reported at the BC database. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

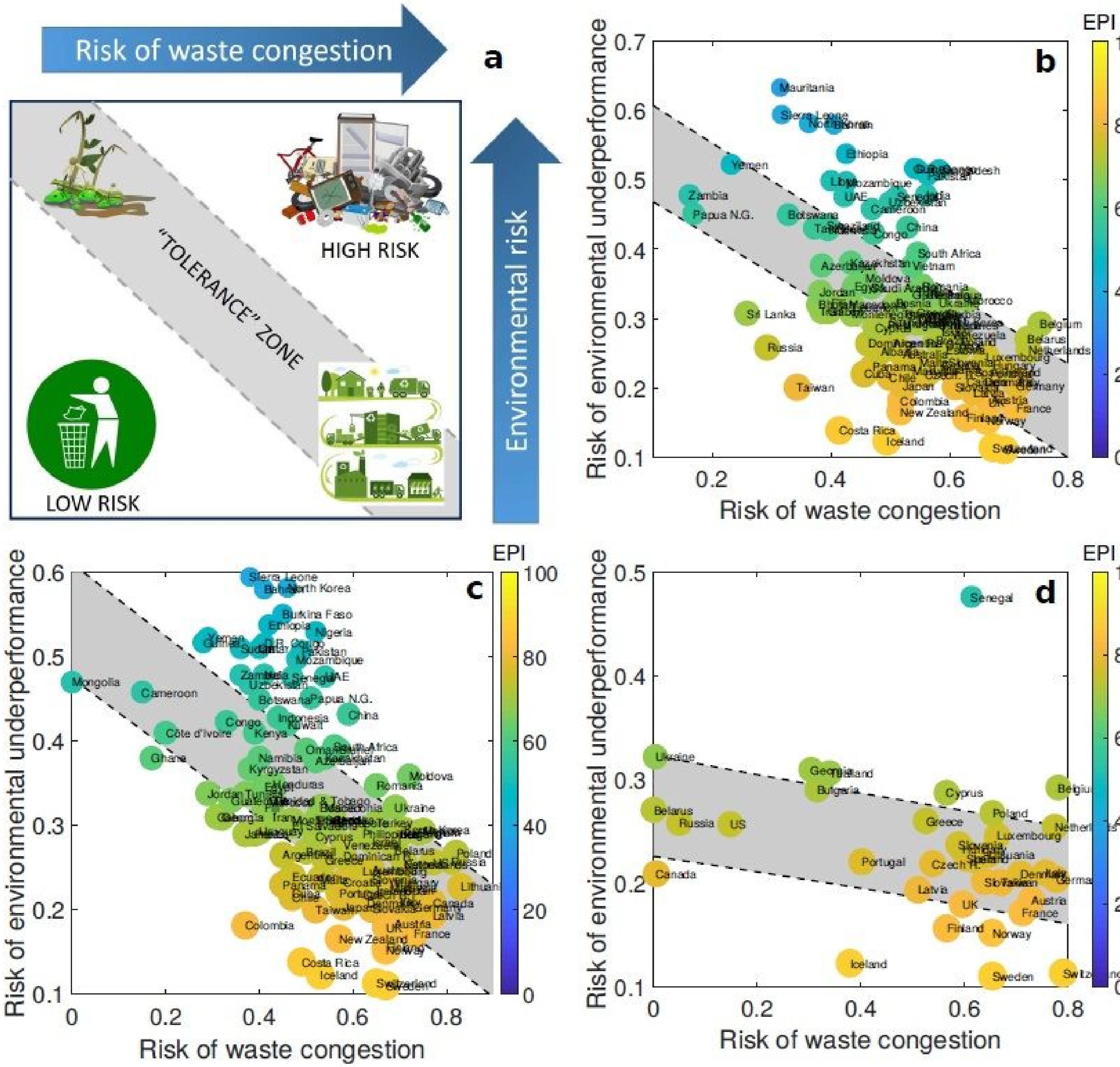

Figure 2

Potential Environmental Impact of Waste Congestion (PEIWC). Plot of the risk of waste congestion versus the environmental performance (a) indicating the central region of \tolerance" where countries process waste with relatively low environmental and human health impacts. The tolerance zone is dened here by the upper and lower 50% prediction bounds for response values associated with the linear regression trend between the two risk indices. Countries over the tolerance zone are at high risk of improper handling and disposal of wastes (HRIHDW). They are countries pressed to manage more waste than what their environmental performances indicate that they can manage. (b)-(d) Illustration of the PEIWC for wastes of types I-III, respec- tively. The risks of waste congestion are calculated from the simulated dynamics using a fractional susceptible-congested model described in Methods. The index of risk of environmental underper- formance is obtained from the of Yale University environmental performance index (EPI). Nodes representing countries are colored by their EPIs.

