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Original citation & hyperlink:
Hu , X, Wang, C, Lim, M, Bai , X & Yao , C 2021, 'Evaluating waste and scrap trade risks in Belt and Road Initiative countries', Resources, Conservation and Recycling, vol. 173, 105728.
https://dx.doi.org/10.1016/j.resconrec.2021.105728

DOI 10.1016/j.resconrec.2021.105728
ISSN 0921-3449

Publisher: Elsevier

Evaluating waste and scrap trade risks in Belt and Road Initiative countries

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An earlier version of this paper was presented at the icRS Urbanisation 2020 Conference, where it received the Outstanding Paper Award and was selected to submit to *Resources, Conservation & Recycling*.

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Abstract

China's Belt and Road Initiative (BRI) is a global development strategy with great potential for multilateral trade cooperation and economic growth in Asia, Europe and Africa. Commodities trade volumes across BRI countries have boomed in the last few years. However, the waste and scrap (WaS) trade, an important aspect of global waste management, has received little attention. In recent years, frequent trade frictions and restrictive import policies due to increasing environmental protection awareness have sent massive shocks through the international WaS trade system. Exploring the impacts of shocks on BRI-WaS trade is an important but unexamined research topic that can help ensure the steady operation of WaS recycling. To address this research gap, this study first provides a panoramic view of the BRI-WaS trade network and analyzes its structural relation to the global WaS trade network. Second, the hidden risks in the BRI-WaS trade are revealed by proposed shock propagation models in three real-life scenarios, namely, a unilateral trade disruption, a bilateral trade crash and an import ban. Third, the global circulations conceptual framework is mathematically examined in the BRI regional context. The findings reveal that BRI countries are increasingly important to global WaS trade and that BRI-WaS trade presents a heterogeneous structure with evenly distributed trade channels. The "most at-risk" sources in the BRI-WaS trade network are uncovered. The BRI circulation system is mathematically feasible but eco-ethically infeasible. Discussions are provided to support authorities in developing effective strategies to manage BRI-WaS trade and responses to future extreme disturbances as well as address the global WaS crisis.

Keywords: Waste and scrap; Trade risk; Complex networks; Belt and Road Initiative

1. Introduction

After the eruption of the 2008 global economic crisis, the globalization process stalled. Trumpism and Brexitism are symptoms of this deglobalization wave (van Bergeijk, 2018), and the COVID-19 pandemic has accelerated the trend, leading to regionalization. The global trade network is gradually giving way to regional economic integration, particularly in Asia. The Comprehensive and Progressive Agreement for Trans-Pacific Partnership (CPTPP) and the Regional Comprehensive Economic Partnership (RCEP) exhibit this new Asian regionalism.

The transition underway from globalization to regionalization provides opportunities to advance the Belt and Road Initiative (BRI) strategy. Statistics from China Customs (2020) show that despite an overall decline in foreign trade imports and exports in 2020, China's foreign trade imports and exports to BRI countries have maintained a growth trend, with a total trade volume of 2.07 trillion RMB, representing an annual increase of 3.2%. The Association of Southeast Asian Nations (ASEAN), whose members are participants in the BRI, overtook the European Union (EU) and became the largest goods trading partner of China since the first quarter of 2020. Moreover, the signing of the RCEP provides a framework for lowering trade barriers and deepening economic integration for BRI participant countries (Petri and Plummer, 2020).

With the massive surge in trade volumes across BRI countries in the last few years, the commodities trade along the BRI region has attracted extensive attention. Due to the complicated connections in the trade network, several strategic commodities have been studied using complex network theory, such as petroleum (Zhang et al., 2019) and agricultural products (Liu et al., 2019). Notably, waste and scrap (WaS), as end-of-life products different from traditional commodities, play a crucial role in the international trade system. In the past decade, the international WaS trade has experienced substantial growth and is an important aspect of global waste management. Due to the high cost or the complexity of waste disposal, some wealth countries export large amounts of WaS to poor countries. For poor countries, importing WaS is an effective approach to alleviate the contradiction of insufficient materials for industrial development. Thus, trade network studies on various types of WaS, including e-waste (Lepawsky, 2015; Petridis et al., 2020), scrap metals (Hu et al., 2020b), plastic waste (Wang et al., 2020c), and scrap copper (Wang et al., 2020a), have emerged. These trade network studies have explored the topological characteristics of the trade system, enabling policymakers to adjust trade policies. With increasing awareness of environmental protection in undeveloped countries, restrictive policies of WaS imports in some countries, such as China, have been issued in recent years. The frequent trade frictions and import bans of some countries have noticeably impacted the steady operation of the WaS trade system. For instance, China's import ban places heavy pressure on the waste recycling system in Japan, the US, Australia and other developed countries. Exploring the impacts of shocks will help authorities make effective policies for ensuring normal waste disposal. Therefore, it is necessary to understand the evolution of the structural characteristics and reveal the impacts of trade shocks in different scenarios. However, WaS trade across BRI countries (hereinafter called BRI-WaS trade) and the influences of WaS trade shocks have received little attention. These research gaps inspire this study.

To address these gaps and in response to an explicit call by the icRS Urbanization 2020 conference supported by this journal (Chan et al., 2020), the following analyses are conducted in this study. First, this study provides a panoramic view of the BRI-WaS trade network and analyzes its structural relation with the global WaS trade network. Second, the "most at-risk" sources in the BRI-WaS trade are revealed by the proposed shock propagation models. An extinction analysis (Foti et al., 2013) is used to understand the hidden risks in three real-life scenarios, including shocks triggered by (a) a unilateral trade disruption, (b) a bilateral trade crash and (c) import bans in a given country. Third, the global circulations conceptual framework is mathematically examined in the BRI regional context with the proposed trade flow redirection model. The study provides an overview of the structural evolution of BRI-WaS trade from a systemic perspective and offers some anticipations of future extreme disturbances and regional economic development trends. Based on the findings, some implications are identified to support authorities in seeking effective strategies to manage the BRI-WaS trade.

This paper is organized as follows. Related research is summarized in Section 2. Section 3 presents the data and methods. Section 4 discusses the dynamic evolution of the BRI-WaS trade networks. Shock propagation in the WaS trade network is simulated in Section 5. This section is followed by the examination of the global circulation conceptual framework in the BRI regional context in Section 6. Finally, conclusions and discussion are provided in Section 7.

2. Literature review

This research evaluates the WaS trade risk posed by the BRI, so this section reviews the related literature in four main areas: the BRI trade network, the WaS trade network, the shock propagation in trade network, and the global circulations conceptual framework. Finally, the research gap and aims of this paper are presented.

2.1 BRI trade network

Since the BRI strategy was proposed by China's leader Mr. Xi in 2013 (Wang et al., 2020b), a vast body of literature focusing on quantitative studies in BRI countries has emerged, as reviewed in Lim (2016), Shahriar (2019), and Thürer et al. (2020).

From a mathematical perspective, the intricate relations among the BRI countries can be described by a network, in which nodes denote the countries, and edges represent the connections between them (Bartesaghi et al., 2020). Hence, the complicated economic connections among BRI countries are studied by constructing various networks, such as correlation networks of exchange rates (Liao et al., 2019), foreign direct investment networks (He and Cao, 2019), and aviation e-services networks (Huo et al., 2019).

Research on the BRI trade network began with Zhou and Liu (2016). By employing network analysis tools, Zhou and Liu (2016) built the traditional BRI trade network and explored the trade groups and core-periphery structure as well as the evolution of this trade network. Following this pioneering work, a few extended studies have emerged. Song et al. (2018) examined the structural relation between BRI trade and international trade. Liu, Zhigao et al. (2018) used the top 2 trade networks to capture the characteristics of trade relations among BRI countries. Chong et al. (2019) discussed the determining factors of BRI trade relationships. Later, international trade networks based on specific commodities among BRI countries were also explored, such as the petroleum trade (Zhang et al., 2019), the agricultural products trade (Liu et al., 2019), the virtual water trade (Qian et al., 2019), and the temporal cultural trade (Chen et al., 2019).

2.2 Waste and scrap trade network

Waste and scrap are valuable commodities sold in the global marketplace and are recycled and globally recognized as substitutes for virgin manufacturing materials (ISRI, 2021). Studies on the WaS trade network began with the seminal work of Lepawsky and McNabb (2010), who analyzed the flows of e-waste trade in 2010 and 2016. Later, Lepawsky (2015) constructed global e-waste trade networks (GEWTNs) using a complex network method. It was found that GEWTNs are highly regionalized. Petridis et al. (2020) detected trade communities in the GEWTNs and compared the trade communities with clustering countries by CO_2 levels, language, geographical distances, regional trade agreements, and colonial ties. Theis (2020) studied the network formation mechanism for GEWTNs and discussed the impacts of ecologically unequal exchange, global political economy and world polity theory on GEWTN formation.

