Transnational Trafficking Networks of End-of-Life Vehicles and E-Waste

Abstract

Based on case studies and interviews, it appears that the transnational trafficking of various waste types follows distinct paths. However, this information only provides a partial view of the global waste trafficking network, as it has never been studied by combining all the known illegal flows of different waste types. To address this gap, we analyzed data from the Basel Convention National Reports to reconstruct networks of countries that engaged in illegal exchanges of end-of-life vehicles, e-waste, or both between 2016 and 2019. Our findings suggest that the structure of these networks and the countries involved in the trafficking vary depending on the waste type, with some similarities. While there are a few reciprocal ties, illegal end-of-life vehicles and e-waste typically move in one direction between countries. Most illegal flows occur from the Global North to the Global South, but trafficking also takes place within each of these regions.

Introduction

Proper waste management and final disposal activities constitute a major cost for many businesses (Martínez et al., 2022). The high costs of proper waste management are mainly caused by a shortage of treatment, disposal and recovery facilities. This shortage, combined with the considerable quantity of waste globally produced, generates a demand for cheaper legal or illegal disposal alternatives. Waste producers in high income countries seek these alternatives in countries with milder regulations, cheaper systems of waste disposal, and less stringent enforcement activities (Bisschop, 2012; Rucevska et al., 2015). As a result, the waste produced in industrialized nations has become both a significant source of legal and illegal income, as well as an environmental threat, to the populations of low income countries (Elliott & Schaedla, 2016; Klenovšek & Meško, 2011).

Legally traded waste is shipped and reported in compliance with national laws and international conventions that govern the transboundary movements of waste and its disposal. However, when waste export violates these laws or conventions, it is illegal. Transnational illegal waste trafficking is facilitated by document forgery, falsification, license misuse, and corruption schemes (Andreatta & Favarin, 2020; Sahramäki et al., 2017). Examples of illegal waste trafficking include the shipment of non-hazardous waste contaminated with hazardous materials, the import of undeclared or unconsented waste, and the false classification of waste as second-hand goods to evade notification requirements. While the literature often refers to these activities as 'illicit waste trafficking' (IWT), we use the term 'illegal waste trafficking' in our study to focus specifically on documented cases of illegal shipments.

The legal trade of waste allows agents operating in low income countries to make profits from collecting, recycling, reusing, or disposing waste from richer countries. Individuals and companies that participate in the illegal trade may earn money from the resale of untreated waste such as plastic, paper, wood, glass, rubber, and metals. On the other hand, the profitability of illegal waste trade differs between waste types, with the intrinsic value and harmfulness of the waste playing key roles. The costs associated with legitimate waste disposal procedures are higher for more harmful waste types, resulting in wider profit margins for illegal disposal methods.

Because of their intrinsic economic value and their possible harmfulness, e-waste and end-of-life vehicles are particularly worth studying. The management and disposal of these waste types are very expensive because of their harmfulness; moreover, low income countries usually seek to import these waste types because their valuable components can be re-used or sold in second-hand markets (Huisman et al., 2015; Okorhi et al., 2017; Rucevska et al., 2015; Yang et al., 2008). According to data contained in the Basel Convention National Reports, the cases of illegal trade involving e-waste and end-of-life vehicles accounted for 62% of the total illegal transboundary shipments of waste that were registered worldwide between 2016 and 2019. Plastic waste illegally traded in the same period accounted for 9% of the total illegal transboundary shipments, metals for 8%, paper for 3%, and chemicals for 2% (UNEP & Basel Convention, 2022).

E-waste, i.e. waste from electrical and electronic equipment, may contain valuable metals, which make its disassembly and recycling particularly profitable. For instance, a ton of mobile phones yields about 128 kilos of copper, 3.63 kilos of silver, 0.35 kilos of gold, 0.15 kilos of palladium, as well as other valuable metals (Valero Navazo et al., 2014). In 2019 alone, 53.6 million metric tons of e-waste was globally generated. This was equal to 7.3 kilos per capita and only 17.4% of this volume was documented as being collected and properly recycled (Forti et al., 2020). Thus, the management of more than four fifths of global e-waste was not documented and a considerable amount of e-waste was trafficked illegally under the guise of being for reuse, or it was claimed to be scrap metal (Forti et al., 2020). This is a cause of concern because, circuit boards contain arsenic, and cooling equipment contains chlorofluorocarbons, which make e-waste hazardous to human health and the environment if dismantled without proper care (Gangwar et al., 2019).

End-of-life vehicles constitute another waste category that causes particular harm if not properly disposed of. Moreover, the automotive sector is rapidly growing; between 2010 and 2018, the global production of vehicles grew by almost a fourth, mainly due to increasing demand in emerging markets (OICA, 2021). The automotive sector is expecting to continue this growth in the next years thanks to the switch to electric vehicles (e.g., car sharing, e-hailing) and the sustained demand in recently opened markets. Therefore, the management of end-of-life vehicles is gaining importance worldwide (Karagoz et al., 2020). For instance, in the EU alone, 5 to 6 million end-of-life vehicles are treated every year in about 13,000 authorized treatment facilities (Eurostat, 2021a). There are a further 3.4 to 4.7 million end-of-life vehicles retired from the active stock that are not registered as treated in authorized treatment facilities or legally exported as second-hand vehicles (European Commission et al., 2018; Williams et al., 2020). There are indications that a substantial share of these vehicles are subject to illegal waste management and export without undergoing proper treatment and depollution. The sale of spare parts and metals generate profits and generate savings obtained by improperly treating the waste (Kitazume et al., 2020).

The available qualitative evidence shows that the direction of illegal waste flows depends on the type of waste trafficked; according to several case studies, e-waste is typically considered to move from EU countries to Africa and South-East Asia; used motor vehicles and associated parts from Western Europe to Eastern Europe and Africa (Andreatta & Favarin, 2020; Bisschop, 2012; Sahramäki et al., 2017). Nonetheless, research that maps the global illegal waste flows of specific waste types is missing in the literature on waste crimes, leaving us with a fragmented picture of the global waste trafficking network. Overall, we tend to know more about origin countries such as the European ones and destination countries such as China and Nigeria, but we know less about the United States, Canada, Russia, South America and their trafficking routes.

This study reconstructs and analyses the structures and characteristics of the networks of countries among which the trafficking of end-of-life vehicles and e-waste occurs. In so doing, it maps the waste flows and identifies differences in the way in which the two types of waste are trafficked all over the world. The results of this analysis yield a clearer picture of the phenomenon of illegal transboundary movements of waste which considers waste-type specificities. International organizations, environmental protection agencies, and law enforcement authorities have stressed that the fight against waste crimes must start to differentiate between waste streams in order to increase its effectiveness (Europol, 2021; Forti et al., 2020; Secretariat of the Basel Convention, 2018). This research makes it possible to verify and integrate the qualitative evidence discussed above with a quantitative study that considers all known illegal transactions between countries, rather than focusing on selected well-known trafficking routes (e.g., France and Nigeria, the Netherlands and China, etc.).

The paper is structured as follows. The next section outlines the literature on transnational waste trafficking. The third section introduces our research questions and hypotheses related to the structure of the trafficking networks, differences and similarities between end-of-life vehicles and e-waste trafficking networks, and the different directions of the transnational flows. The fourth section describes the data used to reconstruct the trafficking networks and the methods and measures employed to analyze them (e.g., analysis of the degree imbalance, analysis of the dyad census). The fifth section presents the results of our investigation and answers our research questions, whilst the sixth section discusses our results and their possible interpretations. The seventh section outlines possible future branches of research stemming from the results presented.

Transnational waste trafficking in the literature

Crime statistics and systematized data on transboundary shipments of illegal waste are almost non-existent. Consequently, empirical research on waste trafficking flows has often adopted a case-study approach and analyzed domestic illegal waste flows, particularly in European countries (e.g., from one area of a country to another area of the same country) or transnational trade along specific routes (e.g., e-waste shipped from Belgium to Ghana or from the Netherlands to China).

Massari and Monzini (2004) conducted a study on national waste trafficking in Italy from 1989 to 2003. They analyzed six judicial cases and interviewed prosecutors and law enforcement agents, with a particular focus on the role played by mafia groups and other actors. Their study found that illegal waste was transported from economically developed provinces in the North of Italy to less affluent provinces in the South, which had weaker legal institutions.

