Structure of the Global Plastic Waste Trade Network and the Impact of China's Import Ban

Chao Wang, Longfeng Zhao, Ming K. Lim, Wei-Qiang Chen, and John W. Sutherland

Original citation & hyperlink:
Wang, Chao, et al. "Structure of the global plastic waste trade network and the impact of China's import Ban." *Resources, Conservation and Recycling* 153 (2020): 104591.
https://dx.doi.org/10.1016/j.resconrec.2019.104591

ISSN 0921-3449

Publisher: Elsevier

Structure of the Global Plastic Waste Trade Network and the Impact of China's Import Ban

Chao Wang [1], Longfeng Zhao [2, 3 *], Ming K Lim [4, 5], Wei-Qiang Chen [6], John W. Sutherland [7]

1. Research Base of Beijing Modern Manufacturing Development, College of Economics and Management, Beijing University of Technology, Beijing, China
2. School of Management, Northwestern Polytechnical University, Xi'an, China
3. School of Management, Xi'an Polytechnic University, Xi'an, China
4. College of Mechanical Engineering, Chongqing University, Chongqing, China
5. Centre for Business in Society, Coventry University, Coventry, UK
6. Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen, China
7. Environmental and Ecological Engineering, Purdue University, West Lafayette, IN, USA.

[*] **Corresponding author: Longfeng Zhao**
Email: zlfccnu@mails.ccnu.edu.cn
Corresponding Author's postal address: School of Management, Northwestern Polytechnical University, Xi'an, Shaanxi 710021, China

Structure of the Global Plastic Waste Trade Networks and the Impact of China's Import Ban

Abstract: Millions of tonnes (teragrams) of plastic waste are traded around the world every year, which plays an important role in partially substituting virgin plastics as a source of raw materials in plastic product manufacturing. In this paper, global plastic waste trade networks (GPWTNs) from 1988 to 2017 are established using the UN-Comtrade database. The spatiotemporal evolution of the GPWTNs is analyzed. Attention is given to the country ranks, inter- and intra-continental trade flows, and geo-visual communities in the GPWTNs. We also evaluate the direct and indirect impacts of China's plastic waste import ban on the GPWTNs. The results show that the GPWTNs have small-world and scale-free properties and a core-periphery structure. The geography of the plastic waste trade is structured by Asia as the dominant importer and North America and Europe as the largest sources of plastic waste. China is the unrivaled colossus in the global plastic waste trade. After China's import ban, the plastic waste trade flows have been largely redirected to Southeast Asian countries. Compared with import countries, export countries are more important for the robustness of GPWTNs. Clearly, developed countries will not announce bans on plastic waste exports; these countries have strong motivation to continue to shift plastic waste to poorer countries. However, the import bans from developing countries will compel developed countries to build new disposal facilities and deal with their plastic waste domestically.

Keywords: Plastic waste; International trade; Complex networks; Geo-visualization; China's import ban; Percolation theory

1. Introduction

Plastics are globally one of the most used and widespread materials and add comfort, convenience, and safety to human life (Alam et al., 2018; Faraca et al., 2019). Surpassing the usage of most other man-made materials, plastics have undergone an extraordinarily rapid growth in production in recent decades (Dilkes-Hoffman et al., 2019). This phenomenon has led to the production of millions of tonnes (teragrams) of plastic waste every year. A recent estimate shows that, as of 2015, approximately 6300 Tg of plastic waste had been generated (Geyer et al., 2017). Recycling plastic waste reduces the demand for virgin plastic in industrial manufacturing and decreases the material prices for manufacturers. Recycled plastic is widely used in the manufacturing industry in China (Bing et al., 2015). In recent years, China's demand for plastic has driven the global recycling waste trade. This condition has allowed China to achieve a low-cost manufacturing advantage, which plays a very important role in making China the world's factory.

According to statistics reported by Brooks et al. (2018), China has accepted nearly half of the world's nonindustrial plastic waste imports – approximately 106 Tg of plastic waste – over the past 25 years. China's economy has partly benefited from the global recycling trade (Qu et al., 2019). However, the flood of imported plastic waste has seriously damaged China's environment. Because of a desire to become a less polluted country (Wang et al., 2019), China passed the National Sword policy (Chinese General Administration of Customs, 2017) in 2017, which permanently banned the import of nonindustrial plastic waste as of January 2018. China's plastic import ban threw the global plastic waste trade into turmoil.

To date, little research has been performed on the global plastic waste trade, especially to quantify the impact of China's plastic import ban on the global plastic waste trade. Velis (2014) analyzed the major role of China in global plastic waste recycling markets. GRID-Arendal (2018) outlined the global plastic waste trade and pointed to the illegal behavior occurring throughout the value chain, including the consequences of informal plastic treatment, which often took place far from where the waste was generated. Brooks et al. (2018) analyzed the historical trade of plastic waste and evaluated the impact of China's import ban using linear regression. The results showed that an estimated 111 Tg of plastic waste would be displaced by 2030 because of the National Sword policy.

The global plastic waste trade reflects the trade relationships among several different countries. The relationships can be mapped as a complex network, where the nodes are countries and the connections in between are the trade relationships. The last decade has witnessed an increasing interest in the study of international-trade issues from a network structural perspective (Barigozzi et al., 2010; Fagiolo et al., 2010; Garlaschelli and Loffredo, 2004, 2005; Serrano and Boguná, 2003), which provides a novel approach to study the dynamics of international trade in terms of the topological features of the global trade network. Complex network methods have been applied to analyze many worldwide commodity trade systems, such as crude oil (An et al., 2014; Ji et al., 2014; Yang et al., 2015; Zhong et al., 2014), fossil energy (Gao et al., 2015; Hao et al., 2016), electricity (Ji et al., 2016), rare earth minerals (Ge et al., 2016; Wang, X. et al., 2016), polysilicon (Liu et al., 2019), iron (Zhong et al., 2018), scrap metal (Hu et al., 2019), waste electrical and electronic equipment (Lepawsky, 2015; Lepawsky and McNabb, 2010; Shinkuma and Huong, 2009; Widmer et al., 2005), secondary raw material (Pu et al., 2019), and second-hand clothes (Botticello, 2012; Brooks, 2013, 2015). In addition, scholars have combined economic theory and complex networks to analyze the impacts of policies or economic crises. For example, Liu, Zhigao et al. (2018) studied the structure and evolution of the trade relations between countries along the paths of the Belt and Road Initiative (BRI). Song et al. (2018) studied the trade network of the BRI and its topological relationship to the global trade network. Lee et al. (2011) built a global macroeconomic network (GMN) and studied the spread of economic crises contained within. Caschili et al. (2015) constructed an interdependent multi-layer model (economic, socio-cultural and physical layers) and explored the propagation of cascading effects at national and global scales. The above studies have proven the great advantages of complex network models for characterizing the evolutionary patterns of global commodity trade and understanding the impacts of a specific event.

Thus, this paper applies the complex network method to quantitatively describe the spatiotemporal evolution of global plastic waste trade networks (GPWTNs) and to explore the impact of China's plastic import ban on the global plastic waste trade. The main contributions are as follows: (1) A more nuanced interpretation of the global plastic waste trade is presented. For over a decade, the global plastic waste trade has been qualitatively framed as the dumping of plastic waste by rich, developed countries in poor, developing countries. We identify the structural evolution of the global plastic waste trade using topological quantities and geographical information system (GIS) data. (2) We use the percolation theory framework to evaluate the robustness of the GPWTN and explore the impact of China's import ban. The remainder of this paper is structured as follows. Section 2 describes the methodologies used in this study. Section 3 analyzes the structural evolution of the global plastic waste trade. The robustness of the GPWTN is assessed in Section 4, along with the impact of China's import ban from a complex network perspective. Finally, Section 5 presents the conclusions and future directions.

2. Methodology

2.1 Data

We employ data on the bilateral trade flows among countries/territories (hereafter countries) from the United Nations Commodity Trade Database (UN-Comtrade, see http://comtrade.un.org/). According to the Harmonized System 1996, the code of plastic waste is HS 3915, which represents waste, parings and scrap of plastics. The units of measurement are available as both the net weight (kg) and value (US dollar). This study uses the weight, and the results obtained for the trade value are similar. The data cover the period January 1988-June 2018. According to the terminology of re-imports and re-exports in the UN-Comtrade database, re-imports are goods imported in the same country as previously exported and are already included in the country imports, whereas re-exports are exports of foreign goods to the same country from which the goods were previously imported, and they are to be included in the country exports. Although re-exports account for a tiny proportion of total exports, this study includes the re-exports with the exports of each country. Hong Kong Special Administrative Region of China (hereafter HK) is an exception. HK plays a very important role as an entrepôt. Many export countries ship plastic waste to HK for re-export to other developing countries, especially mainland China (hereafter China). For example, because of the historical political factors and the efficiency of HK in re-exporting (Keller et al., 2011), country A exports plastic waste to HK, and HK re-exports the waste to China. Thus, to accurately estimate the influence of China's import ban, we consider mainland China and HK separately and regard the re-export of HK from country A to China as the direct export from country A to China.