Due to the global plastic crisis created by WaS import prohibition and restriction in China since 2017, the international trade of plastic waste has attracted scholars' attention (Brooks et al., 2018). The spatiotemporal evolution of global plastic waste trade networks (GPWTNs) was explored (Wang et al., 2020d). The results reveal that Asia is the dominant importer, and North America and Europe are the major sources of plastic waste. In addition, China is the leading country in international trade on plastic waste, so China's import regulations are the main drivers of the expansion and shrinkage of GPWTNs (Shi et al., 2021). After China imposed an import ban, exporting countries have begun turning to Southeast Asia to manage their waste. The direct and indirect influences of China's restrictive import policies on GPWTNs were evaluated by Wang et al. (2020d). In addition, polymer-specific trade network patterns have also been studied. Xu et al. (2020) studied the dynamics of global polyethylene waste trade networks (GPEWTNs). Pacini et al. (2021) divided plastic wastes into four subtypes, including ethylene (PET) wastes, styrene wastes (PS), polyvinyl chloride (PVC) wastes and mixed plastic wastes. Then, the four subnetworks were constructed and explored.

Relatedly, the global trade of steel scrap (Lee and Sohn, 2015), scrap copper (Wang et al., 2020a), scrap metal (Hu et al., 2020a; Hu et al., 2020b), and illicit waste (Favarin and Aziani, 2020) has been studied, emphasizing spatiotemporal evolution in global trade patterns.

Notably, unlike the classic trade network, Hu et al. (2020a) studied the international trade of copper raw materials and copper scrap and constructed multiplex trade networks. Then, the influences of China's import restrictions on this multiplex trade system were evaluated. See Table 1 for a detailed introduction to the above studies. Other WaS materials, such as scrap glass and rubber, have not been empirically investigated in academia thus far.

Table 1. Previous studies on the WaS trade network

Publications	Commodity	Time span	Network type	Comments
Lepawsky and McNabb (2010)	E-waste	2001 and 2006	Trade flow analysis	1. Geographical analysis of the GEWTNs
Lepawsky (2015)	E-waste	1996-2012	Classic trade network	1. The changing geography of GEWTNs
Petridis et al. (2020)	E-waste	2002-2014	Classic trade network	1. Trade communities of GEWTNs were detected. 2. The identified trade communities were compared with clustering countries.
Theis (2020)	E-waste	2015	Classic trade network	1. Network formation mechanism for GEWTNs
Wang et al. (2020d)	Plastic waste	1988-2017	Classic trade network	1. Spatiotemporal evolution of GPWTNs 2. Direct and indirect influences of China's import restriction on GPWTNs
Xu et al. (2020)	Polyethylene waste	1976-2017	Classic trade network	1. Spatiotemporal evolution of GPEWTNs
Shi et al. (2021)	Plastic waste	1992-2018	Classic trade network	1. Expansion and shrinkage of GPWTNs following China's waste management policies
Pacini et al. (2021)	PET, PS, PVC, and mixed plastic waste	2018	Classic trade network	2. Network analysis of international trade in four subtypes of plastic waste
Wang et al. (2020a)	Scrap copper	1988-2017	Classic trade network	1. Dynamic evolution of the international trade of scrap copper
Hu et al. (2020a)	Copper raw materials and scrap copper	1988-2017	Multiplex trade network	1. Exploration of intricate relationships in the multiplex trade network 2. Influence of China's import ban on the multiplex trade system
Lee and Sohn (2015)	Steel scrap	1990-2013	Classic trade network	1. Centrality analysis of the steel scrap network 2. Steel scrap forecasting in 2018
Hu et al. (2020b)	Scrap metal	1988-2017	Classic trade network	1. Characteristics and community evolution of the international trade of scrap metal
Pacini and Golbeck (2020)	Scrap materials (plastics, paper, textiles, and ferrous metals)	2018	Classic trade network	1. A limited analysis comparing plastics, textiles, paper and ferrous metals in the global scrap trade network
Favarin and Aziani (2020)	Illicit waste	2016-2017	Classic trade network	1. An illicit waste trafficking network was explored. 2. The role of specific potential factors that influence the structure of this network was investigated.

2.3 Shock propagation in trade networks

Traditional methods for analyzing trade risks rely on several static indicators. In the current geographical context, some strategic raw materials are often characterized by high concentrations of production within a country (Glöser et al., 2015). For example, a few countries have monopolized the mining and processing of rare earths, including China, the US, Brazil, Russia, and the Democratic Republic of Congo (DRC) (Massari and Ruberti, 2013). Particularly for cobalt, DRC accounted for over 70% of the world's cobalt production in 2019 (van den Brink et al., 2020). Due to the criticality and scarcity of some strategic raw materials, more than 15 indicators have been proposed for evaluating supply risks, such as the Herfindahl-Hirschman Index (European Commission, 2014), the World Governance Index (World Bank Group et al., 2010), and the Substitutability Index (IW Consult, 2011). Although these static indicators are widely used to analyze trade risks, they have been criticized for lacking dynamic evaluation capabilities (Achzet and Helbig, 2013).

The trade network structure created through interaction among countries constructs a set of interdependencies that affect each other. This type of highly interdependent network calls for dynamic network analysis. The propagation of shocks through networks can serve as a theoretical platform for uncovering hidden risks (Bartesaghi et al., 2020). The cascading failure model is widely used to model the shock propagation process (Lee and Goh, 2016). For example, based on the cascading failure model, Fair et al. (2017) removed the export edges of nodes and evaluated the resilience of international trade of wheat. Burkholz and Schweitzer (2019) studied the shocks of export restrictions on global crop trade networks. These studies explore the shock propagation process in the trade network from the supply side, which is an excellent precedent. However, none of the studies explored the hidden risks from the demand side. WaS exporting countries expect to continue this decades-old practice of shipping scrap to poor countries, which is the cheapest way to dispose of WaS (Wang et al., 2020d). In contrast, WaS importing exporting countries are willing to restrict WaS imports. Hence, the WaS trade risks come from the demand side.

2.4 Global circulations conceptual framework

In the past three decades, globalization has reshaped the global supply chain. Generally, goods transfer from not only wealthy countries to poor countries but also raw material to finished products (Gregson and Crang, 2015). In contrast, WaS flow from wealth countries to poor ones (Petridis et al., 2020; Wang et al., 2020d). China was the center of the world's recycling trade. When China decided to stop accepting WaS in 2013, the world's recycling system stopped working, producing a global waste crisis (Walker, 2018).

Recent scholarship proposed building a global circulations conceptual framework according to circular economy theory (see Figure 1). This global circulation system includes dual circulations. Both wealth and poor countries employ domestic circular economy practices (Hartley et al., 2020; Tong et al., 2018). More importantly, a fair trading system is established for waste reutilization globally (Liu, Zhe et al., 2018). In this ideal trading system, wealth countries function as buyers, traders and brokers. Poor countries serve as reuse, recycling, and resource reclamation economies (Gregson and Crang, 2015). Poor countries will not issue import bans and continue to recycle materials for wealthy countries (Crang et al., 2013). However, wealthy countries must transfer processing and recycling technologies and provide funds to help poor countries handle mismanaged waste (Wang et al., 2016). Extended producer responsibility (EPR) will be implemented to support reshaping global circulations (Liu, Zhe et al., 2018). However, no study has mathematically examined the feasibility of a global circulations conceptual framework.

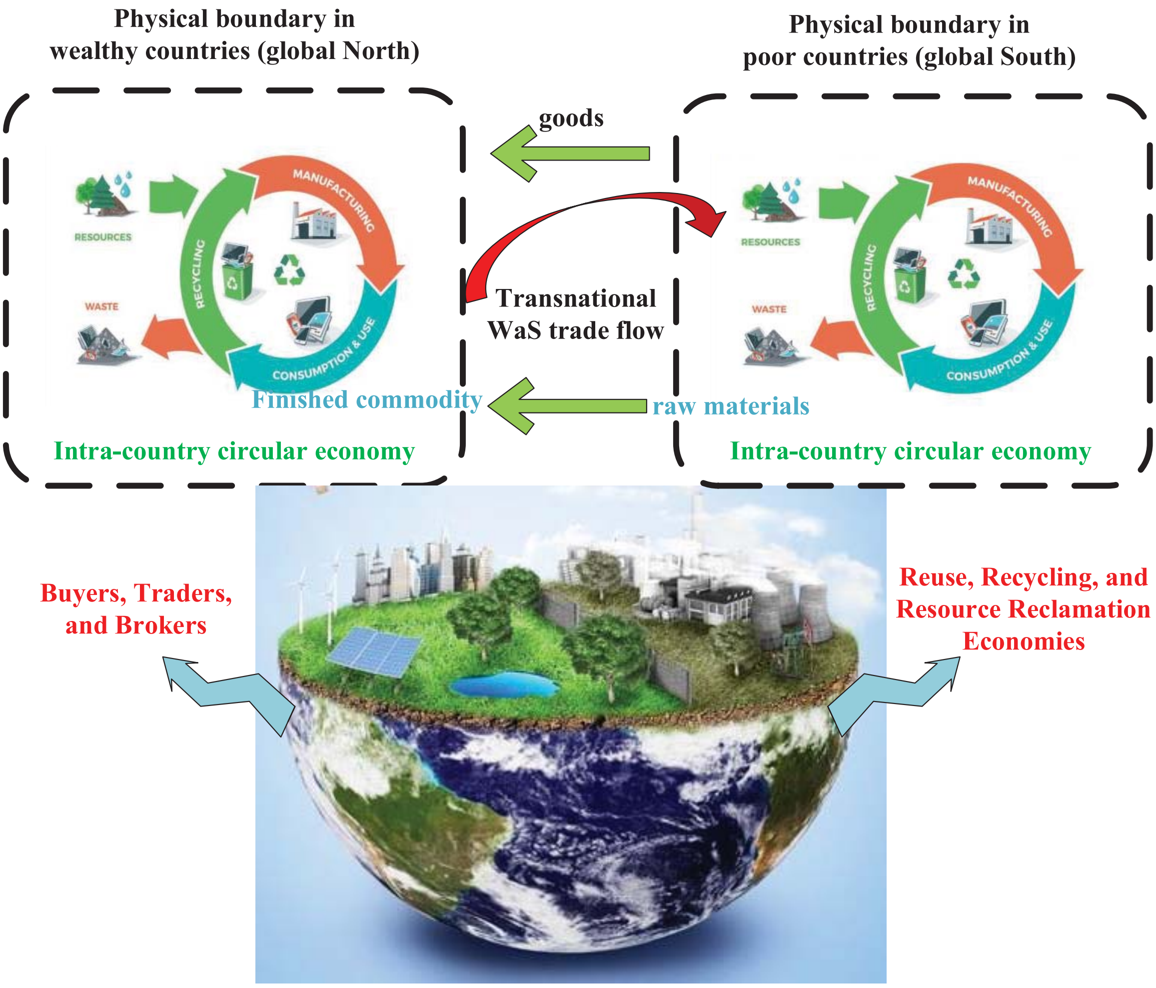


Figure 1. Global circulations conceptual framework.