Bisschop (2012) examined the transnational trafficking of e-waste from the port of Antwerp, in Belgium, to countries in Africa and Asia. The study was based on a document analysis of primary and secondary sources, as well as interviews with key informants and field research in the port of Antwerp (Belgium), the port of Tema (Ghana), and the Agbogbloshie dumpsite (Ghana). The study showed that waste collectors, waste transporters and other actors involved in the e-waste trafficking tread a fine line between legal and illegal practices. Push, pull, and facilitating factors at individual, organizational, and societal levels jointly provide the motivations and opportunities for the illegal transport of e-waste.

Spapens and colleagues (2018) analyzed thirteen criminal investigations of illegal shipments of waste from the Netherlands to China in order to delineate the *modi operandi* of the offenders and the main difficulties of law enforcement agencies in combating this crime. The criminal investigations mainly considered streams of plastic waste, metal waste, used toner cartridges, household waste, and cable and transformer waste. The offenders often sent the shipments via the nearby Belgian port of Antwerp instead of exploiting Rotterdam because inspections are more lenient in Antwerp or because Dutch customs had already flagged the offenders. In addition, Spapens and colleagues (2018) identified countries, such as Hong Kong and Malaysia, reported as fictitious destinations of shipments that are actually trafficked to China. While the country of origin (i.e., the Netherlands in these cases) should be informed when the destination changes (e.g., from Malaysia to China), in practice, this requirement is unenforceable because it is difficult to keep track of the shipments after they leave a harbor (Spapens et al. 2018).

Sahramaki and colleagues (2017) conducted a comparison of thirteen judicial cases of cross-border waste trafficking from the Netherlands, Italy, and Finland. This study provided a broad picture of the various actors involved and the distinct phases of the criminal acts (e.g., creation, collection, storage, transport, treatment, and disposal). Andreatta and Favarin (2020) further analyzed five of those thirteen cases and gave insights into the trafficking routes of several types of waste (e.g., plastic, paper, old garments, e-waste, end-of-life vehicles). Andreatta and Favarin (2020) analyzed transnational shipments of different kinds of illegal waste from Italian harbors (e.g., Genoa, Trieste, Venice, Naples) to China, Syria, Nigeria, Ivory Coast, Vietnam, Pakistan, Malaysia, South Korea, the United Arab Emirates, and India. Slovenia and Hong-Kong were identified as key transit countries for these shipments. According to the qualitative evidence provided by Sahramaki and colleagues (2017) and Andreatta and Favarin (2020), specific waste categories tend to follow particular paths and reach specific destination countries.

Overall, the available studies offer fragmented evidence that sheds light on the functioning of certain trafficking routes. At the same time, previous literature presents an incomplete picture of global waste trafficking. Indeed, to investigate transnational illegal waste trafficking, all flows should be combined to recreate a global network of connections. Favarin and Aziani (2020) made an effort in this direction by creating a global network of countries involved in illegal waste trading. They identified France, the United Kingdom, Germany, Sweden, and Belgium as the main global illegal waste exporters, and China, Poland, Nigeria, and Ghana as the main importers of illegal waste. Other destination countries for illegal shipments at the global level were Benin, Cameroon, Guinea, Senegal, Congo, Cote d'Ivoire, and Gambia in West Africa and India, Pakistan, Malaysia, and Thailand in South and Southeast Asia (Favarin & Aziani, 2020). While Favarin and Aziani (2020) provided a description of the overall structure of waste trafficking at the global level, they did not differentiate among flows according to the type of waste. Therefore, no study has yet assessed how trafficking routes for different waste categories differ from one another, nor has any study investigated the structure of the transnational trafficking networks by type of waste.

Problem formulation

To guide the analysis of the differences and similarities of transnational trafficking flows for various waste types, we formulated three research questions. We focused on the illegal flows of end-of-life vehicles and e-waste between any two countries worldwide. To this end, we created two networks that included all countries known to illegally exchange end-of-life vehicles and e-waste. Our analysis considers the macro-level of illegal waste movements among countries, with the understanding that actors responsible for trafficking activities may include individuals, companies, or groups operating within each country or across multiple countries. Within these two networks, the connections between countries represent illegal waste flows. Thus, identifying France as a main exporter of a specific type of illegal waste implies the involvement of waste traffickers operating within or from France, as an example. This approach is similar to the one taken by scholars who study both legal and illegal trade between countries, where the actions of individuals or businesses operating in one or more countries are aggregated at country level to study the flows of licit and illicit goods and services across the globe (Aziani, 2020; Aziani et al., 2021; Bhattacharya et al., 2008; Bichler & Malm, 2013; Boivin, 2013; Chandra & Joba, 2015; Martínez et al., 2022; Meneghini et al., 2020).

Q1: Does the structure of the networks and the countries involved in trafficking differ according to the type of waste?

The majority of countries generate a surplus of both end-of-life vehicles and e-waste. High income countries have stricter regulations and higher costs of waste disposal compared to low income countries. All high-income countries have a demand for services that make it possible to cut the costs of the treatment and disposal of both types of waste, although to different extents. Therefore, in terms of source countries, we expect the two networks to be similar. By contrast, the demand for the two types of secondary raw material is not homogenous across countries, not only at the global level but also when focusing on the Global South. Differences among countries in their demand for end-of-life vehicles and e-waste are due to the intrinsic values of the two types of waste: higher for e-waste and lower for end-of-life vehicles, whose parts are valuable only in less advanced economies. Consequently, we expect end-of-life vehicles and e-waste to have different destinations, resulting in differences in the trafficking flows in terms of the countries involved and the overall structure of their global networks.

Q2: To what extent do illegal flows of end-of-life vehicles and e-waste move from the Global North to the Global South?

Prior research has highlighted that illegal waste flows tend to go from richer to less affluent countries (Elliott & Schaedla, 2016; Favarin & Aziani, 2020; Klenovšek & Meško, 2011). The mechanism whereby countries in the Global South (e.g., in Central and South America, in Asia, in Africa) are being turned into reservoirs of garbage, toxic waste, and hazardous products is known as an important form of environmental injustice (Adeola, 2000; Clarke, 1997; Cotta, 2020). Since the 1990s, greater awareness of environmental issues has induced most governments in the Global North (e.g., in Europe, in Australia, in North America) to introduce more stringent regulations for waste management. As a consequence, the increased costs of safe and legal waste disposal have contributed to the development of an illegal export trade to many of the countries in the Global South. It is widely believed that illegal waste imports easily cross national borders, particularly in countries with either weak or non-existent inspection systems and technologies (Klenovšek & Meško, 2011; Liddick, 2010; Pereira, 2015).

Despite robust evidence that illegal waste mainly moves from the Global North to the Global South, there are neither quantifications of the amount of these flows nor prior studies that have explored whether the North-to-South relations is much frequent for end-of-life vehicles or e-waste.

Q3: Are illegal flows of end-of-life vehicles and e-waste reciprocal?

Unscrupulous entrepreneurs illegally send discard materials to other countries where disposal costs are lower, regulation is laxer, enforcement is poorer, and the discard materials are of economic interest (Klenovšek & Meško, 2011). From a rational cost-opportunity perspective, we do not expect there to be reciprocal flows of illegal waste. Rather, we expect countries with higher disposal costs, tighter regulation, and better enforcement to export most illegal waste and import little to none of the same waste type. Because of the nature of the illegal waste trade itself, illegal waste flows should go from country A to country B, but not from country B to country A. This feature is common to other transnational illegal markets such as those for heroin and cocaine (Aziani et al., 2021; Giommoni et al., 2021).

Data and method

Because our focus was on source-destination patterns between countries illegally trading in end-of-life vehicles and e-waste, we relied on social network analysis (SNA) to answer our research questions. SNA has been extensively used to study both international legal trade (e.g., Bhattacharya et al., 2008; Martínez et al., 2022; Setayesh et al., 2022; Ward et al., 2013; Ward & Hoff, 2007) and the transnational trafficking of drugs (Aziani et al., 2021; Berlusconi et al., 2017; Boivin, 2013, 2014a, 2014b; Chandra et al., 2011, 2014; Chandra & Joba, 2015; Giommoni et al., 2017, 2021), firearms (Bichler & Malm, 2013), and tobacco products (Meneghini et al., 2020). The application of SNA to interactions between countries has helped identify overall patterns of international trade, countries that emerge as key exporters or importers of specific legal or illegal goods, and the determinants of cross-border flows. SNA has contributed to the study of crime patterns in a globalized world (Morselli, 2009).