2.2 Network construction

We build the global plastic waste trade as a weighted directed network. The network G is denoted by $G \quad (V,E,W)$, where $V \quad \{v_1, v_2, ..., v_n\}$ is the set of N_v nodes (countries),

$E = \{e_{ij}, i = 1,2,...,n; j = 1,2,...,n\}$ is the set of N_e edges (trade channels between the countries), and $W = \{w_{ij}, i = 1,...,n; j = 1,...,n\}$ is the set of weights associated with each edge connecting a pair of countries (v_i, v_j). The weight w_{ij} of an edge linking countries i and j represents the net weight from export country i to import country j.

It is worth noting that the data from UN-Comtrade were obtained through voluntary reporting by individual countries. Bilateral asymmetries in trade data are a well-known phenomenon in official statistics (Javorsek, 2016). Theoretically, the reported imports of country i from country j would match the reported exports of country j to country i. This balance is referred to as mirror statistics. However, one can observe discrepancies in the provided trade data between the reporting country and partner country. There are many reasons for the data inconsistency, such as the use of CIF-type (cost, insurance and freight) values in import statistics and FOB-type (free on board) values in export statistics, the time lag between exports and imports, etc. The global trade in plastic waste is often an illegal, yet profitable, trade, and the possibility of corruption and evasion adds to the statistical discrepancy (Kellenberg, 2015). In addition, exporters do not want to be criticized for unethically using the Third World as a dumping ground because of ill-conceived and irresponsible disposal of waste (Soskolne, 2001), and importers also do not want to be criticized by their people for importing large quantities of toxic byproducts in the interest of short-term economic growth while ignoring long-term human and environmental costs (Singh and Lakhan, 1989). Hence, based on the assumption that exporters and importers are more likely to report less trade data than the actual trade volume, the maximum value of the import and export data is used as the weight in bilateral trade. In fact, the imports of the reporting country are found to be higher than the exports of the partner country in UN-Comtrade. A reasonable assumption is that a country is more likely to be more careful about reporting the plastic waste that is traded into its borders than about reporting the plastic waste that leaves its territory. It seems unlikely that an exporter would report an illicit trade (Lepawsky, 2015). In certain cases, the imports of a reporting country are lower than the exports of the partner country, especially in some developing countries. The possible reason is that the banned plastic waste is smuggled into the country or that officials of the import country are bribed to give consent (Gibbs et al., 2010; Kitt, 1994), and the trade data are reported to UN-Comtrade under a forged trade name.

Due to the space limitation, the brief introduction to the metrics for the GPWTN (including network density, centrality, heterogeneity, clustering coefficient, shortest path length, assortativity, stability of the network members, community structure, and modularity index) is available in Appendix A1.

2.3 Percolation in complex networks

From the perspective of statistical physics, percolation is the simplest process involving a continuous phase transition. There is a critical occupation probability p_c separating two different topological phases. For $p<p_c$, there are small clusters, while $p>p_c$ represents global connectivity and an infinitely large cluster, and $p=p_c$ represents a transition from small clusters to infinite clusters.

A percolation transition of complex networks is an appropriate instance of structural complexity (Saberi, 2015). The integrity of a network can be evaluated with the largest connected component or the giant connected component (GCC) (Havlin et al., 2015). The GCC is the network size of the largest connected subnetwork after certain nodes are removed, and it determines the robustness of the network structure or the ability to withstand failures and perturbations. Usually, the GCC will undergo a sudden phase transition after a certain ratio p_c of the nodes has been removed. The critical ratio p_c of the removed nodes can be used as the robustness metric of the network. A larger p_c indicates that more nodes must be removed to destroy the network completely. In other words, the network is more robust under various disruptions.

3. Structural evolution of the global plastic waste trade network

3.1 A synopsis of the global plastic waste trade network

In the last 30 years, the total trade volume measured by total exports/imports has witnessed a dramatic growth from 0.27 Tg in 1988 to 13.69 Tg in 2017. The total trade volume reached a peak value of 15.99 Tg in 2014. After 2014, the trade volume began to decrease gradually.

To intuitively understand the network structure of the GPWTN, we present the GPWTN in 2010 as an example. Gephi (Bastian et al., 2009), which is a free and open-source software for network analysis, is used to visualize the GPWTN shown in Figure 1. Figure 1 reveals only 30 country names to highlight the main trading countries. Each individual country is represented by a node in the GPWTN. The node size is proportional to the trade volume related to each country.

The trade weight is represented by the width of an edge. The trade flow is represented by the direction of an edge. The node color and edge color are determined according to the Louvain community partition algorithm (Blondel et al., 2008). The community consists of countries that have close trade relationships with each other, and the trade connections between countries in different communities are comparatively sparse. The countries within a community are labeled with the same color. This GPWTN includes two giant communities. The pink community consists of mainland China, HK, USA, East Asian countries, Southeast Asian countries, etc. The green community is mainly composed of European countries.

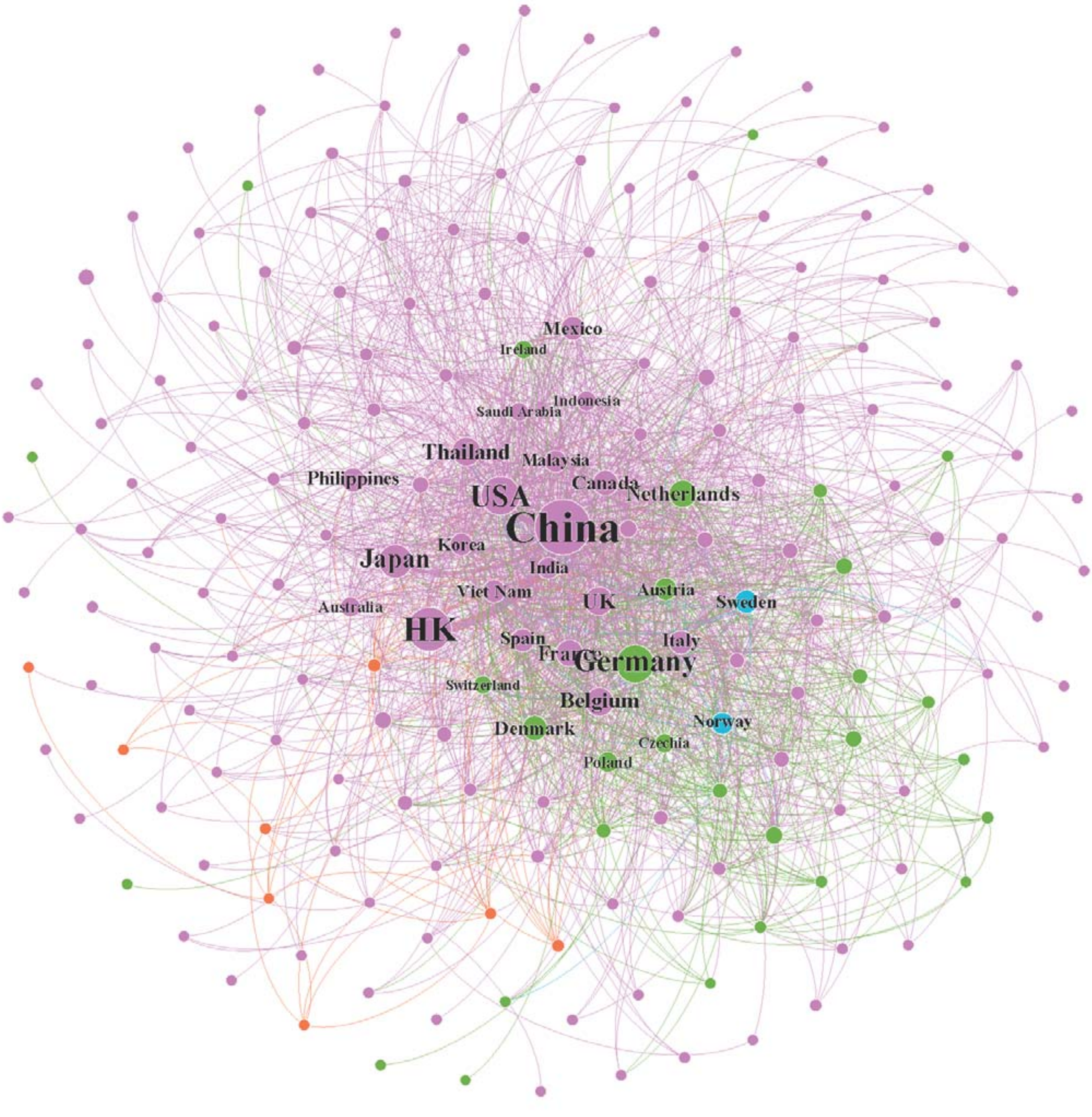


Figure 1. The global plastic waste trade network in 2010.

3.2 Basic topological properties

The basic topological quantities of the GPWTN from 1998 to 2017 are shown in Figure 2. The numbers of nodes and edges display a clear upward trend, which reflects the gradually increasing participation of countries in the global plastic waste trade over the last 30 years. The number of countries participating in the plastic waste trade increased from 71 in 1988 to 211 in 2017. Similarly, the number of edges increased notably from 284 in 1988 to 3231 in 2015, before falling to 3047 in 2017. With the increase in the numbers of nodes and edges, the average degree increased gradually from 4 to its maximum value of 16 after 2010 and has begun to decrease recently.