2.5 Research gap and contributions

Prior studies have quantitatively investigated trade networks along BRI countries. However, the WaS trade among BRI countries has yet to be illuminated. Moreover, the hidden risks in the BRI-WaS trade network remain unexplored, which constitutes a research gap and motivates this study. Specifically, this study aims to evaluate WaS trade risks for BRI countries.

Accordingly, WaS trade records for BRI countries from 1990 to 2019 are collected, and annual trade networks are constructed. This study makes the following three contributions to the literature:

- This study represents the first investigation of the BRI-WaS trade network;
- The "most at-risk" sources in the BRI-WaS trade network are revealed by analyzing the impacts of shocks from the demand side; and
- The feasibility of the global circulations conceptual framework is mathematically

examined in the BRI regional context.

3. Data and methods

3.1 Data description and network construction

Based on the regional characteristics of the BRI region (Yang et al., 2018), 65 BRI participating countries are geographically grouped into six subregions (see Figure 2). The detailed countries are tabulated in Appendix A1. According to ISRI (2021), WaS commodities include 12 categories, such as plastic wastes, scrap ferrous, and scrap glass. In this study, publicly available data from the United Nations COMTRADE were retrieved to obtain all trade records among all countries. Over 0.98 million reported trade transactions from 1990 to 2019 were collected to analyze the BRI-WaS trade network and its relation to the entire WaS trade network. The detailed commodities of the WaS and data preprocessing are shown in Appendix A2.

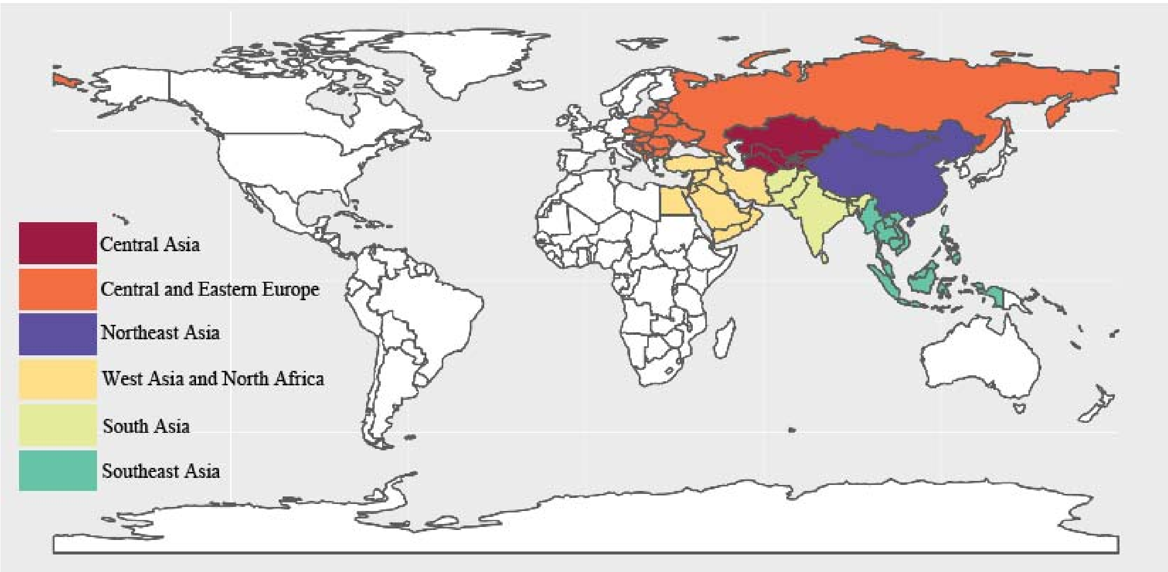


Figure 2. BRI participating countries and subregions

For a particular year t ranging from 1990 to 2019, trade transaction records are used to construct a directed weighted BRI-WaS trade network $G^{[t]}$. The nodes of the network denote countries, represented as $V^{[t]}$. The trade relationships between countries are denoted by edges $E^{[t]} = \{(i, j) \mid i, j \in V^{[t]}\}$. In the network $G^{[t]}$, $\mathbf{A}^{[t]} = \{a_{ij}^{[t]} \mid i, j \in V^{[t]}\}$ is the signal adjacency matrix, where $a_{ij}^{[t]} = 1$ if $(i, j) \in E^{[t]}$ and $a_{ij}^{[t]} = 0$ if $(i, j) \notin E^{[t]}$. The trade value between countries is identified by the weight matrix $\mathbf{W}^{[t]} = \{w_{ij}^{[t]} \mid (i, j) \in E^{[t]}\}$, where $w_{ij}^{[t]}$ is the total export volume of 12 types of WaS from country i to country j. The BRI-WaS trade network is the subnetwork of the global WaS trade network. Hence, it is necessary to understand the relationship of the BRI-WaS trade network to the global WaS trade network. This study also constructs the directed and weighted global WaS trade network $\tilde{G}^{[t]}$. Similar to the definitions for the BRI-WaS trade network, the set of nodes and edges in $\tilde{G}^{[t]}$ is $\tilde{V}^{[t]}$ and $\tilde{E}^{[t]}$. The signal adjacency matrix and the weight matrix are $\tilde{\mathbf{A}}^{[t]}$ and $\tilde{\mathbf{W}}^{[t]}$, respectively.

3.2 Topological metrics of the network structure

To understand the dynamic evolution of the BRI-WaS trade network, the classic topology of the network structure is used to explore the characteristics of trade networks, including node degree (in-degree and out-degree), degree distribution, node strength (in-strength and out-strength), strength distribution, network density, average clustering coefficient, heterogeneity and degree centrality. Because the above topological metrics are widely used to understand network dynamics, an overview of these topological metrics are presented in Appendix A3.

3.3 Shock propagation models

In volatile and uncertain international situations, policymakers must identify hidden risks in BRI-WaS trade. Extinction analysis is widely used in ecology to explore the impact of sudden species extinctions (Foti et al., 2013). To find the "most at-risk" sources in the BRI-WaS trade, extinction analysis is used to conduct a simulation study of the global WaS trade network. This section proposes three types of shock propagation models under three extreme scenarios, including a unilateral trade disruption, a bilateral trade crash, and an import ban.

(1) Scenario I: unilateral trade disruption

If country j stops importing WaS from country i, this situation can be considered a disruption in trade value (weight) for a single edge (i, j). We assume that exporter i tends to maintain stable exports for disposal domestic WaS. Therefore, the reduction of exports from i to country j will be redirected to other importers of country i to keep total exports unchanged. Based on the trade weight preference (Hu et al., 2020a), the reduction $w_{ij}^{[t]}$ is proportional to the trade flows from country i to its importers except for country j in the network $\tilde{G}^{[t]}$. For country k, changes in the volume of imports are calculated by

$$f_1^{[t]}(\tilde{w}_{ij}^{[t]}, k) = \frac{\tilde{w}_{ij}^{[t]} \tilde{w}_{ik}^{[t]}}{\sum_{(i,h)\in \tilde{E}^{[t]}, h \neq j} \tilde{w}_{ih}^{[t]}} \tag{1}$$

where $k \neq i, j$. $f_1^{[t]}(\tilde{w}_{ij}^{[t]}, k)$ indicates the absolute impact of the shock. The relative influence of the shock can be measured by the ratio of the import increase to the total volume of imports in country k, which is expressed as

$$g_1^{[t]}(\tilde{w}_{ij}^{[t]}, k) = \frac{f_1^{[t]}(\tilde{w}_{ij}^{[t]}, k)}{\sum_{(h,k)\in \tilde{E}^{[t]}} \tilde{w}_{hk}^{[t]}} \tag{2}$$

where $g_1^{[t]}(\tilde{w}_{ij}^{[t]}, k)$ ranges from 0 to 1. A larger $g_1^{[t]}(\tilde{w}_{ij}^{[t]}, k)$ indicates that country k requires higher processing capacity for the imported WaS.