To conduct our analyses, we systematized data on transnational cases of waste trafficking that occurred between 2016 and 2019 and was provided by the Basel Convention National Reports. We then plotted networks of countries that were involved in the illegal exchange of end-of-life vehicles and e-waste. Specifically, we created two binary and directed networks where the nodes represented countries, and the edges represented the trade connections for end-of-life vehicles and e-waste.[1] Every time that a country – importer or exporter – was indicated as being involved in a trafficking case with another country a link was established between the two countries.[2] The two networks included 125 countries that illegally exchanged end-of-life vehicles, e-waste, or both, between 2016 and 2019. Not all countries were involved in the trafficking of both waste types, resulting in global networks with 29 isolates in the case of end-of-life vehicles and 11 isolates in the case of e-waste. Each research question was investigated by considering specific measures and characteristics of the networks that are summarized in Table 1.

To answer Question 1 – Does the structure of the networks and the countries involved in the trafficking differ according to the type of waste? – we highlighted differences and similarities between the networks of end-of-life vehicles and e-waste by comparing the statistics pertaining to the two networks. We first considered traditional network-level measures such as centralization (i.e., the extent to which countries tend to have similar or differing levels of trading activity) and density (i.e., the proportion of observed ties out of all possible ties). We then calculated a node-level measure called 'degree imbalance'. The 'degree imbalance' corresponds to the difference between the value of the in-degree centrality and the value of the out-degree centrality of each country to identify the main net exporters and importers in each network.[3] The 'degree imbalance' measure enables us to distinguish between importer countries and exporter countries, where the former are countries for which the in-degree centrality was larger than the out-degree centrality, and the latter are countries for which the out-degree centrality was larger than the in-degree centrality. If the degree imbalance is higher than zero, then the countries are net exporters of waste. If the degree imbalance is lower than zero, then the countries are net importers. If the value of the degree imbalance is zero, the countries are neither net exporters nor net importers; they had a hybrid role in the network. We plot the values of degree imbalance in two maps, one for

[1] 'End-of-life vehicles' category, which is often abbreviated as ELV, predominately includes waste codes 16 01 04, A1160, A1180, B3140 and B1250, which refer to end-of-life vehicles, lead-acid batteries and pneumatic tires. When waste codes are not included in BCNRs we used the specified description to determine the category of waste (e.g., harvesters, work vehicles, car parts, car batteries, tires, damaged vehicles, engines, spare parts of end-of-life vehicles, used cars and used spare parts). The 'E-waste' category, which is often abbreviated as WEEE, predominately includes waste codes A1180, B1010, B1130 and A1160 which refer to electrical and metal components, such as catalysts, lead-acid batteries, cables, accumulators or cathode-ray tubes. When waste codes are not included in BCNRs we used the specified description to determine the category of waste (e.g., batteries, household appliances such as refrigerators, cables, electronics, electronic scarp, mobile phones, printed circuit boards, toner cartridges and monitors). We decided to include batteries and accumulators in the e-waste category because Eurostat (2021b Table 6) stated that "hazardous components from electrical and electronic equipment may include lead batteries, Ni-Cd batteries, mercury-containing batteries and other batteries and accumulators marked as hazardous; mercury switches, glass from cathode ray tubes and other activated glass, etc."

[2] Cases of illegal waste trafficking are detected by enforcement authorities of countries that are part of the Basel Convention and report information on the country of export, import, waste code, waste type, quantity, reason for illegality, responsibility, and actions taken. Only when the national authority identifies both the country of dispatch and the country of destination of the illegal shipment the case was included in the dataset. However, differences in interception capacity and statistical reporting quality suggest caution in using these data. To address this, we follow other scholars' examples (Boivin, 2013; Favarin & Aziani, 2020; Giommoni et al., 2017) and focus exclusively on the presence or absence of connections. We use the data to identify pairs of countries involved in waste trafficking and establish each country's position in the global waste trafficking networks. Our graphs represent the likely most trafficked routes, rather than a detailed schematization of the actual networks. We assume that connections in the BCNRs are more relevant, on average, than those that do not appear, although others likely exist.

[3] Appendix 1, which can be accessed at https://osf.io/4xzk5/?view_only=fe258258dc624f54bed577f4ac3bbc58, reports the node level measures in-degree centrality, out-degree centrality and degree imbalance for each country in each network.

end-of-life vehicles and the other one for e-waste. The map's class breaks are determined by natural groupings inherent in the data using the Jenks natural breaks method. This method groups similar values together and maximizes the differences between the classes. The data values are divided into five classes - importer, mainly importer, importer/exporter, mainly exporter, and exporter. The boundaries for each class are determined by minimizing the average deviation of each class from its mean while simultaneously maximizing the deviation of each class from the means of other classes. In essence, this method aims to reduce the variance within each class and increase the variance between them. We manually set the third class, "importer/exporter," to include only the "0" values, based on the methodological choices specified in the preceding paragraph.

Table 1. Summary of the methods used to answer the research questions and of the interpretation of the results

Research question	Method	Results interpretation
Q1: Does the structure of the networks and the countries involved in the trafficking differ according to the type of waste?	• Analysis of the networks' descriptive statistics: network size, number of isolates, network edge count, density, mean degree, mean indegree, indegree centralization, outdegree centralization, betweenness centralization. • Analysis of the degree imbalance (vertex outdegree minus its indegree) for each country in each network.	• Similar network statistics indicate structural similarity between the networks. Conversely, dissimilar statistics suggest that the structure of the trafficking networks is different. • A degree imbalance higher than zero indicates that the country is a waste exporter (or vice versa importer). If the value is zero, the country is neither an exporter nor an importer. If the countries involved in the networks are the same and play the same (or similar) roles as exporters or importers, then the networks can be considered similar (or conversely dissimilar).
Q2: To what extent do illegal flows of end-of-life vehicles and e-waste move from the Global North to the Global South?	• Analysis of the relative amount of flows for each combination of origin and destination areas (e.g., Global North-Global South, Global North-Global North, etc.) on the total number of flows for each network.	• A higher percentage of flows for the combination Global North-Global South compared to other combinations (e.g., Global North-Global North, Global South-Global South, etc.) will highlight the tendency of illegal waste to be trafficked among these areas.
Q3: Are illegal flows of end-of-life vehicles and e-waste reciprocal?	• Analysis of the dyad census for the two networks which will give information on the number of asymmetric and mutual dyads and the percentage of asymmetric and mutual dyads on the total existing dyads.	• If the number and the percentage of asymmetric dyads is higher than the number of mutual ones the waste flows are considered mostly unidirectional.

To answer Question 2 – To what extent do illegal flows of end-of-life vehicles and e-waste move from the Global North to the Global South? – we first catalogued countries as belonging to the Global North or the Global South.[4] We then used a mixing matrix to count, for each network, the number of flows originating from countries in the Global North that reach countries in the Global South or other countries in the Global North,

[4] In 1980, the Brandt Line was virtually drawn to highlight the disparities and inequalities between the wealthy Global North (e.g., Europe, North America, Australia, and Japan) and the poorer Global South (e.g., Africa, Asia, and Latin America). For many economic, political, social and historical reasons, there is more evidence of continuity than change in the position of the Global South within the international system, so that it is still meaningful to speak about Global North and Global South from an international perspective (Lees, 2021). However, the concept of Global North and Global South has slightly changed over the past forty years. To the authors' knowledge there is not a well-recognized and generally used updated list of countries belonging to the Global North or to the Global South to be used for scientific purposes. For this reason, in Appendix 2 (available at https://osf.io/4xzk5/?view_only=fe258258dc624f54bed577f4ac3bbc58) we present the classification of countries by Global North and Global South that we used in our analyses.