Note: N_v and N_e are the numbers of nodes and edges of the GPWTN, respectively. ρ is the density of the GPWTN. C is the clustering coefficient of the GPWTN. L is the shortest path length of the network. H is the heterogeneity index of the network. k and s are the average degree and strength of the GPWTN, respectively. r_d is the assortativity index of the GPWTN.

Figure 2. The yearly topology evolution of the GPWTN from 1988-2017.

Figure 2 indicates that the GPWTN shows several typical properties of most complex networks. Particularly, the GPWTN conforms to the characteristics of the world trade web (Fagiolo et al., 2010; Garlaschelli and Loffredo, 2004; Serrano and Boguná, 2003). In particular, (i) the GPWTN exhibits a small-world property. The high C and low L are the two primary properties of a small-world network (Watts and Strogatz, 1998; Xu et al., 2019). Roughly speaking, any two countries in the network can reach each other through a short sequence of trade partners. This relation may be explained by trade globalization as well as increasing bilateral and multilateral trade agreements (Fagiolo et al., 2010). Thus, this finding suggests that the GPWTN has the ability to strike a balance between the advantages and costs of having many trade partners (Wilhite, 2001). Furthermore, (ii) the GPWTN exhibits a scale-free network property. According to Estrada (2010), the heterogeneity index of the well-known Barabási-Albert (BA) network is approximately 0.11. In the GPWTN, the heterogeneity index H is between 0.425 and 0.575 in the last three decades, indicating that the GPWTN is a highly heterogeneous network. Thus, the global plastic waste trade is dominated by a few highly connected hub countries that play a central role in mediating interactions among numerous, less connected countries.

The negative assortativity index r_d of the GPWTN in Figure 2 may result from the preferential attachment mechanism (Barabási and Albert, 1999) during the formation of a bilateral trade relationship. That is, the more intensively connected countries tend to trade with other well-connected countries and form highly connected trade triangles in the GPWTN. Finally, a core-periphery structure is formed in the global plastic waste trade and is characterized by a few densely connected core nodes and numerous sparsely connected peripheral nodes. This is a common feature of social and economic networks, which is theoretically backed by Hojman and Szeidl (2008).

Moreover, the topological quantities show that the network structure has reversed since 2010. This turning point may have been related to the changes in trade policies of the core import countries, especially China, which launched a series of very strict import regulations after 2010, and the import volume of plastic waste started to decline after 2010. The detailed structural evolution is discussed in the following sections.

3.3 Centrality and country ranks of the GPWTN

To better illustrate the topological characteristics of the networks and to review the importance of major import and export countries in the plastic waste trade, we display a bump chart for the 10 countries forming the core of the plastic waste trade network between 1998 and 2017 according to the strength centrality (s_i^{in} and s_i^{out}), as shown in Figure 3. The final country list is determined by the strength centrality in 2017. We then trace back the dynamic ranks of these countries for the previous 29 years.

For import countries, a number of Asian countries—most notably China— have played an increasing role in global plastic waste trade. China was in the first position from 1991 to 2017. Vietnam and Malaysia experienced extraordinary growth in their ranks over the last three decades. India maintained a stable position as plastic waste import country and remained between 5th and 10th place. Although Latin American economies are the second largest emerging markets after Asian countries, none of the countries from Latin America appear in this ranking. There can be several reasons for this situation. First, Asian countries are associated with an export-promoting development strategy, and the manufacturing industry has experienced unprecedented growth in the last 30 years (Gereffi and Wyman, 2014). Recycled plastic provides a source for manufacturers and producers that is less expensive than virgin raw materials (Siddique et al., 2008). In contrast, the import substitution development model in Latin America fails to boost industrialization. The resource-rich countries in Latin America mainly export commodities rather than manufactured goods (Kohli, 2012). Second, compared with Latin America, the low disposal costs of waste and abundant workforce in the waste recycling industry of Asia attract developed countries to ship ever-increasing amounts of plastic waste to developing countries in Asia (Weiss and Jalilian, 2004).

For export countries, a small and stable number of long-industrialized countries plays a pivotal role in the GPWTN. For instance, Belgium, Germany, the Netherlands, and the USA maintain stable ranking as plastic waste exporting hubs, whereas Canada, the UK and France are characterized by large fluctuations in their relatively dynamic positions in the ranking. The long-industrialized countries possess good collection facilities and mature waste disposal techniques. However, because of the expensive waste disposal cost and strict environmental regulations, the long-industrialized countries find sending plastic waste to less-regulated developing countries to be an economical alternative. Furthermore, these exporting countries know that the waste may be improperly disposed of in the developing countries, which leads to serious health problems.

Therefore, we suggest that the main export countries should take the further steps to ensure that plastic waste is properly recycled, to help the developing countries establish waste management facilities, and to share their knowledge of materials and treatment techniques.

Currently, 187 countries have ratified the Basel Convention of the United Nations and added plastic waste under the Basel Convention to regulate the trans-border shipments of hazardous waste. However, the USA, as the largest plastic waste exporter, is not among these countries and must be encouraged to participate. In addition, both developed countries and developing countries are required to take responsibility for the disposal of plastic waste, and a global plastic waste management system to address the imbalanced trade is urgently needed (Liu, Zhe et al., 2018; Wang, Z. et al., 2016).

Figure 3. Top 10 countries ranked by strength centrality as of 2017.

3.4 Mapping the inter- and intra-continental plastic waste trade

We divide 1988-2017 into three sub-periods, namely, 1988-1997, 1998-2007, and 2008-2017. Then, we examine the inter- and intra-continental aggregate trade network and discuss the trade patterns of the global plastic waste trade from Africa, Asia, Europe, Middle East, North America, Oceania, and South America. Figure 4 illustrates the distinct differences in the geographic patterns over time. In particular, attention is drawn to the inter- and intra-continental trade flows.

- Asia, Europe, and North America constitute the three largest plastic waste trading regions.

- The cumulative trade volumes of Africa, the Middle East, Oceania, and South America showed an impressive growth and increased from 1.68 Tg during 1988-1997 to 14.19 Tg during 2008-2017. However, the proportion of these four regions with respect to the world's total trade volume was still small, accounting for 9.4%, 11.8%, and 9.2% of the global plastic waste trade from 1988-1997, 1998-2007, and 2008-2017, respectively.
- The ratio of intra-continental trade in North America gradually decreased during the last three decades, from 17.28% in 1988-1997, to 16.87% in 1998-2007, and then to 10.08% in 2008-2017. The ratio of intra-continental trade in Europe reduced sharply from 63.60% in 1988-1997 to 44.61% in 1998-2007 and then slightly increased to 46.25% in 2008-2017. Meanwhile, the inter-continental trade between Asia and these two continents rapidly increased.

For decades, the global plastic waste trade has been generalized as the dumping of waste from the "the rich" regions to "the poor" countries, according to the contemporary orthodoxy. However, after a considerably more nuanced interpretation of the international trade in plastic waste, we detect changing geographical patterns of the inter- and intra-continental plastic waste trade network. At an early point in the story of plastic waste, the intra-continental trade accounted for a significant portion. From 1988-1997, the vast majority of trade was internally oriented in Europe and Asia, i.e., trading for the most part occurred between countries within these regions. In 2003, the destination of the plastic waste trade in Europe's internal market shifted from Europe to Asia, and then, it shifted back to Europe's internal market again in 2015. It is worth noting that we obtain two turning points, i.e., 2003 and 2015, by historical data analysis in Appendix A2. For the Middle East, the majority of the plastic waste was exported to Asia, which was a trade that occurred among developing countries.

