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**Most influential countries in the international medical device trade:
Network-based analysis**

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Abstract: Since the outbreak of the coronavirus disease 2019 (COVID-19) pandemic, the international medical device trade has received extensive attention. To maintain the domestic supply of medical devices, some countries have sought multilateral trade cooperation or simply implemented export restrictions, which has exacerbated the instability and fragility of the global medical device market. It is crucial for government policymakers to identify the most influential countries in the international medical device trade and nip exports in the bud. However, few efforts have been made in previous studies to explore various countries' influence on the international medical device trade in light of their intricate trade relationships. To fill these research gaps, this study constructs a global medical device trade network (GMDTN) and explores the criticality of various countries from a network-based perspective. The evolution patterns and geographical distribution of influence among countries in the GMDTN are revealed. Details on the ways in which the influence of some crucial countries has formed are provided. The results show that the global medical device trade market is export oriented. The formation of some countries' strong influence may be due to their large number of trading partners or the deep dependence of some of those trading partners on that country (namely, breadth- or depth-based patterns). It is worth noting that the US has a dominant position in the international medical device trade in terms of both breadth and depth. In addition, some countries play a critical role as intermediate points in the influence formation process of other countries, although these countries are not critical direct trading partners. The findings of this study provide implications for policymakers seeking to understand the influence of countries on the international medical device trade and to proactively prepare responses to unexpected changes in this trade.

Keywords: Medical device, trade network, complex network, influential countries

1. Introduction

The ongoing global coronavirus disease 2019 (COVID-19) pandemic has given rise to an unprecedented global health crisis and highlighted the significance of the international medical device trade, which has grown steadily over the last three decades, with most countries relying on imports [1]. The global demand for medical devices is increasing as aging populations emerge worldwide and as life expectancy increases [2]. Therefore, medical devices are a crucial part of patient care [3].

However, the international trading environment has become increasingly complicated as a result of global trade frictions, aggressive unilateral nationalism and trade protectionism [4, 5]. These factors have placed unprecedented stress on stable global trading systems and trade cooperation. Recently, to deal with COVID-19, 54 governments have implemented certain export restrictions and trade barriers on medical supplies and medicines [6], amplifying the uncertainty of the international medical device trade. Therefore, to maintain domestic healthcare systems and preserve the essential medical supply trade flow, it is necessary for government policymakers to understand the complicated global medical device trade system. It is especially important for them to quantify the influence of countries in the international medical device trade, identify highly influential countries and their geographical sphere of influence, analyze the variation in such influence, and explore the key factors involved in influence formation.

In previous studies, complex network theory has been used to analyze the global trade structure and evolution patterns [7]. For analyses of the influence of countries on global trade, previous studies have taken mainly a static analysis perspective [8], quantifying countries' influence according to classic indicators, such as degree and strength as well as other centrality indices. However, there are two limitations in previous studies. First, as critical commodities, structural analyses of the global medical device trade network (GMDTN) have rarely been conducted. Second, the static indicators used in previous studies, as part of a simple evaluation method, have ignored some critical information regarding countries' influence, including the dynamic formation patterns of such influence and the detailed propagation paths in real-life scenarios. Moreover, the impact scope and transmission paths of export restrictions in some countries cannot be reflected by static indicators. Analyzing the dynamic influence of countries in the international medical device trade contributes to our understanding of how influence forms in certain scenarios, e.g., when production declines due to COVID-19, trade

traffic accidents occur or new export restriction policies are issued.

To fill these identified research gaps, this study investigates the structural evolution of the global medical device trade from 1990 to 2020 and explores the influence of various countries on the international medical device trade from both static and dynamic perspectives based on complex network theory. The main contribution of this study is twofold. First, the structural evolution of the international medical device trade is reviewed from a network-based perspective, which addresses the limitation of previous studies regarding the systematic review of the global medical device trade. Second, influential countries are identified from both static and dynamic perspectives. In particular, instead of the classic static indicators, a linear threshold (LT) model is introduced to analyze the dynamic influence of countries in a realistic scenario, namely, government-enforced export reduction. The geographical sphere of influence, detailed propagation paths and formation patterns of influence of certain critical countries are revealed. The sophisticated quantitative results support policymakers in formulating effective policies to maintain the security of the medical device trade.