However, importers have bearing capacity limits for importing WaS. When $g_1^{[t]}(\tilde{w}_{ij}^{[t]}, k)$ is larger than a threshold, country k cannot process the excessive WaS. To evaluate the impacts of removing edge (i, j) on the global WaS BRI trade, we define an indicator:

$$e_1^{[t]}(\tilde{w}_{ij}^{[t]}, \lambda) = \sum_{(i,k)\in E^{[t]}} I_1^{[t]}(k, \lambda) \tag{3}$$

where $I_1^{[t]}(k, \lambda)$ is an indicative function, namely, if $g_1^{[t]}(\tilde{w}_{ij}^{[t]}, k) >= \lambda$, then $I_1^{[t]}(k, \lambda) = 1$; otherwise, $I_1^{[t]}(k, \lambda) = 0$. λ is a threshold ranging from 0 to 1. Furthermore, $\max_{(i,j)\in E^{[t]}} e_1^{[t]}(\tilde{w}_{ij}^{[t]}, \lambda)$ indicates the maximum shock impact triggered by the unilateral trade disruption. The trade relationship between country pairs corresponding to a larger $e_1^{[t]}(\tilde{w}_{ij}^{[t]}, \lambda)$ requires special attention to maintain the stability of the WaS trade. The simulation is conducted from 10% to 100% in increments of 10% for λ.

(2) Scenario II: bilateral trade crash

Increasing confrontation between the two nations may disrupt bilateral trade. Hence, a propagation model is proposed to describe the shocks from a trade relations crash between two countries. In this case, all links connecting countries i and j will be removed from the network $\tilde{G}^{[t]}$. First, the net exporter between countries i and j will be identified. If $\tilde{w}_{ij}^{[t]} - \tilde{w}_{ji}^{[t]} > 0$, country i is the net exporter for country j; otherwise, country j is the net exporter for country i. Next, when country i is a net exporter, it will proportionally redirect $\tilde{w}_{ij}^{[t]} - \tilde{w}_{ji}^{[t]}$ to importers except for country j. For country k, the absolute and relative impacts of the shock are calculated by

$$f_2^{[t]}(\tilde{w}_{ij}^{[t]}, k) = \frac{(\tilde{w}_{ij}^{[t]} - \tilde{w}_{ji}^{[t]})\tilde{w}_{ik}^{[t]}}{\sum_{(i,h)\in \tilde{E}^{[t]}, h\neq j} \tilde{w}_{ih}^{[t]}} \tag{4}$$

$$g_2^{[t]}(\tilde{w}_{ij}^{[t]}, k) = \frac{f_2^{[t]}(\tilde{w}_{ij}^{[t]}, k)}{\sum_{(h,k)\in \tilde{E}^{[t]}} \tilde{w}_{hk}^{[t]}} \tag{5}$$

where $k \neq i, j$, and $g_2^{[t]}(\tilde{w}_{ij}^{[t]}, k)$ ranges from 0 to 1. Similar to the previous definition as Eq. (3), an indicator to evaluate the impacts of shocks in this scenario is calculated by

$$e_2^{[t]}(\tilde{w}_{ij}^{[t]}, \lambda) = \sum_{(i,k)\in E^{[t]}} I_2^{[t]}(k, \lambda) \tag{6}$$

If $g_2^{[t]}(\tilde{w}_{ij}^{[t]}, k) >= \lambda$, then $I_2^{[t]}(k, \lambda) = 1$; otherwise, $I_2^{[t]}(k, \lambda) = 0$. $\max_{(i,j)\in E^{[t]}} e_2^{[t]}(w_{ij}^{[t]}, \lambda)$ indicates the maximum number of countries bearing WaS import pressure beyond their capacity.

(3) Scenario III: import ban

Different from the above two scenarios, the third shock affects all of a country's WaS trade relations. For example, China started to gradually restrict the import of solid waste in 2013 and announced a complete ban on the import of all solid wastes on 1 January 2021 (Wang et al., 2020d). In this scenario, country i completely stops WaS imports, namely, $\tilde{s}_i^{[t]}(in)$. Specifically, for exporter j, the absolute and relative reduction in WaS exports is defined as follows:

$$f_3^{[t]}(i,j,d)=\frac{\tilde{s}_i^{[t]}(in)\tilde{w}_{ji}^{[t]}}{\sum_{(k,i)\in\tilde{E}^{[t]}}\tilde{w}_{ki}^{[t]}} \tag{7}$$

$$g_3^{[t]}(i,j)=\frac{f_3^{[t]}(i,j)}{\sum_{(j,k)\in\tilde{E}^{[t]}}\tilde{w}_{jk}^{[t]}} \tag{8}$$

where $j \neq i$. Similar to the definition of $e_2^{[t]}(\tilde{w}_{ij}^{[t]},\lambda)$ in Eq. (6), the indicator for integrated assessment for the impact of shocks $e_3^{[t]}(i,\lambda)$ is calculated by aggregating the indicative function $I_3^{[t]}(j,\lambda)$ for all edges $(j,i)\in E^{[t]}$. When $g_3^{[t]}(i,j)$ is larger than the threshold λ, $I_3^{[t]}(j,\lambda)$ is set as 1; otherwise, $I_3^{[t]}(j,\lambda)$ is 0. All nodes in $G^{[t]}$ are sorted in descending order by $e_3^{[t]}(i,\lambda)$. High-ranking BRI countries are the main focus because of their significant impact on the global WaS trade.

3.4 Trade flow redirection model

To examine the feasibility of the global circulations conceptual framework in the BRI regional context, this subsection proposes a trade flow redirection model according to the following assumption. BRI countries do not import WaS from non-BRI countries and only export WaS to other BRI countries. Specifically, for a BRI country i, the imports from country j ($j\in\tilde{V}^{[t]}$ and $j\notin V^{[t]}$) are set as 0 in the new BRI-WaS trade network after trade flow redirection. For exports from country i to another country, j ($j\in\tilde{V}^{[t]}$ and $j\notin V^{[t]}$) are set as 0 and redirected to other countries belonging to $V^{[t]}$. In other words, for country $k\in V^{[t]}$, the new volume of exports from country i to country k is calculated by

$$\hat{w}_{ik}^{[t]}=w_{ik}^{[t]}+\frac{w_{ik}^{[t]}}{\sum_{k\in V^{[t]}}w_{ik}^{[t]}}\sum_{j\in\tilde{V}^{[t]},\,j\notin V^{[t]}}\tilde{w}_{ij}^{[t]} \tag{9}$$

Therefore, the imports and exports of BRI country i after the flow redirection are $\hat{s}_i^{[t]}(in)=\sum_{j\in V^{[t]}}\hat{w}_{ji}^{[t]}$ and $\hat{s}_i^{[t]}(out)=\sum_{j\in V^{[t]}}\hat{w}_{ij}^{[t]}$. If $\tilde{s}_i^{[t]}(in)-\tilde{s}_i^{[t]}(out)>0$, country i is a net importer in $\tilde{G}^{[t]}$; otherwise, country i is a net exporter. Similarly, country i is a net importer after flow redirection when $\hat{s}_i^{[t]}(in)-\hat{s}_i^{[t]}(out)>0$. To evaluate the change in country

i after flow redirection, an indicator is defined:

$$\hat{r}_i^{[t]} = \frac{\hat{s}_i^{[t]}(out) - \hat{s}_i^{[t]}(in)}{\tilde{s}_i^{[t]}(out) - \tilde{s}_i^{[t]}(in)} \quad (10)$$

A net importer i in $\tilde{G}^{[t]}$ will have lower net imports when $\hat{r}_i^{[t]}$ ranges from 0 to 1. If $\hat{r}_i^{[t]}$ is more than 1, country i will have more imports than that before trade redistribution. A negative $\hat{r}_i^{[t]}$ denotes that country i will change from a net importer to a net exporter.

4. Evolution of the BRI-WaS trade

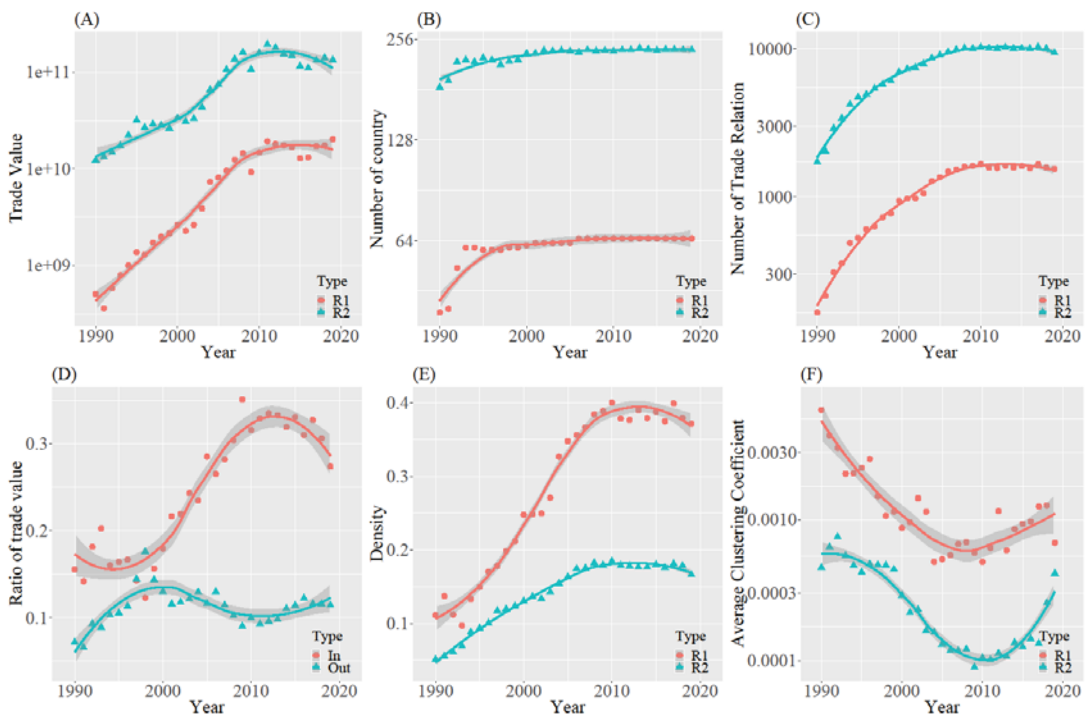
In this section, the evolution of the structural characteristics of the BRI-WaS trade network from 1990 to 2019 is reviewed. Then, important countries measured by different metrics are revealed.