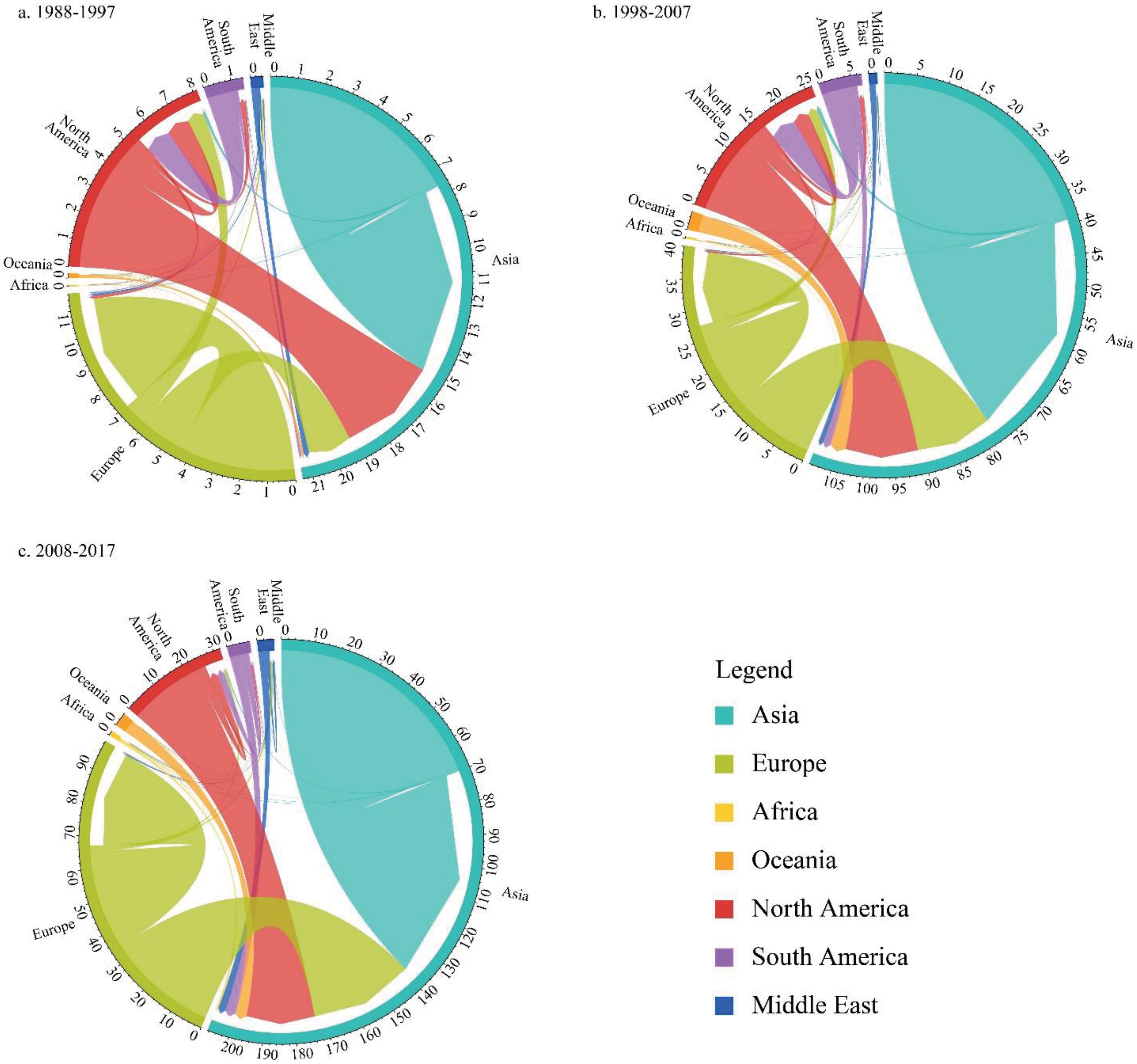


Figure 4. Evolution of inter- and intra-continental trade networks (unit: Tg).

Over the three decades, Asia became the dominant recipient of global plastic waste, partly because of the inexpensive labor, lax environmental regulations and low health costs. The following data characterize the orientation of these trade flows:

- During 1988-1997, the annual total import volume of Asia was 13.74 Tg, which accounted for 63.36% of the world's total trade volume. Asia received imports mainly from Asia, Europe, and North America, which accounted for 96.96% of the import volume of Asia.

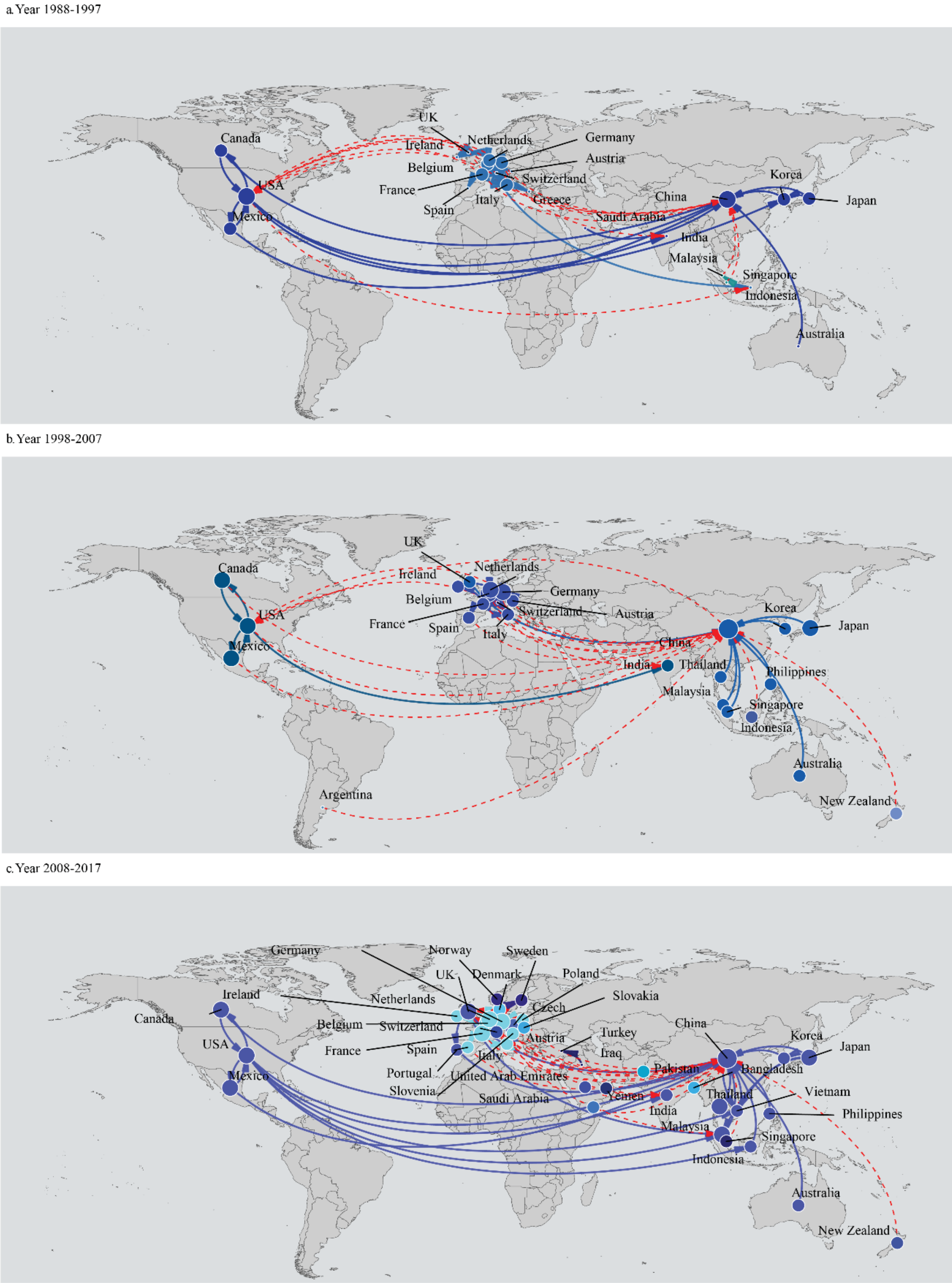
- During the next ten years, from 1998 to 2007, Asia received exports of plastic waste from all seven other regions with a total import volume of 69.26 Tg, which accounted for 74.31% of the world's total trade volume. The volume of the flows from Africa, the Middle East, Oceania, and South America was 4.93 Tg, which accounted for only 7.12% of the import volume of Asia. The volume of the flows from Asia, Europe, and North America was 64.29 Tg, which accounted for 92.83% of the total import volume of Asia.
- Then, in the last ten years, from 2008 to 2017, Asia maintained the leading position as the most import region in the global plastic waste trade with an import volume as large as 136.59 Tg. This volume accounted for 76.78% of the world's total trade volume of 177.89 Tg. Meanwhile, the volume of the flows from Asia, Europe and North America was 126.06 Tg, which accounted for 92.29% of the total import volume exports to Asia. Asia received 86.41% of the exports from North America, 99.11% of the exports from Oceania, 71.70% of the exports from the Middle East, and 51.15% of the exports from Europe.

3.5 The evolution of the trade networks and their communities

In this subsection, we consider the geographic location of countries and combine GIS data to visualize the spatial structure of the GPWTN. We first rank the edges according to the trade volume and then extract the countries linked by edge trade volumes that are in excess of 80% of the total trade volume. Next, we use the method proposed by Blondel et al. (2008) to detect the communities in the network. Finally, we map the filtered trade networks on the world map to better visualize the network structure according to its geographical attributes. We divide global plastic waste trade from 1988 to 2017 into three sub-periods, i.e., 1988-1997, 1998-2007, and 2008-2017, to reveal the evolution patterns of the GPWTN over time, which is shown in Figure 5.

Unsurprisingly, the trade in plastic waste is growing. The growth of the nodes and edges reflects the increasing participation of Asian countries (Bing et al., 2015). The trade in plastic waste has increased 8.6-fold in the past three decades, from 16.97 Tg during 1988-1997 to 146.28 Tg during 2008-2017. Figure 5 shows a very clear geographic network structure, and the main export and import countries are presented in Appendix A3. The dominant countries of the GPWTN are Europe, North America, and Asia.