The remainder of this paper is organized as follows. Section 2 provides an overview of the relevant literature, and Section 3 illustrates the data and methods used. Section 4 reviews the international medical device trade and explores the most influential countries from a network-based perspective. Finally, Section 5 offers a discussion and some conclusions.

2. Literature review

Due to its significance, the international medical device trade has attracted great attention from scholars. A vast number of studies have focused on various aspects of medical device design [9], such as international standards [10], security and reliability [11], environmentally conscious design [12], regulation issues [2] and ethics in medical devices [13]. Given the scope of the current study, the abovementioned literature on medical device design is not presented in this section. Instead, this study summarizes the state of the art from two aspects, the international medical device trade and a network analysis of this global trade.

2.1 International medical device trade

Competitiveness, trade promotion and forecasting for the medical device trade are classic research topics that have been studied by many scholars [14-16]. Recently, the COVID-19 pandemic has

directed considerable attention to the medical device trade. Due to the massive demand for medical devices, some countries have implemented export restriction policies to ensure that domestic needs are met, and some countries have even increased their imports because of massive domestic shortages [17]. Export restrictions have inevitably escalated trade tensions in the current international trading system. In this context, Evenett [6] discussed relevant trade policies on COVID-19-related commodities and found that prepandemic barriers to global medical trade supplies still existed. The above study also critically assessed restriction policies, such as export curbs and import taxes. Similarly, Bown [18] focused on restrictive policies regarding hospital equipment, pharmaceuticals and food adopted by the EU, the US and China.

Many previous studies have found that restrictive export policies and the reduced production capacity of medical devices have negative impacts on certain areas such as public health issues and trade power. Evenett and Winters [19] highlighted that the fragmented production patterns caused by export curtailing are very costly in some countries. In addition, the export restriction of medical devices has not encouraged the much-needed domestic production expansion [20]. Moreover, Barlow et al. [21] explored the adverse impacts of medical device supply reduction on public physical and mental health. The shocks to trade strength and countries' vulnerability due to COVID-19 were evaluated based on the global medical device trade and the trade of other specific commodities [22]. Chugaiev [22] found that 90% of the largest 100 economies have absolute trade vulnerability. In comparison, exporters of medical products and information and communications technology (ICT) services are found to have relatively better trade soundness. In addition to considering impacts at the global level, some analyses have focused on specific regions. Leibovici and Santacreu [23] highlighted the heavy US dependence on the imports of essential medical commodities, revealing that this dependence is an important contributor to the recent increase in the US trade deficit. In recent research, the negative impacts of limited medical supplies on African or developing countries have been explored [18, 24]. In the face of the negative influence of COVID-19 shocks on the global trade of medical goods, many scholars have investigated potential response strategies for such trade disruptions. For instance, global cooperation mechanisms have been proposed to ramp up production and ensure the supply of medical goods [19, 20].

2.2 Network analysis of global trade

Complex network theory has been increasingly utilized in trade-related studies in recent years. In this approach, countries and trade relationships are treated as nodes and edges, respectively, when constructing a trade network. There are different approaches to defining the weight and directions of edges in trade networks [25]. Compared to other methods, complex network theory emphasizes intricate trade relationships, not just the simple direct trade relationships between countries in the trade network.

Previous studies based on complex network theory have focused mainly on the structural characteristics and evolution patterns of the trade network from many aspects, such as detecting trade communities formed by some countries with tight trade relationships [26-28], analyzing the structure of the core and periphery [29], evaluating the centrality of countries [25, 30], identifying the relationships between the centrality of countries and other country characteristics [30, 31], estimating or predicting trade flows in the trade network [32-34], revealing the impact factors of trade network formation [27, 29], investigating changes in structural characteristics during the evolution [35, 36], exploring risk transmission in the trade network [37, 38], and identifying the robustness of the trade network [39, 40].