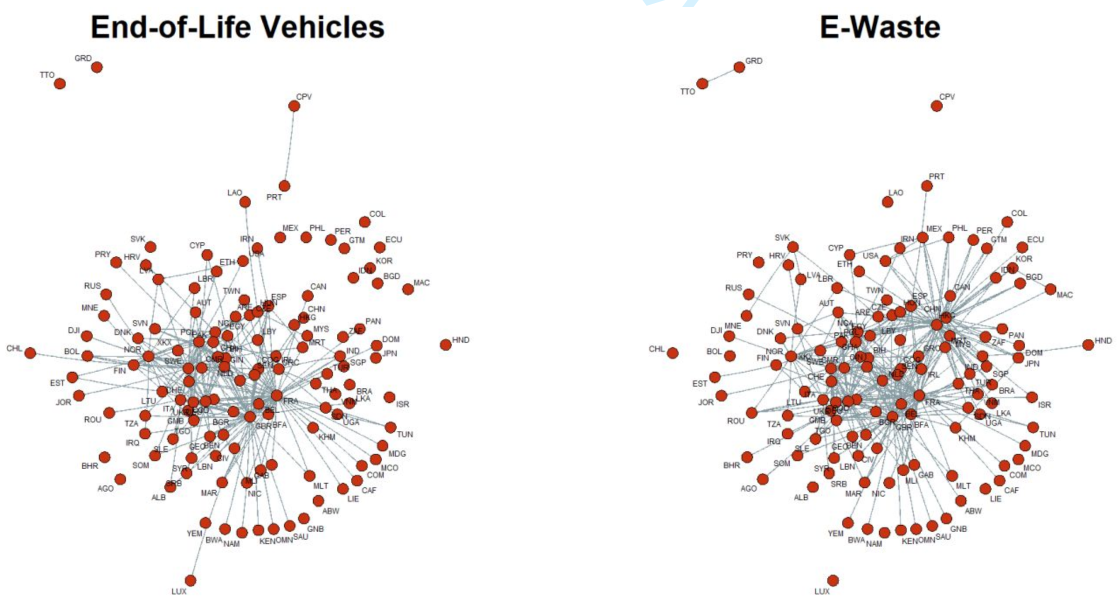
as well as the number of flows originating from countries in the Global South that reach countries in the Global North or other countries in the Global South. Finally, we calculated the percentages of flows for each combination of origin-destination areas (i.e., Global North-Global South, Global North-Global North, Global South-Global North, and Global South-Global South) on the total number of flows for each network.

With respect to Question 3 – Are illegal flows of end-of-life vehicles and e-waste reciprocal? – we calculated the dyad census of each network. Dyads are pairs of nodes (or countries) in a network. In a directed network, we can find three types of dyads—null (that is, when two countries do not share a link), asymmetric (that is, when two countries share a unidirectional link), and mutual (that is, when two countries share a reciprocal link) (Wasserman & Faust, 1994). The dyad census is the count of dyad types within a network. The proportion of asymmetric and mutual dyads on the total number of existing dyads provides the degree to which illegal flows are unidirectional rather than mutual.

Results

This section compares the networks related to end-of-life vehicles and e-waste trafficking. The e-waste network is larger and more connected, comprising a larger main clique (114 nodes) compared to the end-of-life vehicles' network (96 nodes).[5] The mean degree of the e-waste network (5.39) is higher than that of the end-of-life vehicles' network (3.62), indicating that the former is denser and more cohesive than the latter – i.e., density equal to 0.01 and to 0.02, respectively (Figure 1 and Table 2). The e-waste network is also more widespread, with 19 more countries involved in the exchange of e-waste than end-of-life vehicles. Additionally, on average, nodes in the e-waste network have one more connection than nodes in the end-of-life vehicles network.

Figure 1. End-of-life vehicles and e-waste trafficking networks (2016-2019)



[5] A clique is a subset of nodes of an undirected graph such that every two distinct vertices in the clique are adjacent (Luce & Perry, 1949).

The centralization scores reveal that both incoming and outgoing ties are not equally distributed in the two networks (Table 2). Out-degree centralization is 0.33 for both networks, which suggests that most countries export to only one or a few countries, while a small number of exporters have several outgoing edges. In-degree centralization is higher in the e-waste network than in the end-of-life vehicles network (0.27 vs. 0.12, respectively), suggesting that the e-waste network is more likely to include countries acting as hubs or key importers, while incoming ties in the end-of-life vehicle network tend to be more evenly distributed among countries.

Table 2. Descriptive statistics of the end-of-life vehicles and e-waste trafficking networks (2016-2019)

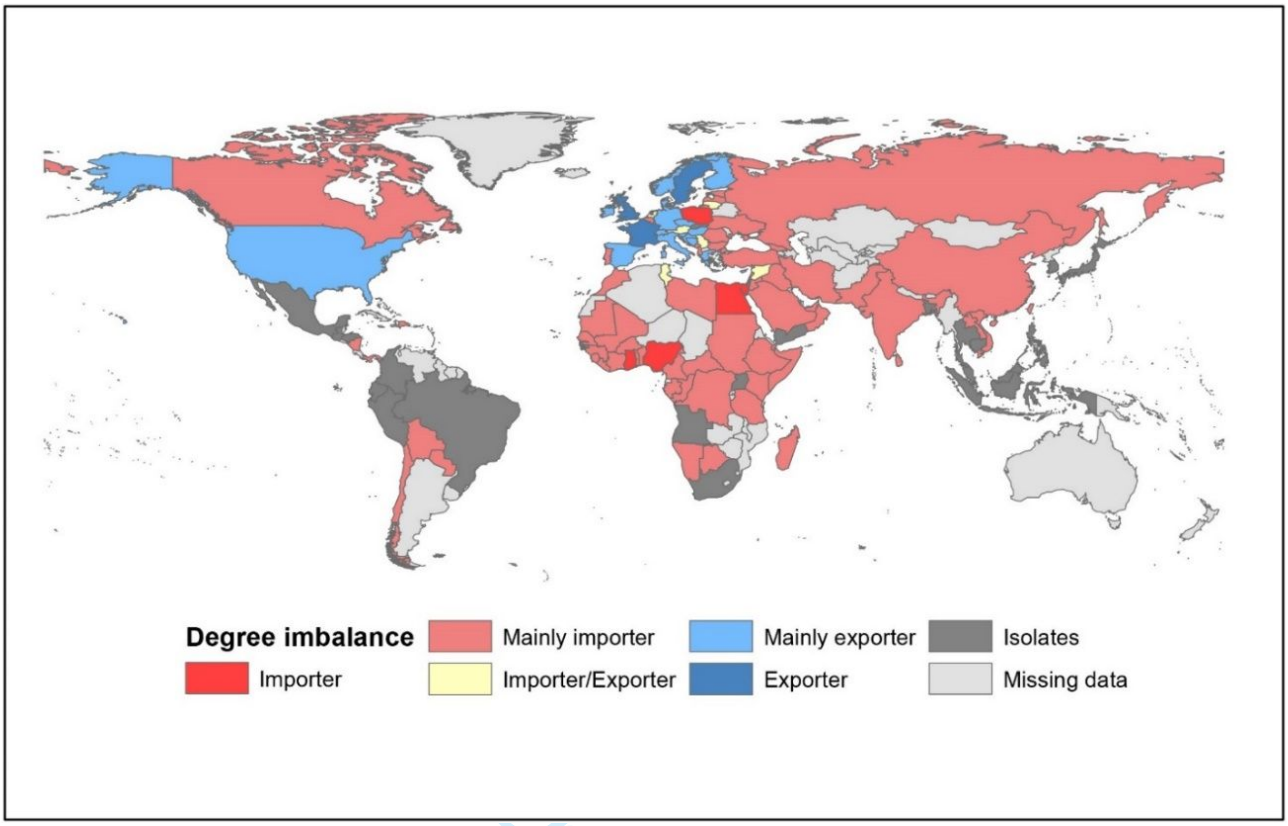
	End-of-life vehicles trafficking network	E-waste trafficking network
Network size	125	125
Number of isolates	29	11
Network edgecount	226	337
Density	0.01	0.02
Mean degree	3.62	5.39
Mean indegree	1.81	2.70
Indegree centralization	0.12	0.27
Outgree centralization	0.33	0.33
Betweenness centralization	0.08	0.26

The node-level measure called ‘degree imbalance’ identifies a few countries as *exporters* and *mainly exporters* of illegal end-of-life vehicles (Figure 2).[6] These countries are mainly in Europe. Most countries in the end-of-life vehicles trafficking network are *mainly importers* or *importers*.[7] Nigeria, Poland, Egypt, and Ghana present high values of degree imbalance, playing a central role as importers of this waste type. Nigeria emerges as one of the main destination countries also in the e-waste trafficking network, along with China and Hong Kong (Figure. 3).