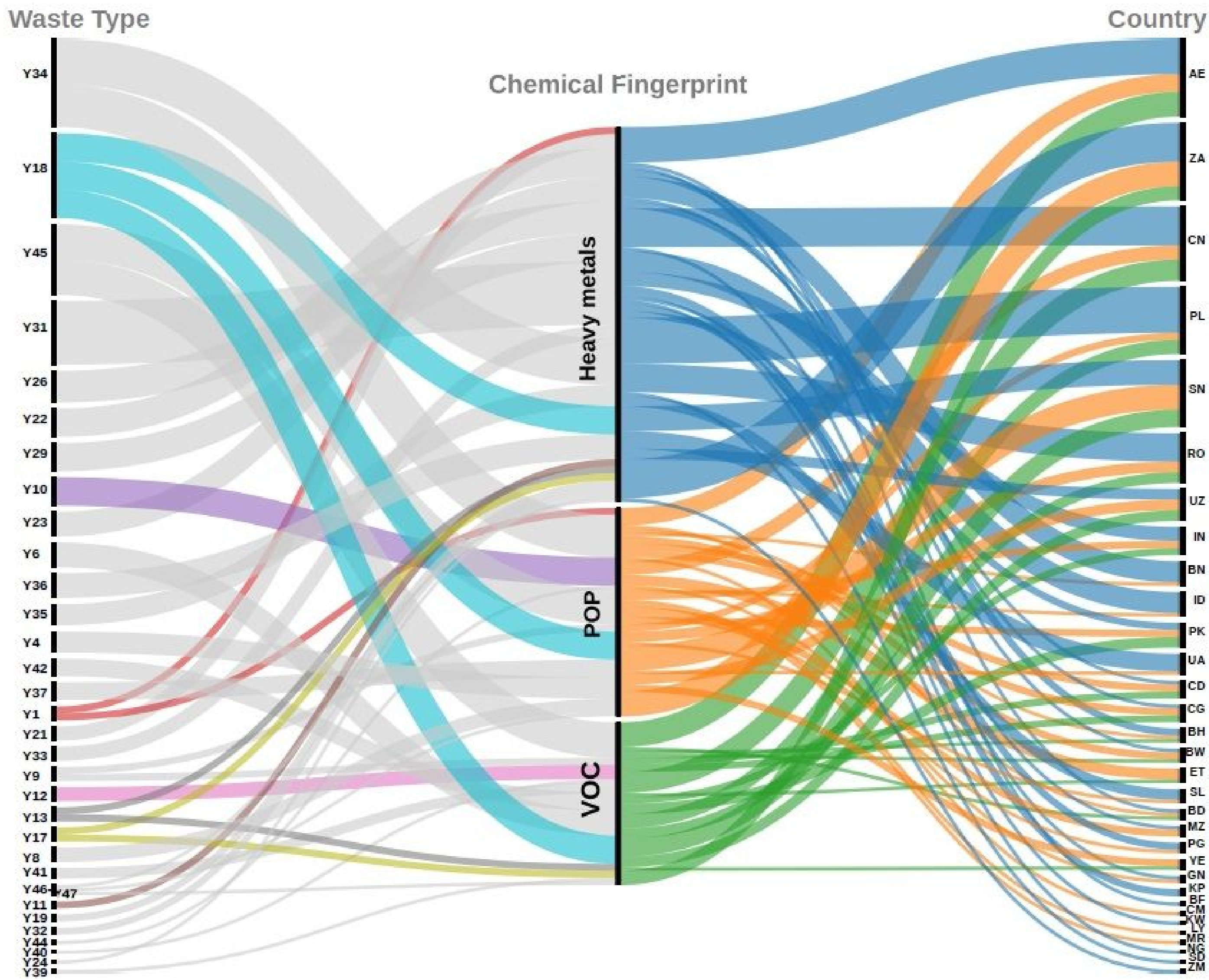

Figure 3

Chemical ngerprints of waste. The three classes of chemical ngerprints left by BC categories of waste Y1-Y47 in the 32 countries at high risk of improper handling and disposal of wastes (HRIHDW). Waste types are described in the SI. Countries are represented by their ISO 3166-1 alpha-2 code.