Notably, the centrality of countries in the trade network is an important issue to investigate in the trade network, which provides some implications for the emphasis of the trade network and the influence of countries in this network [41]. In previous studies, the simplest centrality indicators used were node degree and strength. In the trade network, node degree reflects the number of trade channels of a country, and node strength measures trade flows in a country [42]. With the development of complex network theory, more measures, such as eigenvector centrality [43], betweenness centrality [44] and the PageRank algorithm [45], have been proposed to identify the centrality of nodes in the network. These indicators have been widely used to investigate the centrality of countries in trade networks. For instance, De Andrade and Rêgo [25] identified the most influential countries in a trade network based on centrality indicators, showing that the countries with the tightest connections, highest cash flow, or highest intermediary status in the trade network were the most influential. Moreover, Wang and Li [36] revealed the movement pattern of the centrality of China's interregional coal trade network in terms of geographical location from 1997 to 2016. Xi et al. [30] found that the centrality

of countries in the crude oil trade network has a great impact on their gross domestic product (GDP). Vidya and Prabheesh [34] focused on the changes to countries' centrality following COVID-19-related disruptions and revealed that China's central location in the global trade network remains stable. In addition, the centrality of countries in the global trade network is found to be correlated with infections and deaths as a result of the COVID-19 pandemic. The above studies have not only focused on the overall global trade network [27, 38] but also explored the trade networks of specific commodities, such as energy [29, 30], food [35, 39], animals [37, 40] and e-waste [26].

2.3 Research gaps and contributions of this study

Based on the review of the abovementioned relevant literature, there are two research gaps. First, research activities investigating the GMDTN have rarely been reported in previous studies, as stated in Subsection 2.1. Although many previous studies have found that export restricting policies and the reduced production capacity of medical devices have negative impacts in some areas, the overall structural analyses of the GMDTN have rarely been discussed. Second, the influential countries in the international trade network for other commodities have been identified mainly based on static indicators. The dynamic propagation and formation patterns (width/depth) of influence have not been fully explored. However, it is significant for policymakers to have a comprehensive understanding of which countries are considered influential and thus introduce effective trade policies.

This study is motivated by the above two research gaps. Therefore, building on the above discussion, this study investigates the structural evolution of the global medical device trade from 1990 to 2020, which forms the first contribution of this paper. In addition, this study explores the influence of countries on the international medical device trade from both static and dynamic perspectives as the second contribution. In particular, the dynamic influence of countries is measured based on a realistic scenario: supply restrictions. The development patterns (width or depth) and geographical sphere of countries' centrality/influence in the global medical device trade are revealed. Furthermore, in the dynamic influence analysis, the propagation paths of some critical countries are investigated.

3. Data and methods

3.1 Data and network construction

Data on the global medical device trade from 1990 to 2020 are obtained from the UN Comtrade database. In particular, the Harmonized System (HS) codes of commodities discussed in this study include 9018, 902211, 902213, 902214 and 902221, and the medical device data are presented in [Table A1](#). Each trade record describes the flow of commodities from exporting to importing countries. The unit of trade is the trade value of commodities (dollars). Due to discrepancies in the statistical methods used in different countries, some problems regarding different reporting countries providing inconsistent records exist. To solve these problems, the outliers in the records are filtered, and then, the average value of trade flow reported by different countries is calculated to represent the trade value from exporting to importing countries in this study. The specific data processing method is presented in [Appendix A1](#).

To understand the international medical device trade among countries from a network-based perspective, a complex network is used in this study. This strategy choice provides an in-depth analysis tool with which to examine the intricate trade relationships among countries and evaluate the impact of individual countries on the whole trade system. Therefore, international medical device trade records from 1990 to 2020 are used to construct annual trade networks. Specifically, the analysis examines whether, in year t , if there are trade flows from countries i to j , then trade network $G^{[t]}$ has an edge from nodes i to j , as shown by $e_{i,j}^{[t]}$. If the edge from nodes i to j exists in network $G^{[t]}$, then indicative index $a_{i,j}^{[t]}$ is set to 1. Otherwise, $a_{i,j}^{[t]}$ is set to 0. The weight of edge (i, j) is represented as $w_{i,j}^{[t]}$, calculated by the sum of the trade value of all medical devices. The sets of nodes and edges in $G^{[t]}$ are shown by $V^{[t]}$ and $E^{[t]}$, respectively, denoting all countries and relationships involved in the international medical device trade.

3.2 Measuring countries' influence

3.2.1 Classic static metrics

There are many basic indicators with which to describe the characteristics of each country in the trade network. In particular, in-degree $k_i^{[t]}(in)$, out-degree $k_i^{[t]}(out)$, and degree $k_i^{[t]}$ show the imports, exports, and all trade of country i , which, as the simplest indicators for measuring the influence of countries in the GMDTN, are defined as out-strength, in-strength, and strength,

respectively. Net exports and imports are calculated based on out-strength and in-strength, respectively, to identify the role played by countries in global trade. The detailed calculations of the abovementioned indicators are presented in [Appendix A2](#).