Figure 2. Exporters and importers of illegal end-of-life vehicles (Degree imbalance) (2016-2019)

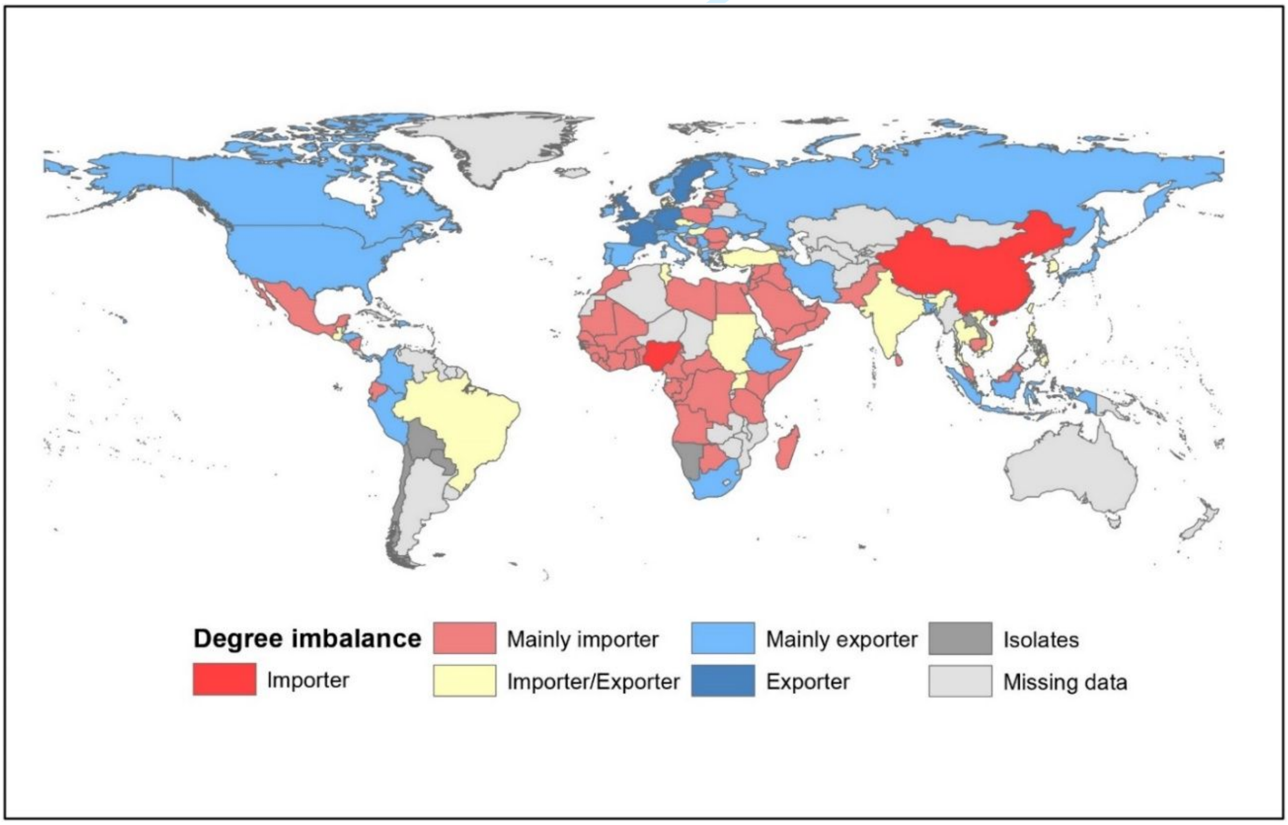
[6] The *Data and method* section explains the procedure used to estimate the ‘degree imbalance’ and its interpretation.

[7] Importer, mainly importer, importer/exporter, mainly exporter, and exporter are the five categories in which the values of the ‘degree imbalance’ have been divided to distinguish among the different roles played by the countries in the network. The *Data and method* section includes additional information about this measure and its classes, as do the notes accompanying Figure 1 and Figure 2.



Note: The figure depicts the Degree Imbalance of nodes in the end-of-life vehicles' network. The class breaks are determined using the Jenks natural breaks method, which identifies natural groupings in the data and groups similar data values together while maximizing the differences among classes. The data values are divided into five classes, and the boundaries are determined by minimizing the average deviation of each class from its mean while simultaneously maximizing the deviation of each class from the means of the other classes. The "Importer/Exporter" class was manually set to include only values of "0".

Figure 3. Exporters and importers of illegal e-waste (Degree imbalance) (2016-2019)



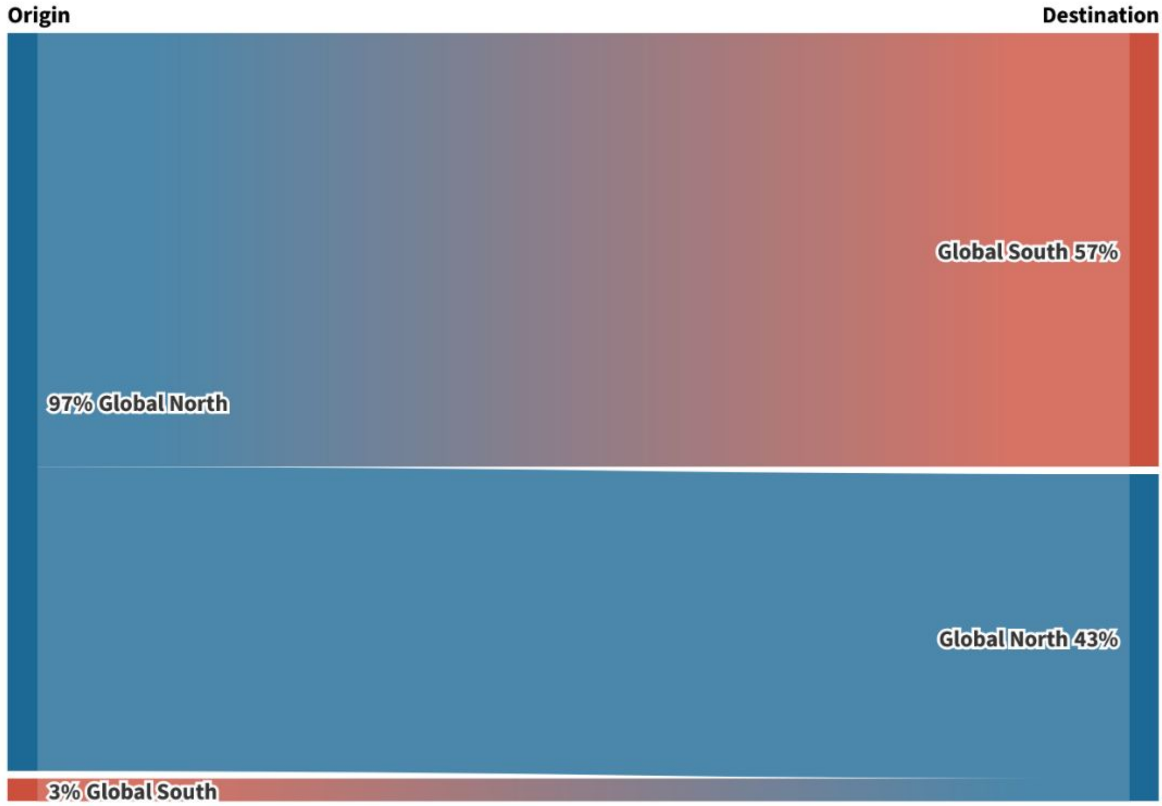
Note: The figure depicts the Degree Imbalance of nodes in the e-waste' network. The class breaks are determined using the Jenks natural breaks method, which identifies natural groupings in the data and groups similar data values together while maximizing the differences among classes. The data values are divided into five classes, and the boundaries are determined by minimizing the average deviation of each class from its mean while simultaneously maximizing the deviation of each class from the means of the other classes. The "Importer/Exporter" class was manually set to include only values of "0".