- From 1988-1997, as shown in Figure 5 (a), the trade volume among 23 countries exceeded 80% of the total trade volume. These countries are grouped into three communities, i.e., the North America-Asia-Oceania community, the Europe community, and the Singapore-Malaysia community.
- With the globalization of the plastic waste trade, more countries became involved in the network from 1998-2007, as shown in Figure 5 (b). However, the North America-Asia-Oceania community polarized into two communities, i.e., the North America-India community and the Asia-Oceania community. The North America community is likely a reflection of the close trade relationships among USA, Canada, and Mexico under the North American Free Trade Agreement (NAFTA). In addition, the connections between the different communities increased dramatically, especially the connections between the Europe community and the Asia-Oceania community.
- From 2008-2017, as shown in Figure 5 (c), the North America community and the Oceania-Asia community merged into the North America-Asia-Oceania community. In addition, more Asian countries became destinations for the global exports of plastic waste. The Europe community became divided into four communities, i.e., the Norway-Sweden, the Austria-Czech, the Iraq-Turkey, and the rest of Europe community.



Note: The trade networks account for 80% of the total trade volume. The countries within a community are labeled by the same color. The red dashed lines indicate the inter-community trade flows, and the blue solid lines indicate the intra-community trade flows.

Figure 5. Spatiotemporal evolution of the trade communities during the three sub-periods.

The topological quantities in Subsection 3.2 measure the evolution of the GPWTN. However, even though at times the topological quantities remain unchanged, the members in the network may not have remained the same. Hence, we present the auto-correlation function J_t to reflect the stability of the network members in the GPWTN from 1988 to 2017, which is shown in Figure 6 (a). The figure shows that J_t begins to increase gradually in 1990 and becomes relatively stable after 2010, revealing that the countries in the global plastic waste trade tended to establish stable trade relationships. After 2010, J_t remains at a stable level, which indicates that the global plastic waste trade entered a relatively stable phase.

Then, we utilize the modularity index to quantify the clustering structures of the GPWTN. A turning point is also quite clearly around 2010 in Figure 6 (b), during which the modularity index reaches its minimum value. In previous studies (An et al., 2014), a modularity below 0.6 was regarded as a small value. Hence, the small modularity in the GPWTN reveals that the GPWTN was not significantly partitioned into communities. Nevertheless, we can still find that the modularity index displays a downward trend before 2010, which is related to an increase in the globalization of the plastic waste trade before 2010. After 2010, the plastic trade waste trade began to shrink, and the borders of trade communities became clearer.

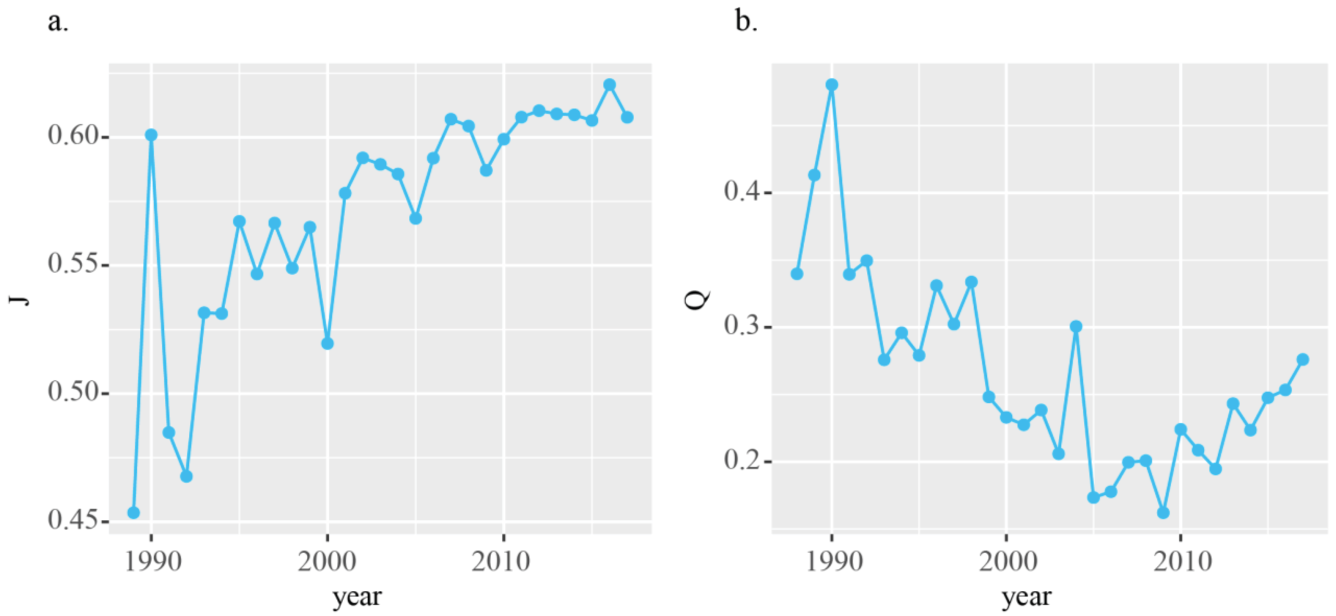


Figure 6. The time evolution of (a) the autocorrelation function J_t in the GPWTN and (b) the modularity Q of the GPWTN.

4. Impact of China’s import ban

4.1 China—the unrivaled colossus in the global plastic waste trade

Before evaluating the direct and indirect impacts of China’s import ban, we first examine China’s recent role in the global plastic waste trade. Figure 7 (a) shows that the increase and decrease in China’s trade volume are largely synchronized with the change in the world’s total trade volume. China has been the major driver of global plastic waste trade over the last three decades. After 2010, new regulations regarding plastic waste imports in China were released annually from 2011 to 2013 (China Federation of Logistics and Purchasing, 2013), indicating the government’s efforts to control the import of plastic waste. Consequently, the worldwide plastic waste trade suffered a cliff-like drop. Meanwhile, the gradual increases in the trade volumes of the remaining countries excluding China can be recognized as a signal of the load redistribution of the worldwide plastic waste trade. Figure 7 (b) presents the ratio of the trade volumes related to China. The ratio increases sharply after the 1990s and reaches its maximum value around 2010 with a peak value higher than 80%.

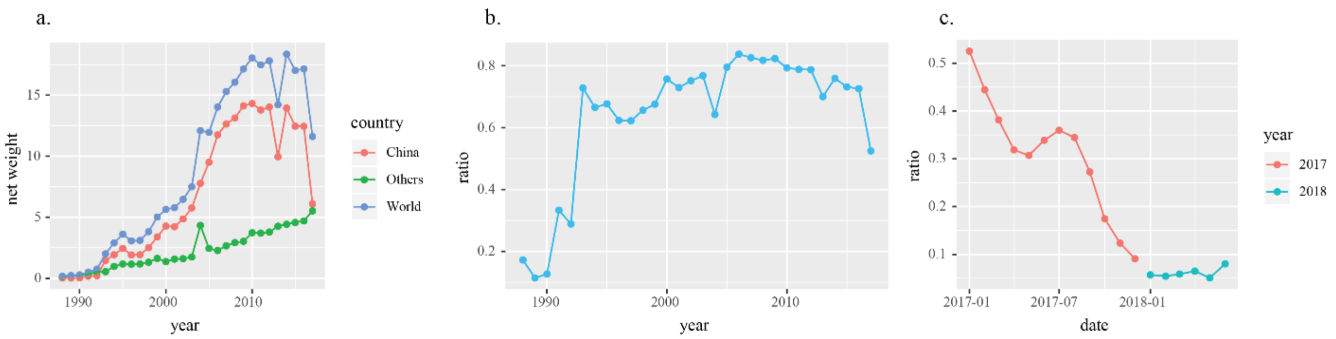


Figure 7. (a) Comparison among the world trade volume, the trade volume of China and the trade volume of the rest of the world. (b) The ratio of China’s trade volumes. (c) The ratio of China’s trade volumes for the year 2017 and the period 2018/01-2018/06.

Due to a major delay in the updating of the UN-Comtrade database, we use only the data of the first six months in 2018. Figure 7 (c) presents the ratio of China’s trade volumes for the year 2017 and the period 2018/01-2018/06. Although China banned the import of nonindustrial plastic waste in January 2018, China’s trade volume has actually decreased sharply since January 2017. In the first half of the year 2018, the total trade volume was 3.84 Tg. If we double this value as a rough estimation of the total trade volume of 2018, the total trade volume will be slightly lower than that of 2017. Nevertheless, the very large drop in the trade volume after 2017 has grabbed the world’s attention with respect to managing plastic waste around the world.

4.2 The direct impact of China's import ban

In Figure 8 (a), we summarize the trade volume variations for both China and the world. This figure indicates the high correlation between the trade volume changes in China and in the world, with a correlation coefficient of 0.94. We can conclude that the evolution pattern of the global plastic waste trade is mainly driven by China, which is in line with Figure 7 (a).