Moreover, there are some significant indicators with which to measure the structural features of the whole network. In particular, in-degree centrality $c^{[i]}(in)$ reflects the competition of import channels, and out-degree centrality $c^{[i]}(out)$ measures the monopoly of export channels in the GMDTN. A high value of in- and out-degree centrality reflects intensified competition in import channels and a severe monopoly in export channels, respectively. The average clustering coefficient $c^{[i]}$ is used to show the tightness of the network. The specific definitions of the above indicators are shown in [Appendix A2](#).

3.2.2 LT-based dynamic influence model

Due to their simplicity, the imports and exports mentioned in [Subsection 3.2.1](#) are widely used to measure the influence of countries on international trade. These indicators provide a holistic and static perspective but occlude the role of some critically influential countries. For instance, the massive exports of country i are evenly distributed across many partner countries. In this context, import partner countries have a low-level dependency on country i . The export reduction of country i does not have a strong influence on its partner countries. Moreover, country j , having lower exports than country i , is the main import partner of influential country k . Moreover, if country j restricts its exports, then country k is seriously affected, and then, the partner countries of country k cannot maintain their normal operations. In this situation, based on export and import measurements, country i has a greater impact than country j . However, the export reduction in country j affects a greater number of countries than does that of country i .

In this context, an LT-based dynamic influence model is proposed [\[46, 47\]](#); this model is used to measure the influence of countries in the GMDTN. The proposed model depicts how the risk of export reduction in a certain country spreads throughout the entire trade network. In the model, nodes have two possible states, a normal state and an avalanched state. In the initial step, country i in network

G restricts its exports, and the other countries are in their normal state. In the spread step, due to the export reduction in seed country i , the imports of partner country j , where $(i, j) \in E$, decrease. If the import decrease in country j is more than threshold γ , then country j changes from its normal state to an avalanched state, and its exports are restricted. Thus, threshold γ indicates the capacities of a country to withstand import reduction. The spread step, after various iterations and the risk transformation process, ends when no more countries change to an avalanched state. The number of avalanched countries caused by export restrictions in seed country i is used to measure its influence. To analyze the change in the influence in country i , in consideration of the different scales of the global medical device trade market, the avalanched ratio, defined as the ratio of the number of avalanched countries to the number of all countries in the trade network, is used. In addition, the geographical distribution of avalanched countries caused by the seed country reveals the main affected region. Therefore, in this study, countries are divided into seven regions, namely, Asia, Europe, North America, South America, Africa, Australia, and Other.

4. Medical device trade and the most influential countries

To understand the development of the international medical device trade, this section first provides an overview of the structural evolution. Then, the influence of countries on the international medical device trade is analyzed from both static and dynamic perspectives. In addition, the dynamic influential analyses involve two parts: a time series analysis and a geographical distribution analysis.

Based on the indicators introduced in [Subsection 3.2](#), the impacts of countries on the international medical device trade are analyzed from static and dynamic perspectives. In the static view, imports/exports/net imports/net exports are used to measure the impacts of countries. In consideration of frequent trade conflicts and the outbreak of COVID-19, the exports of medical devices in every country have likely been dramatically reduced. In this context, the influence of a country is indicated by the ratio of avalanched countries to all countries as a result of the given country's export restriction from the dynamic perspective. The detailed results are shown in the subsequent subsections.

4.1 Overview of the international medical device trade

Figure 1(A-C) shows the development trends of the international medical device trade from 1990 to 2020. During the period from 1990 to 2012, an increasing number of countries participated in the international medical device trade and established increasingly transnational interconnections. This fact reflects the rapid development of economic globalization. The tipping point came in 2013 and 2014, when there was a significant decline in total trade amount, the number of involved countries, and the number of trade channels. Since then, the global medical device trade market has shown slow and continuous downsizing. The outbreak of COVID-19 at the end of 2019 significantly exacerbated the shrinkage of the global device trade market. By comparing the trade value, trade channels and involved countries in 2019 and 2020, dramatic reductions were found to occur in every way. In particular, the total trade value in 2020 was only 64.7% of that in 2019. Moreover, more than 10% of countries withdrew from the market, and 36.7% of trade connections were disrupted.