The e-waste trafficking network has a larger number of net exporters in many parts of the world, including Europe (e.g., the United Kingdom, France, Germany, Sweden), North America (e.g., the United States, Canada), Latin America (e.g., Peru, Colombia), Eastern Asia (e.g., Japan, Indonesia) and Africa (e.g., South Africa), when compared to the end-of-life vehicles network. Indeed, the e-waste network exhibits a higher percentage of illegal flows originating from the Global South, amounting to 15%, compared to the end-of-life vehicles network, where only 3% of illegal flows originate from the Global South and 97% from the Global North (Figure 4).

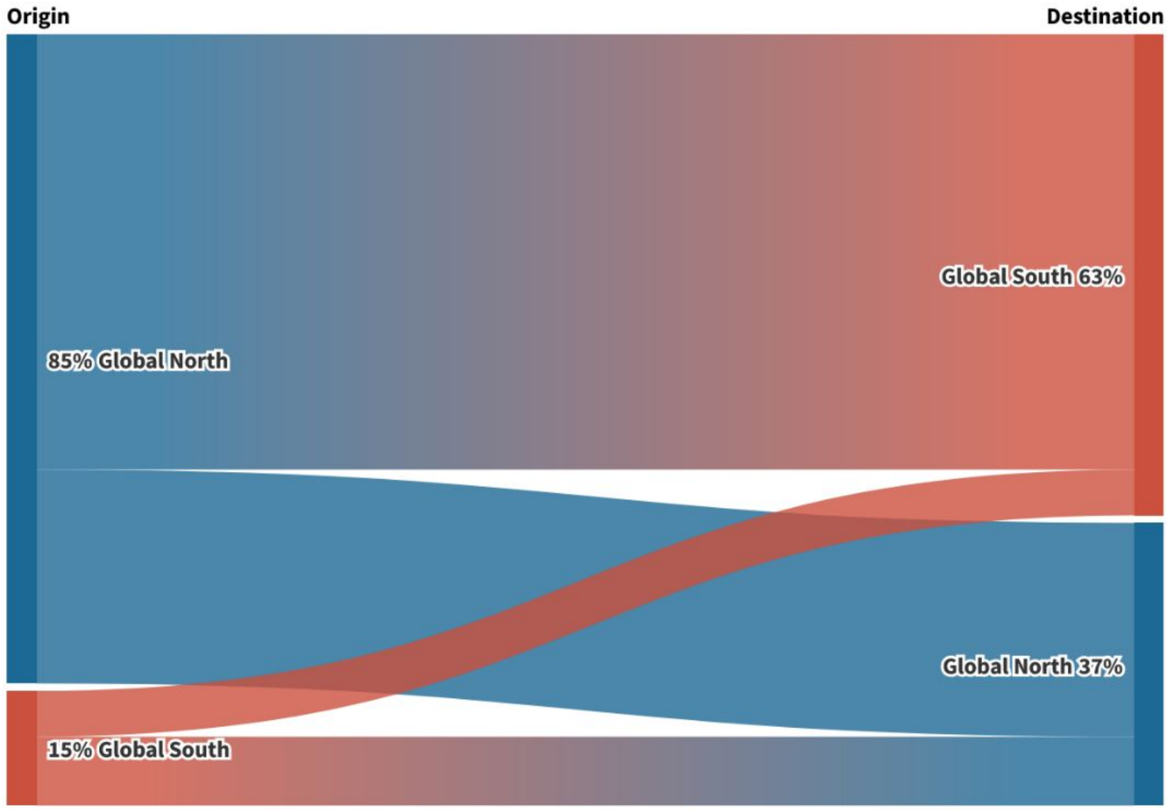
Illegal flows of both end-of-life vehicles and e-waste primarily move from countries in the Global North to countries in the Global South; 57% of trafficking routes for both waste types follow this path (Figure 4, 5, 6). Nevertheless, 40% of the illegal flows involving end-of-life vehicles and 28% of the illegal flows of e-waste that originate in the Global North are sent to other countries in the Global North. Only a small percentage of illegal flows originate in the Global South, with 3% of all connections in the end-of-life vehicles network going from a country in the Global South to a country in the Global North, and 9% of connections in the e-waste network originating in the Global South and heading to countries in the Global North. Illegal e-waste is also exchanged among countries in the Global South, accounting for 6% of the recorded global illegal flows of this waste type. Despite this, the role that countries in the Global South can play as exporters has been overlooked in the literature, even though 3% of the connections in the end-of-life vehicles network and 15% of the connections in the e-waste network originate from countries in the Global South (Figure 4).

Figure 4. Flows of illegal waste by origin and destination area (2016-2019)

End-of-life vehicles



E-waste



Note: The ‘mixingmatrix’ function in the R package ‘network’ was used to calculate the number of edges between any two countries based on whether they belong to the Global North or the Global South (Butts, 2008, 2015).

Figure 5. Flows of illegal end-of-life vehicles, country-to-country connections (2016-2019)