4.1 Topological structure

As shown in Figure 3(A)-(C), the trade value of 12 types of commodities in the BRI-WaS trade network shows a continuous increase from 1990 to 2010 and then fluctuates over the next 9 years. The number of countries involved in the BRI-WaS trade increased dramatically from 1990 to 1993. The number of WaS trade relationships between BRI countries showed an upward trend since 1990 and remained stable from 2010. Compared to BRI-WaS trade, the global WaS trade showed a similar tendency in terms of trade value, the number of involved countries and trade relationships. In addition, the ratio of BRI-WaS trade value to global WaS trade value grew gradually from 4.1% in 1990 to 15.1% in 2019. The ratio of WaS trade relationships among BRI countries increased and reached its peak in 2019 (16.5%), indicating that BRI-WaS trade is increasingly important to the global WaS trade.

The trade relationships between BRI countries and non-BRI countries are further revealed in Figure 3(D). Specifically, it can be found that the ratio of imports from non-BRI countries to BRI countries grew dramatically from 16.0% in 1994 to 35.1% in 2009 and decreased starting in 2010. The figure also reveals that 65 BRI countries disposed a large amount of WaS from non-BRI countries. The reduction in recent years results from increasing awareness of environmental protection in BRI countries. For instance, China issued a series of restrictions on WaS imports. Different from the ratio of imports, the ratio of exports from BRI countries to non-BRI countries fluctuated at a low level of 10% from 1990 to 2019.

Figure 3(E) indicates an upward trend of density, which reflects the increasingly close trade connections in two WaS trade networks. Notably, compared to the global WaS trade networks, BRI-WaS trade networks have a much higher value of density, indicating that BRI countries work closely with each other in WaS disposal. However, Figure 3(F) depicts a distinct trend of the average clustering coefficient. This indicator decreased sharply and was at a low level in 2010. Combining the density and the average clustering coefficient showed that despite increasing trade relations among BRI countries, the considerable disparity of trade value in edges led to a low level of tightness.



Notes: R1 denotes the BRI-WaS trade network. R2 denotes the global WaS trade network. In subfigure (D), the red line represents the change in the ratio of WaS imported from non-BRI countries by BRI countries to all trade value among countries, namely, $\sum_{i\in\tilde{V}^{[t]}-V^{[t]},j\in V^{[t]}} \tilde{w}_{ij}^{[t]} \Big/ \sum_{i,j\in\tilde{V}^{[t]}} \tilde{w}_{ij}^{[t]}$. The green line represents the change in the ratio of WaS exported to non-BRI countries by BRI countries to all trade value, namely, $\sum_{j\in\tilde{V}^{[t]}-V^{[t]},i\in V^{[t]}} \tilde{w}_{ij}^{[t]} \Big/ \sum_{i,j\in\tilde{V}^{[t]}} \tilde{w}_{ij}^{[t]}$.

Figure 3. Dynamic evolution of the network structure from 1990 to 2019

Furthermore, the distribution of node degree and node strength is investigated to explore patterns in the BRI-WaS trade network in Appendix A4. Figure A1 shows the cumulative probability distribution of in-degree, out-degree and degree in 1990, 2000, 2010 and 2019 (see Appendix A4). Comparing Figure A1(A) and Figure A1(D), it is found that the in-degree distributions in 1990 and 2019 are significantly different. A similar situation occurs in the cumulative probability distribution of out-degree and degree, as shown in Figure A1(E)-(H). This result indicates that most BRI countries in the BRI-WaS trade network only had a small number of trading partners in 1990. However, with the dynamic evolution of the BRI-WaS trade network structure, the cumulative probability distribution of in-degree/out-degree/degree shows a straight upward trend in 2019. This finding denotes that the ratio of countries having different numbers of trading partners is nearly equal. Compared to the BRI-WaS trade networks, the global WaS trade networks have a similar distribution of in-degree/out-degree/degree in each year, and the distribution is becoming more uniform.

Figure A2 shows the cumulative probability distribution of in-strength, out-strength and strength in 1990, 2000, 2010 and 2019 (see Appendix A4). The distribution patterns of the BRI-WaS trade networks and global WaS trade networks remained essentially unchanged. Specifically, most countries in the network have a small trade value, and WaS trade is concentrated in a few countries. Combining the results shown in Figure A1 and Figure A2, it is found that the distribution of WaS trade value is more heterogeneous compared to the distribution of trade connections.

Although the degree distribution (Figure A1) and the strength distribution (Figure A2) provide an intuitive sense of the network patterns, it is necessary to evaluate the heterogeneity of edges in networks. Figure A3(A) depicts a decreasing trend in the heterogeneity from 1990 to 2019, indicating that the uneven distribution pattern of the WaS trade relations reached a relatively low level in the last 10 years. Compared to the global WaS trade network, the BRI-WaS trade network has lower heterogeneity. This finding reflects that the distribution of trade relations among BRI countries is more even, which is line with the results shown in Figure A1. Figure A3(B) presents the changes in the in-degree centrality from 1990 to 2019, indicating the level of competition among WaS importing countries. Compared to the global WaS trade network, the BRI-WaS trade network shows a different trend for in-degree centrality. Specifically, the in-degree centrality of the BRI-WaS trade network decreased in the early years and fluctuated by approximately 50% from 2010 to 2019. However, the in-degree centrality of the global WaS trade network increased from 1995 to 2005 and then fluctuated by approximately 55%. In recent decades, the level of competition among BRI-WaS importers has been lower than that among global WaS importers. As shown in Figure A3(C), the degree of exporting monopolization measured by the out-degree centrality of the BRI-WaS trade networks gradually increased from 1990 to 2019. This change indicates that BRI-WaS trade shows an increasingly monopoly pattern. Different from the BRI-WaS trade networks, the exporting monopolization in the global WaS trade network remained at a higher level from 1990 to 2019.

4.2 Important BRI countries in the WaS trade network

The top 10 countries are identified based on in-degree, out-degree, in-strength and out-strength, and variations in the core countries are explored in this subsection.

Table A4 in Appendix A5 tabulates the core countries in the BRI-WaS trade network $G^{[t]}$ in 1990, 2000, 2010 and 2019. Countries with high in-degree are mainly located in Southeast Asia, such as Indonesia, Thailand, and Singapore. Over time, countries in Central and Eastern Europe, West Asia and North Africa, such as Turkey, the United Arab Emirates (UAE), Poland and Egypt, have clear advantages in terms of the number of importing channels. In terms of WaS import value, the geographical location of the core countries underwent a similar change from 1990 to 2019. In particular, the Central and Eastern European countries, including Poland, Russia and Belarus, were all in the top ten sorted by import value. Notably, there is a large gap between the top three importing countries (India, Singapore and India) and other BRI countries. Regarding WaS exports, the core countries with a high out-degree are clearly different from the core countries with a high out-strength in 2019. Specifically, China had the maximum number of exporting partners in 2010 and 2019, followed by Thailand and India. In terms of export value, it is surprising to find that China was not in the top ten countries in 2010 and 2019. Based on the above results, it is found that the Southeast Asian countries and the Central and Eastern European countries are located in the central positions in terms of the WaS imports and exports network $G^{[t]}$.

The core BRI countries in the global WaS trade network $\tilde{G}^{[t]}$ are also presented in this subsection. Table A5 in Appendix A5 tabulates the top 10 BRI countries measured by in-degree/out-degree/in-strength/out-strength in the network $\tilde{G}^{[t]}$. Comparing Tables A4 and A5, the core countries with more import and export channels in network $\tilde{G}^{[t]}$ are similar to those in network $G^{[t]}$, although the rankings change slightly. Southeast Asian countries in the network $\tilde{G}^{[t]}$ have more trade links than the other BRI countries. For the in-strength, comparing Tables A4 and A5 shows that BRI countries import more WaS from non-BRI countries. For instance, China's imports from BRI countries account for only 11% of its total imports. In addition, compared to other BRI countries, Southeast Asian countries and South Asian countries, such as India, Singapore, Malaysia, Vietnam, Indonesia and Thailand, play an increasingly important role in the global WaS trade network. Specifically, Vietnam, not in the list of the top 10 import countries in Table A4, is an important import country in Table A5. This finding indicates that Vietnam imports more WaS from non-BRI countries. Different from the imports of BRI countries, BRI countries' exports in $G^{[t]}$ and $\tilde{G}^{[t]}$ are similar. To some extent, it denotes that the exports of BRI countries are disposed within the BRI region.