As shown in Figure 1(D-E), the competition of import channels and the monopoly of export channels in the international medical device trade vary. During the period from 1990 to 2020, in-degree centrality showed a slow upward trend at a low level. Namely, the competition for import channels between countries was still moderate. In contrast, the monopoly of export channels was at a high level, despite an obvious decrease before 2000. In a comparison of import and export channels, the global medical device trade market was found to be export oriented, reflecting the industry characteristics of medical devices. On the one hand, the development of medical devices is greatly influenced by the level of basic industries in corresponding countries, and on the other hand, with the continuous integration of modern scientific and technological achievements into medical procedures, the medical device industry has become an important embodiment of a country's comprehensive technological level. Therefore, there are some barriers to industry development in terms of medical devices, which has led to the current export-oriented status quo. Furthermore, it is worth noting that the change in the competition of import channels and the monopoly of export channels is not as drastic as the change in the market size of the global device trade from 2019 to 2020. Specifically, the intense degree of competition of import channels rose slightly during this period. In comparison, the monopoly of the export channels has become markedly enhanced since the outbreak of COVID-19. To some extent, this reflects the greater weakness of undeveloped countries under the shock of the pandemic.

Figure 1(F) shows that the average clustering coefficient of the GMDTN remains at a low level

from 1990 to 2020, which reflects the relatively prominent heterogeneity of the global medical device trade market. In other words, most of the trade value is focused on a few countries. In addition, the average clustering coefficient shows a fluctuating declining tendency, indicating that the connections between countries became loose in terms of trade value during this period.

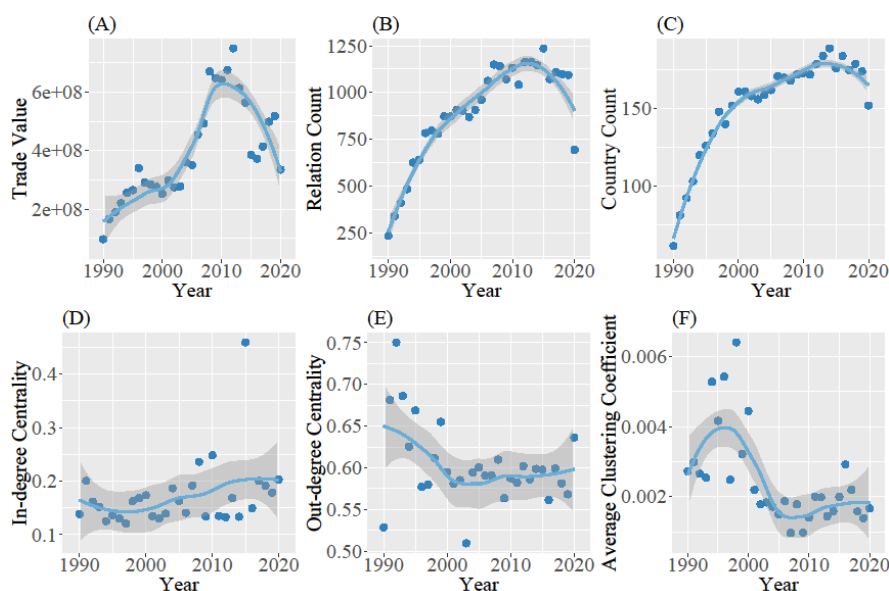


Figure 1. Overview of the GMDTN from 1990 to 2020.

4.2 Influential countries from a static perspective

Based on the indicators introduced in [Subsection 3.2.1](#), imports/exports/net imports/net exports are used to measure the impacts of countries from a static perspective. [Appendix A3](#) presents the detailed information on the critical import and export countries in 1990, 2000, 2010 and 2020. As shown in [Table A1](#), Russia, China and India were the most influential importing countries in 2020, having a significantly higher amount of imports than those of other countries. Specifically, the trade value of imports in Russia, China and India was approximately 39.12, 38.90 and 33.50 million dollars, respectively, together accounting for approximately 36% of the total imports in the international medical device trade. In comparison, the imports of countries ranked from 4th to 10th accounted for only approximately 23% of all imports, highlighting the heterogeneity of import markets. In the top 10 import countries, Asian countries, including China, India, Japan and Kazakhstan, imported 27% of medical devices, followed by European countries (25%). Unlike in previous years, countries in Asia and Europe became major import markets for medical devices. Additionally, the top 10 import countries accounted for approximately 50-70% of the total volume, highlighting the heterogeneity of