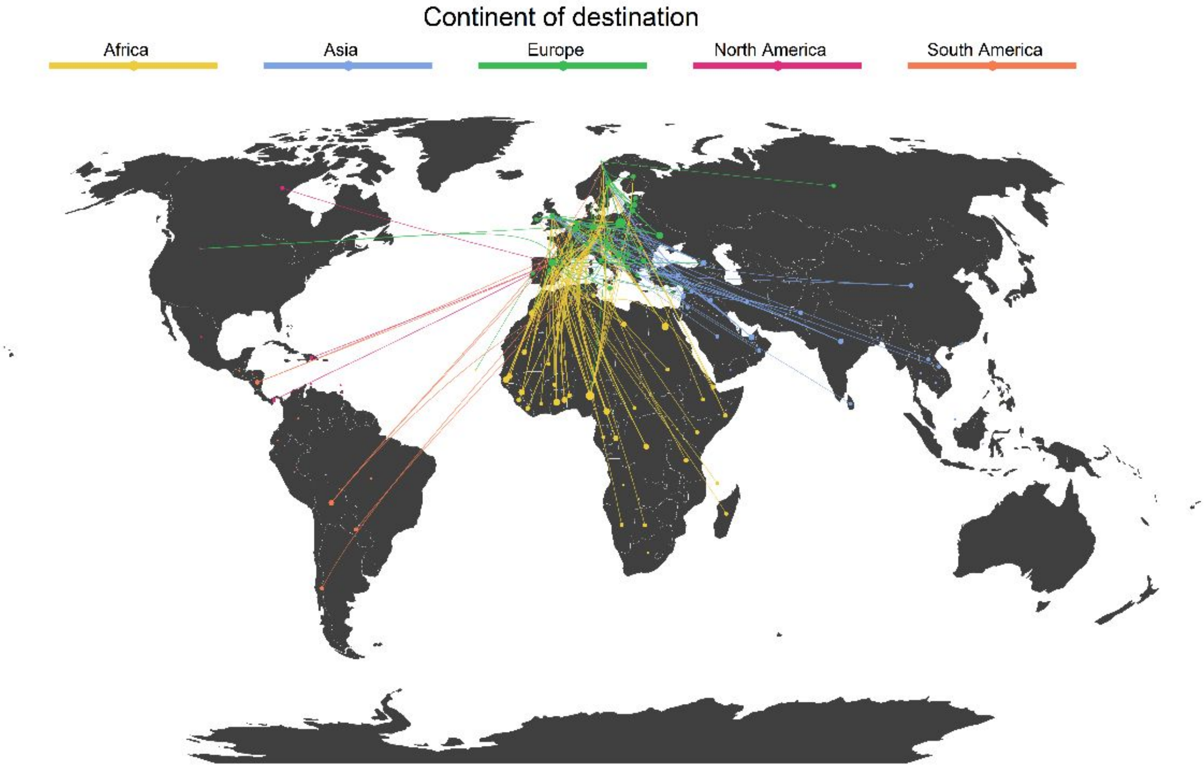
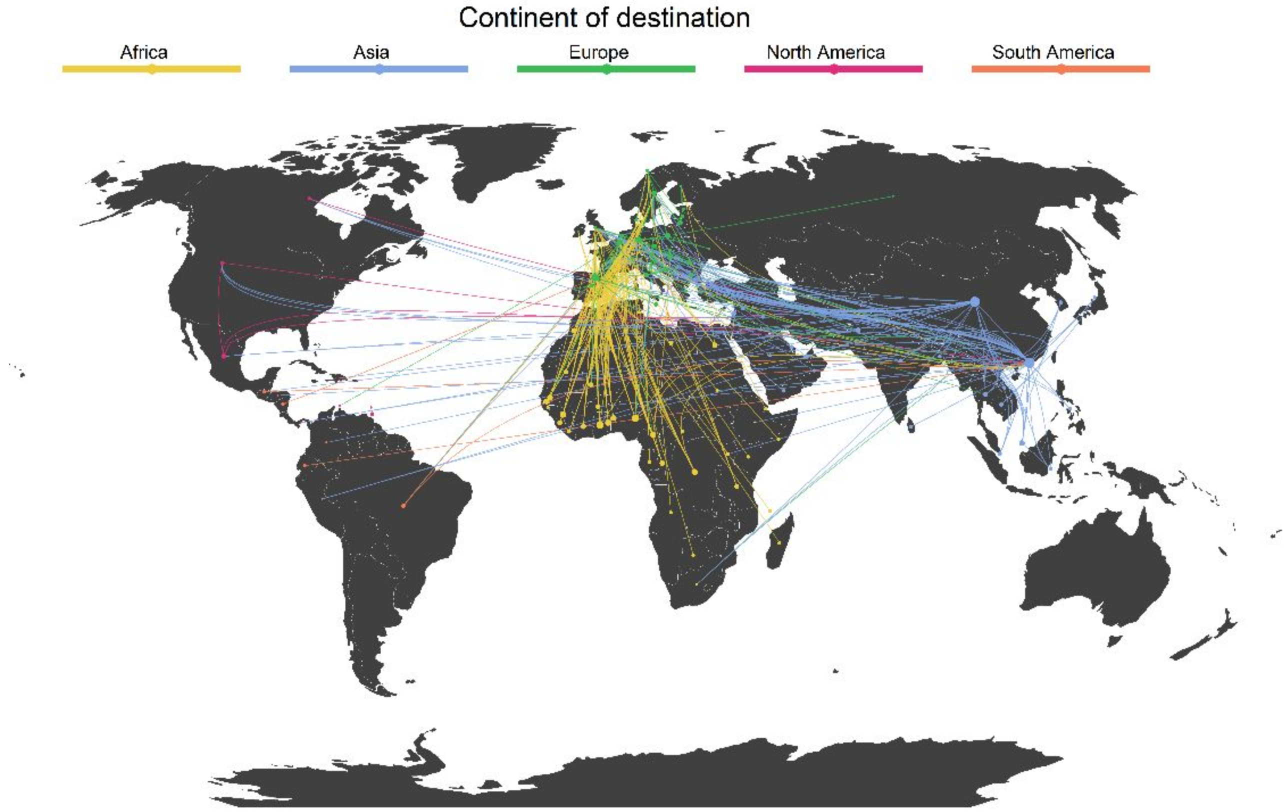


Figure 6. Flows of illegal e-waste country-to-country connections (2016-2019)



The trafficking flows of end-of-life vehicles and e-waste are primarily unidirectional. Both networks present asymmetric and mutual dyads as well as null dyads (i.e., any two countries that are not directly linked). The dyad census of both networks shows a higher number of asymmetric dyads compared to mutual dyads (Table 3). In the end-of-life vehicle network, 94% of the dyads are asymmetric and 6% are mutual, whereas in the e-waste network the asymmetric dyads are 90% and the mutual dyads are 10%. A few recurrent countries appear multiple times in the mutual dyads. In the end-of-life vehicles network, these countries are primarily France, the United Kingdom and Poland. In the e-waste network, they are primarily Hong Kong, France and Germany.

Table 3. Dyad census of the two networks (with isolates)

	End-of-life vehicles trafficking network	E-waste trafficking network
Mutual	13 (6%)	32 (10%)
Asymmetric	200 (94%)	273 (90%)
Total existent dyads	213 (100%)	305 (100%)

Note: The dyad census also includes 7,537 null dyads for the end-of-life vehicles trafficking network and 7,445 null dyads for the e-waste trafficking network. Null dyads indicate the absence of any direct connection between a pair of countries.

Discussion

In both the end-of-life vehicles and e-waste networks, many countries export to just one or a few countries, while few countries ship illegal waste to numerous destinations. Similarly, in both trafficking networks, a few significant importing countries receive waste from numerous countries; notably, Nigeria and Poland receive end-of-life vehicles while China, including Hong Kong, receives e-waste. Conversely, most countries import only from one or a few countries.

Despite the fact that the illegal flows of both waste types concentrate in important receiving hubs, our analysis shows that the structure of the trafficking networks and the countries involved in the trafficking depend on the type of waste trafficked. In particular, the transnational trafficking network of e-waste has a larger main clique, more connections, and a higher indegree centralization than the end-of-life vehicles' network (Table 4). These results, particularly the higher indegree centralization of the e-waste network, support our expectations that the illegal import of e-waste is more geographically widespread than the illegal import of end-of-life vehicles, possibly due to the higher value of e-waste.

Differences between illegal flows of end-of-life vehicles and e-waste also regard the role of specific countries in the two traffics. Although there are some recurrent countries that are significant exporters (e.g., France, the United Kingdom, and Sweden) or importers (e.g., Nigeria, Cameroon) of both waste types, the main source countries of end-of-life vehicles and e-waste are often different. Additionally, the principal destination countries tend to differ according to the waste type. Overall, the end-of-life vehicles trafficking network has a smaller number of origin countries, located mainly in Europe, compared to the e-waste trafficking network, which has a higher number of source countries in several areas of the world (e.g., Europe, North America, Latin America, Africa, South-East Asia). The different spreads and distinct life cycles of the two products might provide an explanation of the higher number of source countries in the e-waste network compared to the end-of-life vehicles one. Electronic products, particularly mobile phones, are widely used across the world, both in the Global North and the Global South (Olaleye et al., 2019), while the availability of vehicles is more heterogeneous across countries. In addition, electronic devices are often less durable than vehicles. Hence, the need to manage e-waste emerges more frequently in a larger number of countries.

Our analysis identifies three distinctive patterns with respect to flows of illegal waste across macro areas. For both e-waste and end-of-life vehicles, the majority of the flows go from countries in the Global North to countries in the Global South. This result is not surprising and is largely supported by prior qualitative evidence (Andreatta & Favarin, 2020; Bisschop, 2012; Sahramäki et al., 2017). Previous studies have shown that former colonizers continue to exploit their former colonial territories environmentally, which began during the colonial era (Adeola, 1996; Favarin & Aziani, 2020; Heger, 2017). Moreover, societies that are weak due to their subordinate position in the world economy are prone to receive illegal waste (Adeola, 2000). Improper waste management poses a threat to human health and the environment (Boldrocchi et al., 2018; Chen et al., 2011), and the illegal trade of waste directed toward the Global South provides additional evidence of the exploitation of poorer by richer countries.

On the other hand, we also observe a North-North dynamic which is more marked for illegal end-of-life vehicles than for illegal e-waste. 40% of the illegal flows of end-of-life vehicles and 28% of the illegal flows of e-waste originating in the Global North are headed to other countries in the Global North. Previous studies have shown that, everything else being equal, geographically proximate countries are more likely to exchange illegal waste compared to distant ones (Favarin & Aziani, 2020). In this respect, the geopolitical proximity between European countries may reduce the costs of the illegal trade and facilitate the exchange of illegal waste among those countries located in the Global North. The geopolitical proximity contributing to illegal trade is not unique to the illegal waste trade, but it is also observed in other illegal markets, such as drug trafficking (Aziani et al., 2021; Giommoni et al., 2021). Furthermore, strong commercial connections and well-functioning legal trade channels for waste between countries in the Global North may also contribute to the exchange of illegal waste among them (Favarin & Aziani, 2020). Entrepreneurs already working in the legal sector can more easily hide the illegal nature of shipments, produce accompanying documents, and find buyers for the products (Andreatta & Favarin, 2020; Sahramäki et al., 2017). For instance, in 2019, EU countries exported 8.1 million tons of hazardous waste to other countries of the Global North, with 89% of the total outgoing shipments reaching other EU countries, 7% European Free Trade Association countries, mainly Switzerland and Norway, and 4% OECD countries, mainly the UK and Turkey (Eurostat, 2021b).