5. Hidden risks in the BRI-WaS trade

Based on the shock propagation models defined in Subsection 3.3, this section analyzes the impact of three types of shocks, including a unilateral trade disruption, a bilateral trade crash, and an import ban. The propagation models are simulated in the 2019 global WaS trade network, and the "most at-risk" sources in the BRI-WaS trade are revealed. Table 2 shows the top six shocks and their impacts on the BRI-WaS trade for three types of scenarios.

Table 2. Shocks with high impacts in three scenarios

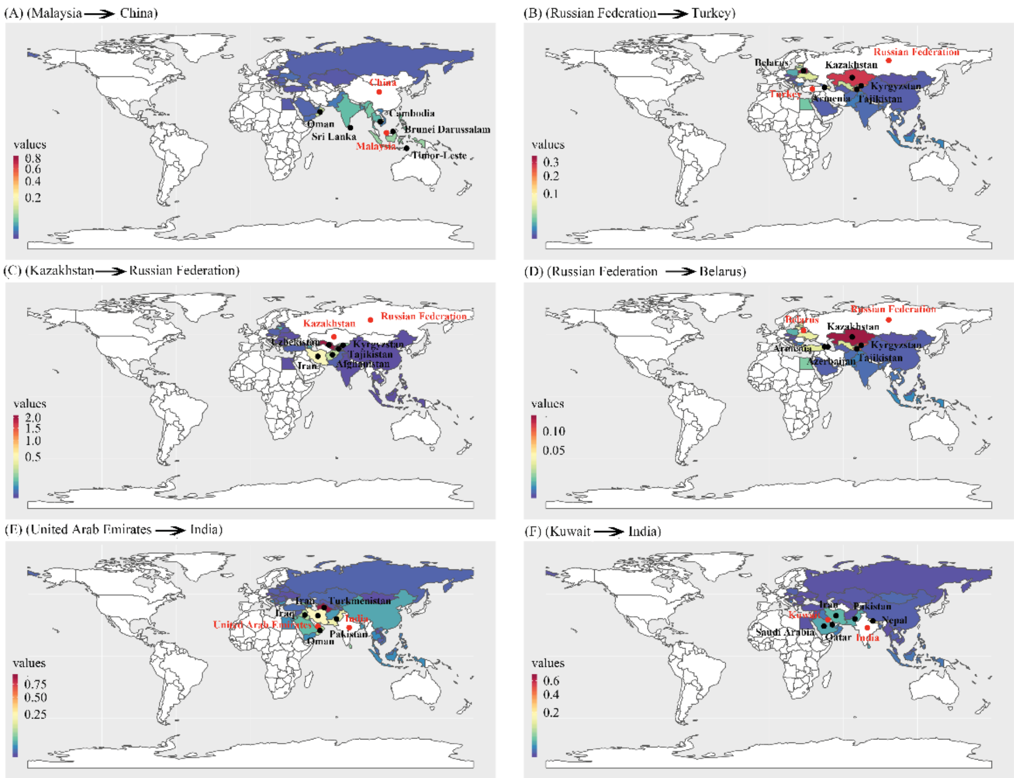
Rank	Scenario I		Scenario II		Scenario III	
	$i \rightarrow j$	$e_1^{[t]}$	(i, j)	$e_2^{[t]}$	i	$e_3^{[t]}$
1	Malaysia → China	5	(Kazakhstan, Russia)	5	Turkey	17
2	Russia → Turkey	5	(Russia, Turkey)	5	India	16
3	Kazakhstan → Russia	5	(Malaysia, China)	3	Pakistan	7
4	Russia → Belarus	3	(UAE, India)	3	Russia	6
5	UAE → India	3	(Kuwait, India)	2	China	5
6	Kuwait → India	2	(Romania, Turkey)	2	Singapore	5

Note: The parameter λ is set as 0.1 in Scenarios I, II, and III. The main results in different parameter λ remained essentially unchanged, with a slight change of the shock's rankings. $e_1^{[t]}$, $e_2^{[t]}$ and $e_3^{[t]}$ reflect the impacts of shocks triggered by a unilateral trade disruption, a bilateral trade crash and an import ban, respectively, on the BRI-WaS trade network, namely, the number of countries bearing import pressure beyond their capacity.

5.1 Unilateral trade disruption

As defined in Subsection 3.3, for the given parameters of λ, the country pairs with a high value of $e_1^{[t]}(w_{ij}^{[t]},\lambda)$ emphasize the importance of stable WaS trade. Table 2 shows the top six shocks for the three examined scenarios. Based on the evaluation of $e_1^{[t]}(w_{ij}^{[t]},0.1)$, it is found that unilateral trade disruptions from Malaysia → China, Russia → Turkey, and Kazakhstan → Russia will have the worst impact. Specifically, five countries will be under pressure to import excessive WaS, which exceeds their processing capacity. As noted in subsection 4.2, China, Turkey, Malaysia and Russia were important WaS importers and exporters in 2019. Therefore, the shock impacts of the trade between these countries are greater than the other shocks are. Notably, Kazakhstan and Kuwait were not on the list of important countries in 2019, and the reduction in trade value from Kazakhstan → Russia and Kuwait → India also led to a serious impact. This result may be ignored, but attention should be given.

As shown in (A), due to the reduction in the WaS trade value of Malaysia → China, the top five affected countries are geographically distributed in Southeastern and South Asia, namely, Cambodia, Brunei Darussalam, Timor-Leste and Sri Lanka. Different from the shock from Malaysia → China, the shocks from Russia → Turkey, Kazakhstan → Russia, Russia → Belarus, UAE → India, and Kuwait → India have serious impacts on Central Asia and West Asia, including Kyrgyzstan, Tajikistan, Kazakhstan, Iran and Iraq, as shown in (B)-(F). To some extent, the countries in these regions are susceptible to trade risks. It is necessary for countries in these regions to enhance their waste disposal capacity. In addition, it is found that the highly affected countries are mainly closer to the export countries. For instance, the core countries affected by the shock from UAE → India are closer to the UAE, including Oman, Iraq and Iran, as shown in (E).



Note: Countries are labeled with different colors that indicate the relative influence of the shock triggered by the unilateral trade disruption, namely, the ratio of import increase to the total volume of imports in the country $g_1^{[t]}(w_{ij}^{[t]},k)$. A warmer color indicates that the country is severely affected. The black dots denote the top five countries sorted by indicator $g_1^{[t]}(w_{ij}^{[t]},k)$ under the shock from (i,j), and the red dots represent countries i and j.

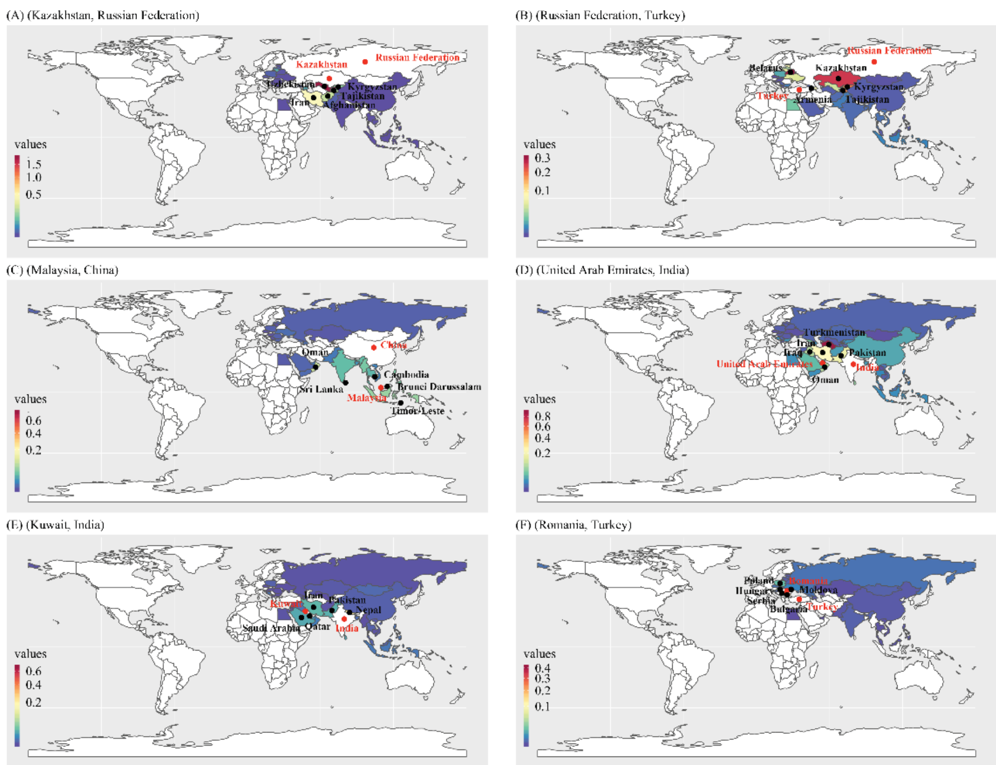
Figure 4. Shocks triggered by the unilateral trade disruption

5.2 Bilateral trade crash

Table 2 also presents the top six shocks in Scenario II. Comparing the lists in Scenario I and Scenario II shows that the countries with high impacts in shocks are similar, including Russia, Turkey, Malaysia, China, UAE, India, Kuwait and Kazakhstan. Therefore, the deterioration in trade relations between these countries should be is given special attention.