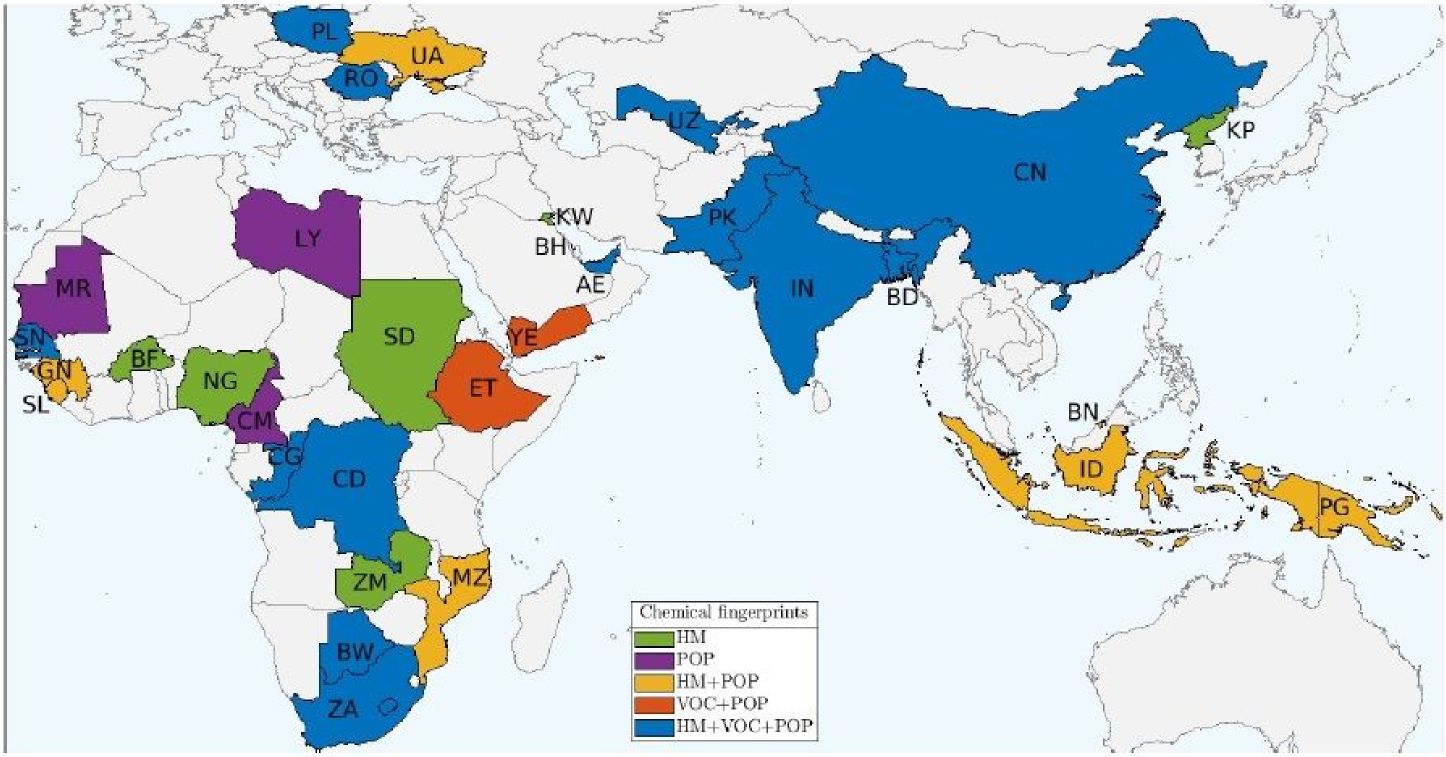

Figure 4

High risk of improper handling and disposal of wastes. Illustration of the 32 countries at HRIHDW of types I-III wastes and the chemical ngerprints left by these HW in their environment and/or human health. Countries with impact of heavy metals (HM) (green), persistent organic pollutants (POP) (purple), HM and POP (yellow), volatile organic compounds (VOC) and POP (red), HM and VOC and POP (blue) are illustrated. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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