We also observe reverse journeys from the Global South to the Global North and, in the case of e-waste, from South to South. However, such flows originating in the Global South are rare. Only 3% of all connections in the network of end-of-life vehicles and 9% of all connections in the e-waste network move from the Global South to the Global North. The flows of e-waste connecting a country in the Global South to a country in the Global North account for about 6% of all connections. The rarity of illegal flows originating in the Global South or the lower occurrence of South-South routes may be due to the challenges involved in detecting these illegal shipments by law enforcement authorities in countries of the Global South. Therefore, further qualitative and quantitative research is needed to investigate connections from the Global South to the Global North and from the Global South to the Global South.

The presence of three distinctive patterns suggests that our understanding of the determinants of transnational illegal waste needs further refinement. Different factors are likely to explain transnational illegal waste trade directed from the Global North to the Global South and the Global North, as well as from the Global South to other countries in the North and in the South. Factors such as less stringent environmental regulations, poor enforcement, economic needs, former colonial ties, and secondary markets may explain shipments directed from the Global North to the Global South. In contrast, prior economic and legal ties, geographic proximity, and social proximity might explain the existence of trafficking directed from countries in the Global North to countries in the Global North, as well as from countries in the Global South to countries in the Global South. Therefore, rigorous analyses of these factors are necessary.

Finally, as expected, we observed that both e-waste and end-of-life vehicles move in a single direction between each pair of countries, rather than being reciprocal. We only identified a few countries (e.g., France, the United Kingdom, Poland, Hong Kong, and Germany) that both export to and import from the same country. The fact that these countries both send and receive illegal waste to/from the same country may indicate that they serve as transit hubs, connecting source and destination countries all over the world. This interpretation is supported by case-study analyses by Spapens and colleagues (2018) and by Andreatta and Favarin (2020). In particular, Spapens and colleagues (2018) have highlighted the role of Hong Kong as a popular stopover for illegal paper waste. Although Hong Kong does not have major facilities to treat or to reuse waste, traffickers use Hong Kong as a destination to disguise the actual destination of the shipments (i.e., China) and make it harder for law enforcement agencies to trace the shipments (Spapens et al., 2018).

Our analysis has some limitations. In particular, the construction of the network is affected by the fact that countries have varying inclinations and capabilities to intercept illegal waste shipments and report them to the Basel Convention. Several countries do not report at all, and some reports appear incomplete. As a result, the final networks may underestimate the complexity of actual transnational waste trafficking, depicting only the main trafficking connections and over-representing the role of countries that are either more active than the average in combating waste trafficking or more diligent in reporting their seizures. However, the relevance of this issue is mitigated by the fact that a country's role in the network is inferred from information provided by both the country itself and other countries. Additionally, the data used in this study span multiple years, four years to be precise. The use of multi-year data to identify trafficking routes is a common strategy in studies on transnational trafficking (e.g., Aziani et al., 2021; Berlusconi et al., 2017) because it reduces the impact of missing reports for some of the years included in the analysis. Lastly, the construction of a binary network limits the importance of reporting countries in the network, as we only focus on the presence or absence of a tie rather than estimating its weight. While this mitigates the impact of countries' reporting behavior on the final networks, it prevents us from assessing the weight carried by each connection between any two countries involved in waste trafficking.

Table 4. Summary of the results per each research question

Research question	Summary of the results
Q1: Does the structure of the networks and the countries involved in the trafficking differ according to the type of waste?	The structure of the trafficking networks and the countries involved in the trafficking differ according to the type of waste, although some similarities exist: • The e-waste trafficking network has a larger main clique and more connections than the end-of-life vehicles network does; • In both networks, most countries export to only one or a few other countries, while a small number of exporters have several outgoing edges; • Both trafficking networks are characterized by the presence of a few countries with several incoming ties, while most countries import only from one or a few countries, but in the end-of-life vehicles network, differences among countries are less prominent than in the e-waste network; • The main exporting countries in the end-of-life vehicles network are France, the UK, and Sweden, while the UK, France, Germany, and Sweden are the main exporting countries in the e-waste network; • The main importing countries in the end-of-life vehicles network are Nigeria, Poland, and Egypt, while China, Hong Kong, and Nigeria are the main importing countries in the e-waste network; • Despite the differences among the countries that export and import illegal end-of-life vehicles and e-waste, France, the UK, and Sweden play a central role as exporters, and Nigeria plays a central role as an importer in both networks.
Q2: To what extent do flows of end-of-life vehicles and e-waste move from the Global North to the Global South?	Illegal flows of both end-of-life vehicles and e-waste primarily move from countries in the Global North to countries in the Global South; 57% of trafficking routes for both waste types follow this path. However, countries in the Global North also exchange illegal waste among themselves, and countries in the Global South send their illegal waste to both Global North countries and other countries in the Global South.
Q3: Are illegal flows of end-of-life vehicles and e-waste reciprocal?	The flow of illegal waste is predominantly unidirectional. In the end-of-life vehicle trafficking network, 94% of the dyads are asymmetric, while only 6% are mutual. In the e-waste trafficking network, 90% of the dyads are asymmetric and 10% are mutual.

Conclusions

This study has, for the first time, mapped the global transnational flows of illegal waste by type of product trafficked, namely end-of-life vehicles and e-waste. Our results provide evidence that the structure of the trafficking flows and the countries involved in the trafficking differ according to the type of waste. We have quantified the extent to which waste moves between countries in the Global North and the Global South, as well as among countries in each region.

This study contributes to the growing stream of quantitative studies in green criminology, which scholars in the field have advocated for (Andreatta & Favarin, 2020; Favarin & Aziani, 2020; Lynch et al., 2017, 2019; Lynch & Pires, 2019). It gives generalizability to previous qualitative evidence on transnational waste trafficking by considering all known illegal transactions between countries, rather than focusing on a few selected trafficking routes (e.g., Andreatta and Favarin 2020; Sahramäki et al. 2017; Spapens, Mehlbaum, and Neve 2018; Bisschop 2012).

Our results generally confirm previous qualitative evidence: (i) trafficking networks differ according to the type of waste trafficked; (ii) illegal waste primarily moves from countries in the Global North to countries in the Global South; and (iii) illegal waste flows between countries are mainly unidirectional. However, the reality is more complex. Despite differences among countries exporting and importing illegal end-of-life vehicles and e-waste, France, the UK, and Sweden emerge as central exporters in both networks, while Nigeria serves as a key importer in both. Both networks exhibit a pattern where a handful of countries have multiple incoming connections, while most countries only import from one or a few countries. Although most illegal waste flows move from Global North countries to Global South countries, some Global North countries exchange illegal waste among themselves, and Global South countries send their illegal waste to other Global South and Global North countries. Our analysis also suggests that trafficking flows are typically unidirectional, with only a few countries engaging in bidirectional exchanges. Recurring countries in bidirectional exchanges may serve as transit hubs that connect source and destination countries worldwide. Future studies should investigate the role of transit countries within trafficking routes.

The Basel Convention National Reports provide a unique source of data to study waste trafficking and its flows. Further exploration of these data is necessary to map trafficking routes of other types of waste (such as plastic, metals, wood, and paper) to increase knowledge about new illegal waste flows at the global level and their determinants. Specifically, the mechanisms behind North-North trafficking routes and South-North or South-South trafficking flows need to be investigated further. Studies on the nature of macro-regional waste flows should aim to identify rigorously the determinants of the direction of illegal flows of various types of waste (such as end-of-life vehicles, e-waste, and others) and shed light on the role of exporters in countries in the Global South and recipients in countries in the Global North. These are topics that have been overlooked in the literature and that deserve future attention.

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