Then, we analyze the trade flow redirection to evaluate the direct impact of China's import ban. Two datasets are used to predict the trends for Southeast Asian countries and for the remaining countries excluding China and Southeast Asian countries, which are shown in Figure 8 (b) and Figure 8 (c), respectively. The first dataset is the historical data of last three decades from 1988 to 2017, denoted by "Old" in Figure 8. The second dataset is the merged dataset, which combines the first dataset with the data of the first half year of 2018, denoted by "Add 2018" in Figure 8. In Figure 8 (b), the green line indicates the trend estimated with the first dataset. The plastic waste trade volume from Southeast Asian countries will experience quite a slow growth in this scenario. The red line indicates the trend estimated with the second dataset, which shows that the trade volume related to Southeast Asian countries will tend to increase rapidly. In Figure 8 (c), according to the first dataset and the second dataset, the estimated trade volume related to the remaining countries excluding China and Southeast Asian countries will remain steady. Combining Figure 8 (b) and Figure 8 (c), the results signal that the plastic waste trade flows have been largely redirected to Southeast Asian countries since China's plastic import ban.

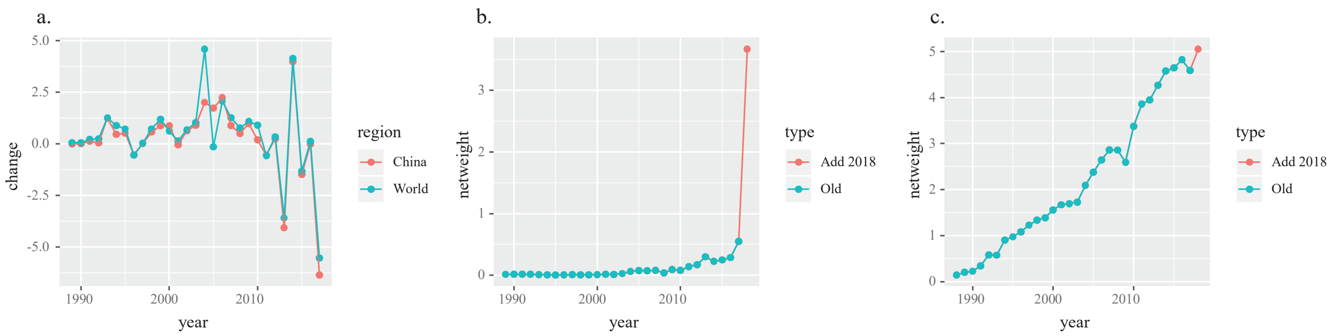


Figure 8. (a) Trade volume changes for China and the world. (b) Trade volumes for Southeast Asian countries. (c) Trade volumes excluding those of China and Southeast Asian countries.

4.3 The indirect impact of China's import ban

With China refusing to accept nonindustrial plastic waste, Europe and North America have redirected the destination of plastic waste and exported the waste to Southeast Asian countries.

According to plastic recycling media sources, compared with the same period of the previous year, Thailand's plastic waste imports increased by 640% from January to June 2018 (Resource Recycling Inc., 2018). Malaysia experienced a similar increase, with a rise of 273% to 0.16 Tg in the first six months of 2018 (The Guardian, 2018). To avoid being the recipient of global plastic waste, several Southeast Asian countries have started to take action to protect themselves (Geng et al., 2019). For example, Thailand issued a temporary ban on the import of all scrap plastic waste in June 2018 and is now presenting a set of policies that include banning plastic waste imports permanently within the next two years. Vietnam stopped issuing plastic recycling import licenses in June 2018. Malaysia revoked the approved permits for plastic waste imports for three months effective 23 July 2018, as a temporary preventive measure.

With an increasing number of countries restricting the imports of plastic waste, more importers will quit the GPWTN. Subsection 3.2 shows that the GPWTN is extremely heterogeneous, which means that it is resilient to accidental failures but vulnerable to coordinated attacks (Barabási and Bonabeau, 2003). The core-periphery structure of the GPWTN implies that the removal of one of the peripheral nodes will not damage the functional integrity of the system. Functional integrity describes statistical patterns of dynamic interactions among countries, while the effective function in the GPWTN ensures smooth trade flows. However, attacking the core will amplify shocks that spread throughout the whole network, potentially leading to a systemic crisis. In this subsection, we use percolation theory to quantify the robustness of the GPWTN according to two different node removal strategies, i.e., import bans from developing countries and export bans from developed countries.

The GCC is used to estimate the robustness of the GPWTN (Havlin et al., 2015). The ratio of GCCs is measured to evaluate the functional integrity after removing specific countries. For instance, China's import ban means the removal of the China node from the trade network, and hence, the import trade flows related to China will also be removed. Here, we perform two different removal scenarios: a random removal and a targeted removal. In the random removal situation, we assume that a fraction p of randomly chosen countries will lift export or import bans. The restrictions implemented by these countries will eventually cut off the trade flows (edges) related to these countries. For the targeted removal situation, a fraction p of countries is determined according to the centrality ranking. Countries with a higher centrality are more likely to lift export or import bans. This finding means that these countries will be removed with a higher priority.

When the removal procedure is executed, we estimate the size of the GCC (normalized by the system size to be in the range [0, 1]) as the functional integrity of the GPWTN. If the size of the GCC remains on the order of the system size after the removal, we can say that the GPWTN's integrity has been preserved. With the increase in the initial removal ratio p, the GPWTN will eventually collapse at a certain critical removal ratio p_c. Thus, p_c can be used to compare the robustness of different networks when facing different removal strategies, i.e., the import and export bans in our study.

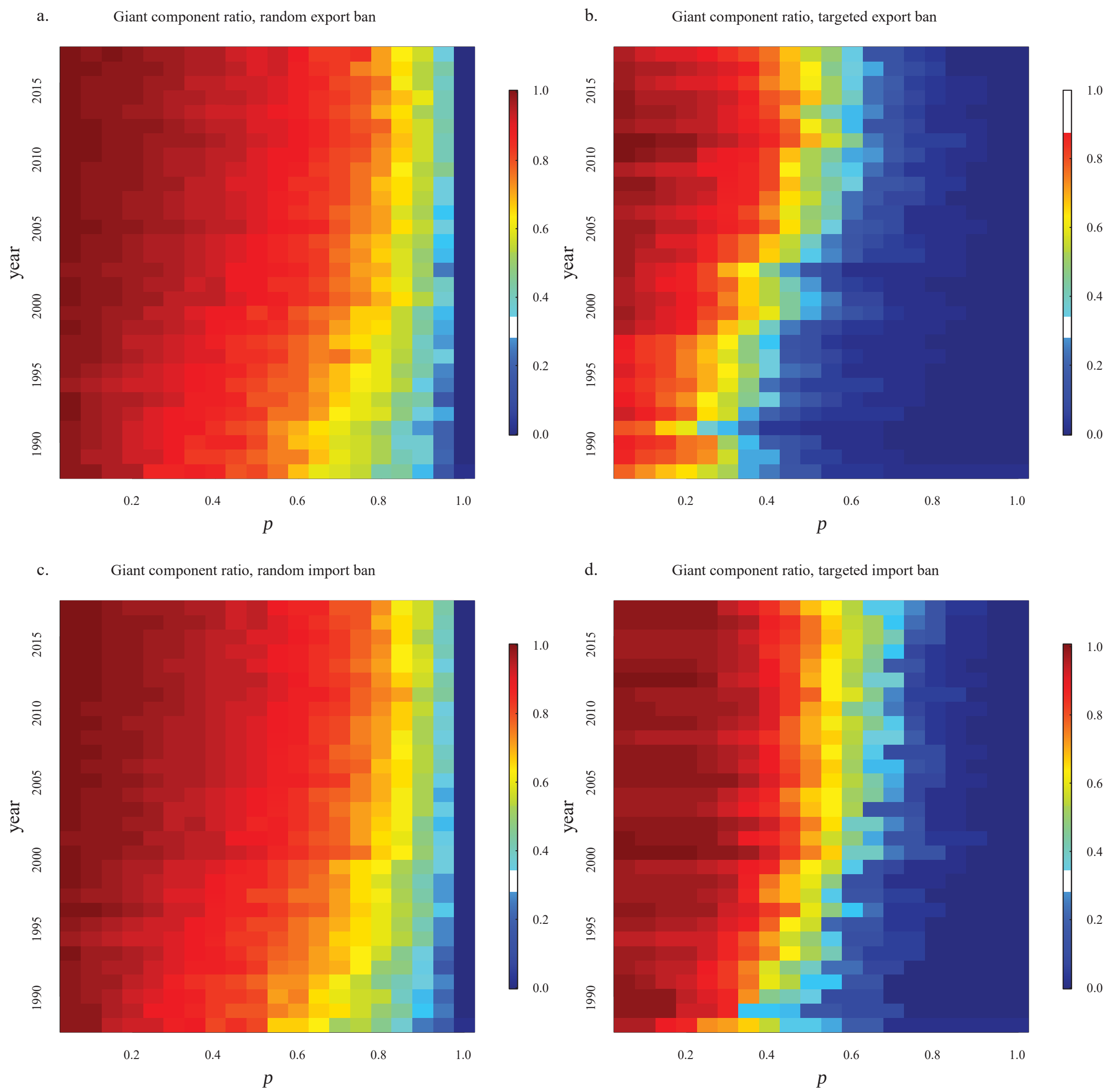


Figure 9. The impacts of the export bans and import bans on the robustness of the GPWTN.