However, there are some general differences between Scenario I and Scenario II. Specifically, the bilateral trade crash between Kazakhstan and Russia will lead to the maximum value of the indicator $e_2^{[t]}$. In other words, five countries will have to face the pressure of disposing more than 10% of their original WaS imports under this shock. It will significantly impact global WaS circulation and threaten the BRI-WaS trade.

In addition, Figure 5(A) shows that the highly affected countries shocked by the trade relation crash in Kazakhstan, Russia are mainly geographically distributed in Central Asia and West Asia. Similar results occur in the shock from (Russian, Turkey), (UAE, India), (Kuwait, India), as illustrated in Figure 5(B)(D) and (E). The countries with a high value of $g_2^{[t]}(w_{ij}^{[t]},k)$ affected by the shocks from (Romania, Turkey) are mainly located in Central and Eastern Europe, including Poland, Hungary, Moldova, Bulgaria and Serbia, as shown in Figure 5(F).



Note: Countries are colored based on the relative impacts of the shock triggered by the bilateral trade crash, namely, the ratio of import increase to the total volume of imports in the country $g_2^{[t]}(w_{ij}^{[t]},k)$. A warmer color reflects that the country is more impacted. The black dots denote the top five countries sorted by indicator $g_2^{[t]}(w_{ij}^{[t]},k)$ under the shock from the bilateral trade crash between countries i and

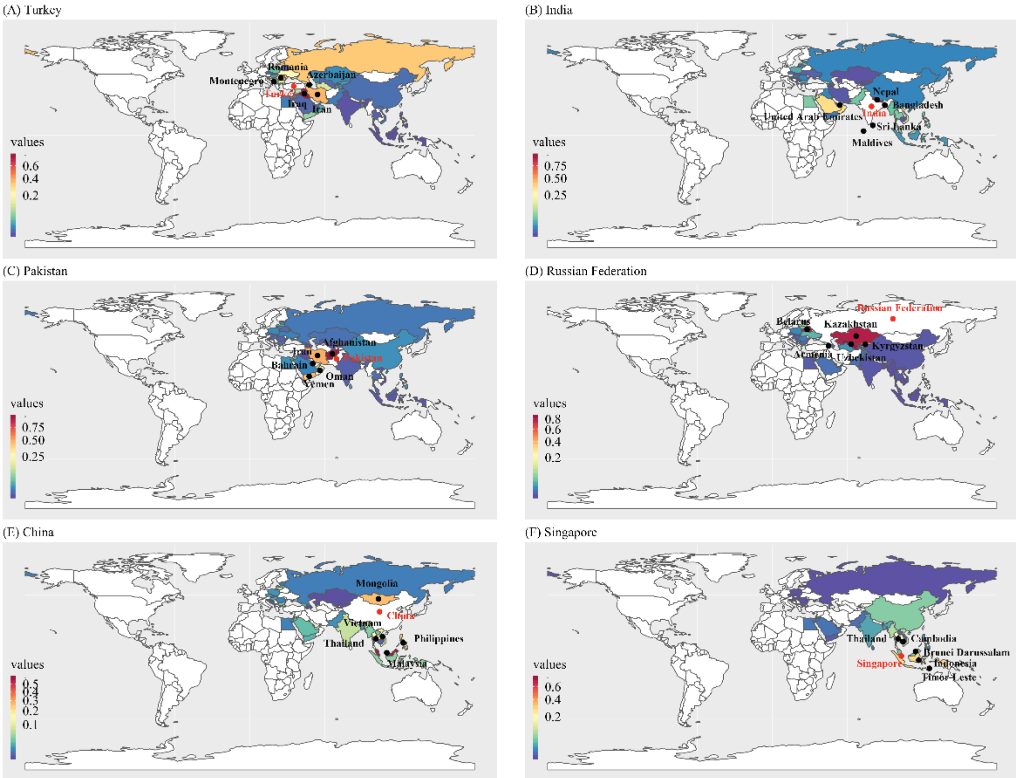
j, and the red dots show countries i and j.

Figure 5. Shocks triggered by the bilateral trade crash

5.3 Import ban

The results for scenario III are also tabulated in Table 2. This table shows that the WaS import ban in Turkey, India, Pakistan, Russia, China, and Singapore will have a considerable impact on the global BRI-WaS trade network. In particular, approximately one-third of countries in the BRI region cannot export WaS normally due to the import ban in Turkey, followed by the import ban in India.

As shown in Figure 6(A), the countries affected by the shock from Turkey are mainly geographically distributed in West Asia and Central and Eastern Europe, including Iran, Iraq, Romania and Montenegro. In addition, India's import ban, which causes the second largest shock, has a large impact on South Asia, including Nepal, Bangladesh, Sri Lanka and Maldives, as shown in Figure 6(B). Figure 6(C) and (D) indicate that the affected countries with a high $g_3^{[t]}(i,j)$ shocked by Pakistan and Russia are mainly located in West Asia and Central Asia, respectively. Notably, Singapore and China are the second and third largest importers in the BRI-WaS trade network, while the number of affected countries exceeding their threshold is lower than Turkey, Pakistan and Russia. We supposed that China and Singapore import more WaS from non-BRI countries. Their shocks propagated more to non-BRI countries than BRI countries. Similar to China, the WaS import ban in Malaysia and Singapore has a noticeable effect on Southeast Asia, as displayed in Figure 6(E) and (F). The above results indicate that the shocks triggered by the import ban for one country have prominent geographical characteristics. The most affected countries are geographically close to the country imposing the import ban.



Note: Countries are colored based on the effect of shocks on them, measured by the relative reduction in WaS exports $g_3^{[t]}(i,j)$. A warmer color indicates a greater effect on the country. The black dots denote the top five countries sorted by indicator $g_3^{[t]}(i,j)$ under the shock from country i, and the red dots represent country j.

Figure 6. Shocks triggered by the import ban

The main findings obtained from comparing the impacts of shocks under three scenarios, including unilateral trade disruptions, bilateral trade crashes and import bans are as follows:

- *The import ban of a certain country has more serious impacts on global BRI-WaS trade than do unilateral trade disruptions and bilateral trade crashes*. As shown in Table 2, the import ban of Turkey and India, as the top two sources of shocks, will lead to 17 and 16 countries bearing imports beyond capacity, which is more than two times the impacts from the shocks generated by the other two scenarios. In addition, combining shock results from the three scenarios, it is found that the break in trade relationships between Turkey/India and other countries and the import ban of Turkey/India had an important impact on the BRI-WaS trade.
- *The regional characteristics of the shock impacts created by different countries under the three scenarios are prominent.* As shown in -6, the countries influenced greatly surround the shock sources from three scenarios. In particular, the countries affected heavily by unilateral trade disruptions are geographically distributed around the exporting countries. For

instance, the disruption of trade from Malaysia to China will have a great influence on countries in Southeast Asian countries, including Timor-Leste, Brunei Darussalam and Cambodia.

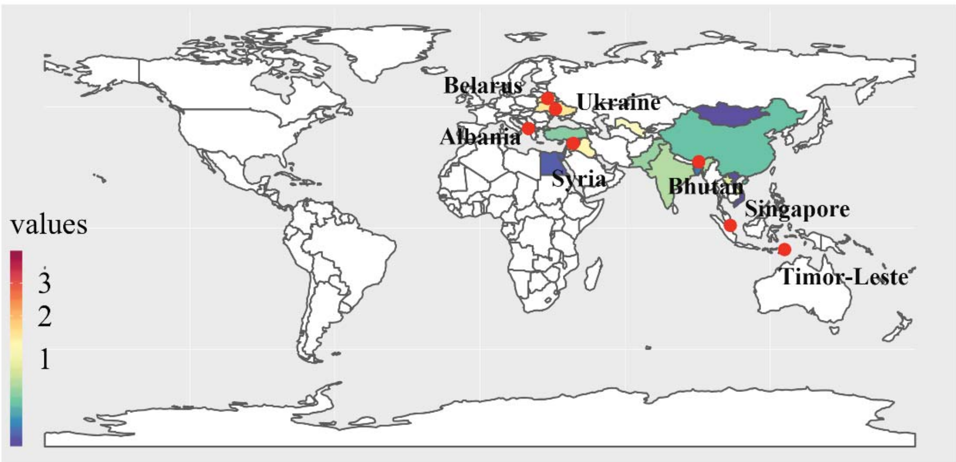
6. Global circulations conceptual framework in the BRI context

According to the proposed trade flow redirection model in subsection 3.4, the global circulations conceptual framework in the BRI context is mathematically examined based on the WaS trade records in 2019. In other words, the BRI circulation system forms. In addition, the results after trade redirection reveal the possible potential trend of BRI-WaS trade under the extreme events of regionalization development. They provide a direction of future trade change in the BRI region. Table A6 in Appendix A6 shows the change in the top 15 net import/export BRI countries after trade redirection. By comparing the change in BRI countries after trade redirection, the following conclusions emerge.