The simulation results are given in Figure 9 to present the consequences of the import or export bans that are potentially implemented by the countries. In Figure 9, the ratio of the GCC with respect to the initial removal node ratio p and the year are presented in heatmaps. Figure 9 (a) and (c) show that the GPWTN for the last 30 years has been quite robust with respect to both random export and import bans. The ratio of the GCC starts to decrease when p is larger than 60%.

The ratios of the GCC for both targeted export and import bans are shown in Figure 9 (b) and (d), respectively. The targeted import bans can be regarded as the execution of import bans from top import countries, such as China. Similarly, the targeted export bans are related to top exporting countries, such as the USA and Germany. The targeted export and import bans both show that the GPWTN is more robust after the year 2000 (the GPWTN maintains its functional integrity with a larger initial removal ratio p after the year 2000). However, the performance of the GPWTN is different in response to targeted export and import bans. When p=0.5, all of the GPWTN before 2000 will completely collapse for the targeted export bans. In contrast, the GPWTN will survive for the targeted import bans with a removal ratio p=0.5. This result means that the critical removal ratio p_c for a targeted export ban is smaller than that of a targeted import ban. Thus, compared with the targeted export bans, the GPWTN is more robust against the targeted import bans (with a larger critical removal ratio p_c).

Based on the different performances of the GPWTN when implementing export or import bans, we can conclude that the export countries are more important contributors for the robustness of the GPWTN since using export rather than import bans will more easily totally disrupt the functional integrity. In other words, from the perspective of network robustness, the GPWTN is largely dominated by export countries, which mostly consist of the developed countries described in Subsection 3.3. This finding is reasonable because the developed countries are the sources of plastic waste. If the developed countries stop exporting plastic waste to developing countries, the volume of the global plastic waste trade will sharply decrease, and the GPWTN will be destroyed.

4.4 Practical implications

The global trade in plastic waste has grown dramatically in recent decades. Countries engage in this trade for economic benefits. Developing countries import plastic waste to decrease the manufacturing cost of plastic products and to earn hard currency. Developed countries save the cost of waste disposal. Gradually, the developing countries have become dumpsites, and China has become an unrivaled colossus in the global plastic waste trade. The developed countries have therefore lost the motivation to build new disposal facilities.

Since China stopped accepting nonindustrial plastic waste, the developed countries have redirected the destination of plastic waste and exported the waste to Southeast Asian countries. The sharp increase in the import volume for Southeast Asian countries in the first half year of 2018 is a direct consequence, as shown in Figure 8. As an increasing number of developing countries realize the true cost of importing plastic waste, they will also implement strict customs inspections to avoid accepting plastic waste. Figure 9 shows that the functional integrity of the GPWTN is substantially more difficult to preserve when the major export countries lift export bans.

Clearly, the developed countries are unlikely to announce bans on plastic waste exports. They have strong motivation to maintain the function of the global plastic waste trade and expect to continue to shift their environmental responsibility to poorer countries with laxer environmental laws.

In the long term, the import bans from developing countries will close these types of cost-effective and easy routes for dumping plastics. This process will compel developed countries to build new disposal facilities to deal with their plastic waste domestically, which will have the same effects as export bans.

5. Conclusions and future directions

In this study, a complex network method is used to analyze the structural evolution of the global plastic waste trade and to evaluate the impacts of China's import ban. Certain meaningful conclusions are drawn.

First, through the analysis of the basic topological quantities of the GPWTN from 1998 to 2017, it can be found that the GPWTN exhibits small-world and scale-free characteristics and has a core-periphery structure.

Second, the metric of centrality reveals the major hubs of the network. For import countries, a number of Asian countries—most notably China—have played an increasing role in the global plastic waste trade. For export countries, a small and stable number of long-industrialized countries play pivotal roles in the GPWTN. The USA is the largest source of plastic waste. The USA is not among the Basel Convention members and must be encouraged to participate. Both developed countries and developing countries must take responsibility for the disposal of plastic waste, and a global plastic waste management system to address the imbalanced trade is urgently needed.

Third, inter- and intra-continental plastic waste trade shows that, at an early point in the story of plastic waste, the trade occurring within a given continent accounted for a significant portion of the total trade in plastic waste. After three decades, Asia has become the dominant recipient of the global exports of plastic waste.

Fourth, the evolution of the trade networks and their communities shows that the GPWTN is evolving into a stable system. There are two major communities. One community mainly consists of European countries, and the other community includes countries from North America and Asia. In addition, 2010 served as a turning point in the evolution of the GPWTN because new regulations regarding plastic waste imports were issued annually from 2011 to 2013 in China.

Fifth, China is the unrivaled colossus in the global plastic waste trade. After China's import ban, the plastic waste trade load has been largely redistributed to Southeast Asian countries. To evaluate the indirect impacts of China's import ban, we conduct a series of simulation experiments that mimic random and targeted import or export bans. The simulation results indicate that the functional integrity of the GPWTN is significantly more difficult to preserve when the major export countries lift export bans. In other words, compared with the import countries, the export countries have a strong impact on the integrity of the network. The import bans from the developing countries will compel developed countries to build new disposal facilities and treat the plastic waste within their own borders, which will have effects similar to those of export bans.

In addition, there is no single, one-size-fits-all solution to the global plastic waste crisis. Our future work will include a scenario study and present multiple types of scenarios to evaluate the environmental and policy impacts, e.g., (1) redirecting the global plastic waste trade flow, (2) reducing single-use plastics by imposing bans or taxes, and (3) promoting the development of waste management infrastructure in developing countries. The findings will enrich the policy discussion of plastic waste as a global issue of economic growth and environmental justice.

Acknowledgements

This work has been supported in part by the National Natural Science Foundation of China (61603011, 71901171, and 41671523). Wei-Qiang Chen acknowledges the financial support from the CAS Pioneer Hundred-Talent Program. We gratefully acknowledge the discussions with and the support of Professor H. Eugene Stanley from Boston University.

Appendix A. supplementary data

Appendix A1 briefly introduces the metrics for the GPWTN. Appendix A2 tabulates the inter- and intra-intracontinental plastic waste trade flows per year from 1988 to 2017. Appendix A3 shows the communities and main export/import countries in the GPWTN for three sub-periods, i.e., 1988-1997, 1998-2007, and 2008-2017.

References:

Alam, O., Billah, M., Yajie, D., 2018. Characteristics of plastic bags and their potential environmental hazards. Resources, Conservation and Recycling 132, 121-129.

An, H., Zhong, W., Chen, Y., Li, H., Gao, X., 2014. Features and evolution of international crude oil trade relationships: A trading-based network analysis. Energy 74(5), 254-259.

Barabási, A.-L., Albert, R., 1999. Emergence of scaling in random networks. Science 286(5439), 509-512.

Barabási, A.-L., Bonabeau, E., 2003. Scale-free networks. Scientific american 288(5), 60-69.

Barigozzi, M., Fagiolo, G., Garlaschelli, D., 2010. Multinetwork of international trade: A commodity-specific analysis. Physical review E 81(4), 046104.

Bastian, M., Heymann, S., Jacomy, M., 2009. Gephi: an open source software for exploring and manipulating networks, Third international AAAI conference on weblogs and social media.

Bing, X., Bloemhof-Ruwaard, J., Chaabane, A., van der Vorst, J., 2015. Global reverse supply chain redesign for household plastic waste under the emission trading scheme. Journal of Cleaner Production 103, 28-39.

Blondel, V.D., Guillaume, J.-L., Lambiotte, R., Lefebvre, E., 2008. Fast unfolding of communities in large networks. Journal of Statistical Mechanics: Theory and Experiment 2008(10), P10008.

Botticello, J., 2012. Between classification, objectification, and perception: processing secondhand clothing for recycling and reuse. Textile 10(2), 164-183.

Brooks, A., 2013. Stretching global production networks: The international second-hand clothing trade. Geoforum 44, 10-22.

Brooks, A., 2015. Clothing poverty: The hidden world of fast fashion and second-hand clothes. Zed Books Ltd.

Brooks, A.L., Wang, S., Jambeck, J.R., 2018. The Chinese import ban and its impact on global plastic waste trade. Science Advances 4(6), eaat0131.

Caschili, S., Medda, F.R., Wilson, A., 2015. An interdependent multi-layer model: resilience of international networks. Networks and Spatial Economics 15(2), 313-335.

China Federation of Logistics and Purchasing, 2013. New regulations on plastic waste trade. URL. http://www.chinawuliu.com.cn/zhxw/201309/22/255937.shtml, Accessed 02 Dec. 2019.

Chinese General Administration of Customs, 2017. Chinese General Administration of Customs launches a campaign “Natiaonal Sword” to combat smuggled waste, URL: http://www.customs.gov.cn/customs/302249/302425/636280/index.html, Accessed 13 Jul. 2019.

Dilkes-Hoffman, L.S., Pratt, S., Laycock, B., Ashworth, P., Lant, P.A., 2019. Public attitudes towards plastics. Resources, Conservation and Recycling 147, 227-235.

Estrada, E., 2010. Quantifying network heterogeneity. Physical review E 82(6), 066102.
Fagiolo, G., Reyes, J., Schiavo, S., 2010. The evolution of the world trade web: a weighted-network analysis. Journal of Evolutionary Economics 20(4), 479-514.
Faraca, G., Martinez-Sanchez, V., Astrup, T.F., 2019. Environmental life cycle cost assessment: Recycling of hard plastic waste collected at Danish recycling centres. Resources, Conservation and Recycling 143, 299-309.
Gao, C., Sun, M., Shen, B., 2015. Features and evolution of international fossil energy trade relationships: a weighted multilayer network analysis. Applied Energy 156, 542-554.
Garlaschelli, D., Loffredo, M.I., 2004. Fitness-dependent topological properties of the world trade web. Physical review letters 93(18), 188701.
Garlaschelli, D., Loffredo, M.I., 2005. Structure and evolution of the world trade network. Physica A: Statistical Mechanics and its Applications 355(1), 138-144.
Ge, J., Wang, X., Guan, Q., Li, W., Zhu, H., Yao, M., 2016. World rare earths trade network: Patterns, relations and role characteristics. Resources Policy 50, 119-130.
Geng, Y., Sarkis, J., Bleischwitz, R., 2019. How to globalize the circular economy. Nature 565, 153-155.
Gereffi, G., Wyman, D.L., 2014. Manufacturing miracles: paths of industrialization in Latin America and East Asia. Princeton University Press.
Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Science Advances 3(7), e1700782.
Gibbs, C., McGarrell, E.F., Axelrod, M., 2010. Transnational white-collar crime and risk: Lessons from the global trade in electronic waste. Criminology & Public Policy 9(3), 543-560.
GRID-Arendal, 2018. A GRID-Arendal Story Map: The Trade of Plastic Waste, URL: https://grid-arendal.maps.arcgis.com/apps/Cascade/index.html?appid=002738ffb18548818a61cc88161ac464, Accessed 14 Jan. 2019.
Hao, X., An, H., Qi, H., Gao, X., 2016. Evolution of the exergy flow network embodied in the global fossil energy trade: Based on complex network. Applied Energy 162, 1515-1522.
Havlin, S., Stanley, H.E., Bashan, A., Gao, J., Kenett, D.Y., 2015. Percolation of interdependent network of networks. Chaos, Solitons & Fractals 72, 4-19.
Hojman, D.A., Szeidl, A., 2008. Core and periphery in networks. Journal of Economic Theory 139(1), 295-309.
Hu, X., Wang, C., Lim, M.K., Koh, S.C.L., 2019. Characteristics and community evolution patterns of the international scrap metal trade. Journal of Cleaner Production, 118576.
Javorsek, M., 2016. Asymmetries in International Merchandise Trade Statistics: A case study of selected countries in Asia and the Pacific. ARTNeT Working Paper Series.
Ji, L., Jia, X., Chiu, A.S., Xu, M., 2016. Global electricity trade network: structures and implications. PloS one 11(8), e0160869.
Ji, Q., Zhang, H.-Y., Fan, Y., 2014. Identification of global oil trade patterns: An empirical research based on complex network theory. Energy Conversion and Management 85, 856-865.
Kellenberg, D., 2015. The economics of the international trade of waste. Annual Review of Resource Economics 7(1), 109-125.
Keller, W., Li, B., Shiue, C.H., 2011. China's foreign trade: Perspectives from the past 150 years. The World Economy 34(6), 853-892.
Kitt, J.R., 1994. Waste exports to the developing world: A global response. Georgetown International Environmental Law Review 7, 485.

Kohli, A., 2012. Coping with globalization: Asian versus Latin American strategies of development, 1980-2010. Brazilian Journal of Political Economy 32, 531-556.
Lee, K.-M., Yang, J.-S., Kim, G., Lee, J., Goh, K.-I., Kim, I.-m., 2011. Impact of the topology of global macroeconomic network on the spreading of economic crises. PloS one 6(3), e18443.
Lepawsky, J., 2015. The changing geography of global trade in electronic discards: time to rethink the e-waste problem. The Geographical Journal 181(2), 147-159.
Lepawsky, J., McNabb, C., 2010. Mapping international flows of electronic waste. The Canadian Geographer/Le Géographe canadien 54(2), 177-195.
Liu, D., Liu, J.C., Huang, H., Sun, K., 2019. Analysis of the international polysilicon trade network. Resources, Conservation and Recycling 142, 122-130.
Liu, Z., Adams, M., Walker, T.R., 2018. Are exports of recyclables from developed to developing countries waste pollution transfer or part of the global circular economy? Resources, Conservation and Recycling 136, 22-23.
Liu, Z., Wang, T., Song, J.W., Chen, W., 2018. The structure and evolution of trade relations between countries along the Belt and Road. Journal of Geographical Sciences 28(9), 1233-1248.
Pu, Y., Wu, G., Tang, B., Xu, L., Wang, B., 2019. Structural features of global recycling trade networks and dynamic evolution patterns. Resources, Conservation and Recycling 151, 104445.
Qu, S., Guo, Y., Ma, Z., Chen, W.-Q., Liu, J., Liu, G., Wang, Y., Xu, M., 2019. Implications of China's foreign waste ban on the global circular economy. Resources, Conservation and Recycling 144, 252-255.
Resource Recycling Inc., 2018. Thailand bans scrap plastic imports, URL: https://resource-recycling.com/plastics/2018/06/27/thailand-bans-scrap-plastic-imports/.
Saberi, A.A., 2015. Recent advances in percolation theory and its applications. Physics Reports 578, 1-32.
Serrano, M.A., Boguná, M., 2003. Topology of the world trade web. Physical review E 68(1), 015101.
Shinkuma, T., Huong, N.T.M., 2009. The flow of E-waste material in the Asian region and a reconsideration of international trade policies on E-waste. Environmental Impact Assessment Review 29(1), 25-31.
Siddique, R., Khatib, J., Kaur, I., 2008. Use of recycled plastic in concrete: A review. Waste management 28(10), 1835-1852.
Singh, J.B., Lakhan, V.C., 1989. Business ethics and the international trade in hazardous wastes. Journal of Business Ethics 8(11), 889-899.
Song, Z., Che, S., Yang, Y., 2018. The trade network of the Belt and Road Initiative and its topological relationship to the global trade network. Journal of Geographical Sciences 28(9), 1249-1262.
Soskolne, C.L., 2001. International transport of hazardous waste: Legal and illegal trade in the context of professional ethics. Global Bioethics 14(1), 3-9.
The Guardian, 2018. Huge rise in US plastic waste shipments to poor countries following China ban, URL: https://www.theguardian.com/global-development/2018/oct/05/huge-rise-us-plastic-waste-shipments-to-poor-countries-china-ban-thailand-malaysia-vietnam.
Velis, C., 2014. Global recycling markets-plastic waste: A story for one player–China, International Solid Waste Association—Global Waste Managament Task Force. pp. 1-66.

Wang, C., Ghadimi, P., Lim, M.K., Tseng, M.-L., 2019. A literature review of sustainable consumption and production: A comparative analysis in developed and developing economies. Journal of Cleaner Production 206, 741-754.
Wang, X., Ge, J., Wei, W., Li, H., Wu, C., Zhu, G., 2016. Spatial dynamics of the communities and the role of major countries in the international rare earths trade: a complex network analysis. PloS one 11(5), e0154575.
Wang, Z., Zhang, B., Guan, D., 2016. Take responsibility for electronic-waste disposal. Nature News 536(7614), 23.
Watts, D.J., Strogatz, S.H., 1998. Collective dynamics of 'small-world'networks. Nature 393(6684), 440.
Weiss, J., Jalilian, H., 2004. Industrialization in an age of globalization: some comparisons between East and South East Asia and Latin America. Oxford Development Studies 32(2), 283-307.
Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Böni, H., 2005. Global perspectives on e-waste. Environmental Impact Assessment Review 25(5), 436-458.
Wilhite, A., 2001. Bilateral trade and 'small-world'networks. Computational Economics 18(1), 49-64.
Xu, Y., Wang, Z., Jiang, Y., Yang, Y., Wang, F., 2019. Small-world network analysis on fault propagation characteristics of water networks in eco-industrial parks. Resources, Conservation and Recycling 149, 343-351.
Yang, Y., Poon, J.P., Liu, Y., Bagchi-Sen, S., 2015. Small and flat worlds: A complex network analysis of international trade in crude oil. Energy 93, 534-543.
Zhong, W., An, H., Gao, X., Sun, X., 2014. The evolution of communities in the international oil trade network. Physica A: Statistical Mechanics and its Applications 413(11), 42-52.
Zhong, W., Dai, T., Wang, G., Li, Q., Li, D., Liang, L., Sun, X., Hao, X., Jiang, M., 2018. Structure of international iron flow: Based on substance flow analysis and complex network. Resources, Conservation and Recycling 136, 345-354.