First, the overall WaS disposal pressure in BRI countries will degrade significantly. Approximately 37.6% of the WaS imports will be reduced, indicating that the BRI countries share a substantial amount of WaS disposal from non-BRI countries. Therefore, under the trend of deglobalization and regionalization, non-BRI countries should strengthen the domestic waste recycling system and establish export relationships with other non-BRI countries to reduce exporting dependence on BRI countries. At the same time, it is necessary for BRI countries to form an efficient cooperation mechanism, such as transferring waste disposal technologies from developed countries to undeveloped countries and collaborating to develop the waste recycling industry chain. Consequently, the potential for waste disposal of BRI countries is fully realized, and waste management in the BRI region is optimized.

Second, some countries change their role in the WaS trade after trade flow redirection. Macedonia, Serbia and Slovakia were net exporters in the global WaS trade network, but became net importers in the BRI circulation system. In addition, the ratio of change in Serbia $\hat{r}_i^{[t]}$ is much less than that in Macedonia and Slovakia, -1.78, -0.36 and -0.39, respectively. Therefore, for countries whose roles change, there is a need to increase domestic capabilities for disposing of WaS. In addition, it is necessary for Serbia, Macedonia and Slovakia to seek new export partners in the BRI region and rationally devise trade relations in response to the trend of regional cooperation. Notably, Malaysia is the only country that switched from being a net importer in the global WaS trade network to being a net exporter in the BRI circulation system. This finding indicates that most WaS exports for Malaysia come from non-BRI countries, and trade flow redirection based on the original trade connections does not fully exploit Malaysia's WaS disposal capacity. Thus, BRI countries are advised to build WaS trade connections with Malaysia.

Third, net importers are the focus of WaS disposal to ensure unimpeded WaS trade. Figure 7 shows the geographical distribution of indicator $\hat{r}_i^{[t]}$ in net importers in BRI countries. Countries with a high indicator are mainly geographically concentrated in Southeast Asia and Central and Eastern Europe, including Bhutan, Singapore, Timor-Leste, Belarus, Ukraine and Albania. This finding indicates that these countries will have great import potential for their partners in BRI countries. Therefore, it is necessary for countries with a high $\hat{r}_i^{[t]}$ to pay more attention to their import partners in the BRI region and develop the WaS disposal capacity to cope with potential increases in imports. BRI countries should improve the quality of export waste and thus maintain strong exporting relationships with countries with a high $\hat{r}_i^{[t]}$ to improve export competitiveness and build new export relationships with other BRI countries to ease competitive exporting pressures.



Note: The net importers are colored according to the value of indicator $\hat{r}_i^{[t]}$. The red dots denote the countries whose $\hat{r}_i^{[t]}$ is higher than 1.5.

Figure 7. Change in the countries in the BRI region after trade redirection

7. Discussion and conclusion

With the recent wave of deglobalization, regional development is increasingly becoming a global development strategy. The China-led Belt and Road Initiative (BRI) has attracted considerable attention due to the massive amount of trade value in this region. In recent years, the scale of waste and scrap (WaS) has expanded rapidly, and international WaS trade has become an important method of global waste management. WaS exports from wealthy countries to poor countries have continued for many years. However, growing awareness of environmental protection has led to the import ban of WaS in certain countries, such as China's restrictive policy on solid waste and scrap. Frequent trade frictions between countries and the import ban in some countries have led to shocks in the international WaS trade system and have had crucial impacts on global waste management.

Therefore, it is necessary to understand the evolutionary characteristics of the BRI-WaS trade network and reveal the impacts of the shocks. Although numerous studies have quantitatively investigated the trade network among BRI countries, few studies have explored WaS trade among BRI countries and investigated trade risks. To address this gap in the literature, this study first provides a panoramic view of the BRI-WaS trade network from 1990 to 2019 and investigates the structural evolution of the network based on complex network theory. Then, the shock propagation process in the WaS trade network is modeled in three real-life scenarios using extinction analysis. Finally, according to the global circulations conceptual framework, this study mathematically examines the feasibility of the BRI circulation system. The main results are highlighted next.

First, BRI countries have become increasingly important to global WaS recycling. Specifically, the ratio of BRI-WaS trade value to global WaS trade value increased from 4.1% in 1990 to 15.1% in 2019. In addition, as shown in Figure 3, the ratio of WaS exports from non-BRI countries to BRI countries grew and fluctuated by approximately 30% in the last decade. Therefore, for BRI countries, there is an increasing need to couple environmental and economic considerations within waste management. Building more formal recycling infrastructure is recommended (Gui, 2020).

Second, BRI-WaS trade presents a heterogeneous structure with evenly distributed trade *channels*. Figures A1 and A2 reveal that the degree distribution is becoming more uniform and that the trade value is concentrated in a small number of core countries. This topological characteristic shows the fragility of the BRI-WaS trade network. This fact indicates that the WaS policies in a few core countries will have a great impact on the entire BRI-WaS trade system. However, due to the even distribution of trade connections, the BRI-WaS trade network still has a certain resilience. Therefore, it is necessary for BRI countries to maintain diverse trade connections with other BRI countries and redistribute their trade value among other BRI countries evenly.

Third, countries in Southeast Asia and Central and Easter Europe play a significant role in WaS trade. China, Indonesia, Malaysia, Singapore, Russia and Turkey are located in the central positions measured by the WaS imports and exports in the BRI-WaS trade network. In the context of the global WaS trade, Southeast Asian countries and South Asian countries, such as India, Singapore, Malaysia and Vietnam, play an increasingly important role compared to other BRI countries. Therefore, it is necessary for countries to pay close attention to these core countries.

Fourth, the "most at-risk" sources in the BRI-WaS trade network deserve attention from policymakers. As shown in Table 2, the shocks bearing great effects in the three scenarios are mainly focused on some core countries. For instance, the reduction of unilateral trade from Malaysia → China, Russia → Turkey, Russia → Belarus and the UAE → India will place great pressure on importing WaS in BRI countries. The shocks from the import ban in India, Turkey, China, Russia, Singapore and Pakistan have a considerable influence on the BRI trade community. Notably, Kazakhstan, Kuwait and Romania were not on the list of important countries in 2019. However, the reduction in trade value from Kazakhstan → Russia and Kuwait → India and the bilateral trade relation crash in (Kuwait, India), (Romania, Turkey) also have serious impacts. The hidden risks triggered by the trade relationships between these countries cannot be ignored to ensure trade security.

Fifth, the risks posed by changes in trade between different countries have prominent geographical distributions. shows the geographical distribution of the impacts generated by shocks in the three scenarios. The following patterns can be identified: 1) in the shocks from the unilateral trade disruption, highly affected countries are mainly closer to the exporting countries; 2) the shocks from the bilateral trade crash between two countries have great influence on the surrounding countries; and 3) in terms of the import ban, some countries have a significant influence on the countries in the same region. For instance, Singapore (India), as a Southeast Asian country (South Asian country), has a great impact on the countries in Southeast Asia (South Asia). However, some countries have serious impacts on different regions, such as China, Turkey, Russia and Pakistan. China, as a Northeast Asian country, has a great influence on Southeastern Asian countries. In addition, the countries greatly impacted by the shocks resulting from Turkey, Russia and Pakistan are mainly located in Central Asia and West Asia. Therefore, it is necessary for countries to trace the patterns in different shock scenarios, pay attention to changes in the corresponding countries and adopt timely adjustment strategies to maintain stable WaS trade.

Sixth, the BRI circulation system is mathematically feasible but eco-ethically infeasible. International neoliberalism fosters global WaS trade and enables more waste to flow to poor countries with weak environmental laws and enforcement (Gareau and Lucier, 2018). The global circulations conceptual framework was proposed in previous studies according to circular economy theory. Section 6 shows that the global circulations conceptual framework in the BRI regional context is mathematically feasible. However, the utopian BRI circulation system lacks practical feasibility. All politics is considered to be local. Poor countries bear environmental harm caused by Not-In-My-Backyard (Nimby) movements in wealthy countries.

The foregoing work could be extended in the following two directions. In this study, a simple but useful shock propagation model is proposed. The hidden risks in the BRI-WaS trade are uncovered by analyzing the simulation results from the direct impact of shocks. In future work, we will consider the complete cascading failure process of the shocks. In other words, the indirect impact of shocks will be studied. Moreover, the global circulations conceptual framework lacks practical feasibility in terms of environmental ethics; however, it provides a structure for moral reflection in the global environmental context. A framework that offers a more practically feasible solution is recommended to better equip countries to contend with a global waste crisis.

Appendix A. Supplementary data

Appendix A1 lists the 65 BRI participating countries. Appendix A2 shows the HS Code of the WaS trade. Appendix A3 briefly introduces the classic topological metrics of the network structure. Appendix A4 shows the structural characteristics of the BRI-WaS trade network. Appendix A5 tabulates important BRI countries in the BRI-WaS trade network and the global WaS trade network. Appendix A6 shows the change in the top 15 import/export BRI countries after trade flow redirection.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (72071006 and 62073007), the Chongqing Science and Technology Commission (Project no. cstc2019jscx-msxmX0189) and Beijing Municipal Natural Science Foundation (9192005). Dr. Xiaoqian Hu acknowledges the financial support from the Fundamental Research Funds for the Beijing Universities (XRZ2021067).

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