the global medical device trade market. Comparatively, it can be seen that there are two different import patterns in these core import countries, one of which is represented by China and India and the other of which is represented by European and North American countries. As countries with large populations and rapid national economic development, China and India have had significant medical needs in recent years. However, due to the lack of advanced technologies for the in-house production of medical devices, these countries are highly dependent on the import of high-end medical devices. For instance, the ratio of China's medical device imports to all imports fluctuated by approximately 7-12% from 2010 to 2020. In contrast, North American countries, which are highly industrialized and have production means for advanced medical technologies, imported mainly middle- to low-end products and raw materials to produce high-end products based on cost reduction considerations.

[Table A2](#) shows the top 10 exporting countries in 1990, 2000, 2010 and 2020. In 2020, the top 5 exporting countries were Germany, the US, Estonia, the UK and Sweden, accounting for 71% of total exports. Approximately 90% of exports came from the top 10 exporting countries. Therefore, the heterogeneity of exporting markets was shown to be more significant than that of importing markets, which is in line with the results measured by the out-degree centrality shown in [Subsection 4.1](#). In addition, the list of the top 10 export countries in different years was more stable than that of the top importing countries, reflecting the solid dominance of some critical export countries, such as the US, the UK, Germany, Sweden and the Netherlands. The geographical distribution of the top 10 exporting countries was significantly different from that of the top 10 importing countries. In particular, Asian countries, as a major medical device import market, did not play a crucial role in the export market. Moreover, Japan had a top place in the list of exporting countries in the early years, but its ranking fluctuated and declined in recent years. Japan's large scale of exports came from its advanced level of science and technology but was limited by its poor resources. In contrast, some emerging economies, such as China, saw a rise in the status of their export market due to rapidly intensifying industrialization. Israel, as the only country in this study from the South West Asian/North African (SWANA) region, was always in an important position in the export market due to its strong scientific innovation capacity in the medical device industry. A comparison of imports and exports in different years shows that the outbreak of COVID-19 had an enormous impact on the international medical device trade, with the imports and exports of countries declining to the same levels as those of 2000.

To obtain a deep and comprehensive understanding of the role of countries in the international medical device trade, this study analyzes the net exports and imports of countries over three decades. [Table 1](#) shows the top 10 net import/export countries from 1990 to 2020. The major import and export markets had significantly different geographical distributions. Except for Israel, the critical net export countries were located mainly in Europe and North America. In contrast, Asian countries, such as South Korea, China, Japan, India, Turkey, and Thailand, were major net importers. It is worth noting that some net export/import countries also had large-scale imports/exports. For instance, the US, as the second-highest net export country, as shown in [Table 1](#), is always ranked in the top 10 import countries in [Table A2](#). Similarly, China, which was on the list of the top 10 net import countries, had extensive exports, as shown in [Table A2](#). This finding reflects a clear split in the geographical distribution of the mid-to-low- and high-end production markets. To some extent, the high technical advances of high-end medical device production and the international division of labor led to the splitting of the import/export markets.

[Table 1](#). Top 10 net import and export countries from 1990 to 2020

Rank	Net export countries		Net import countries	
	Country	Trade value	Country	Trade value
1	Sweden	1,401.12	Russia	996.02
2	US	1,358.32	South Korea	647.10
3	UK	1,112.55	China	503.80
4	Israel	856.62	Brazil	338.80
5	Germany	585.23	Japan	314.41
6	Netherlands	375.96	India	291.63
7	Belgium	246.29	Turkey	177.30
8	France	155.17	Italy	158.66
9	Canada	149.55	Australia	146.31
10	Switzerland	112.43	Thailand	133.94

Note: The trade value unit is 10^6 dollars.

4.3 Influential countries from a dynamic perspective

Due to frequent trade conflicts and the outbreak of COVID-19, 54 countries have implemented some type of restrictive export policies on medical supplies and medicines [6]. Within this context, the influence of countries is indicated by the ratio of avalanched countries caused by the given country's export restrictions to total countries from a dynamic perspective. The proposed LT-based dynamic

influence model in [Subsection 3.2.2](#) is simulated in the GMDTN from 2010 to 2020 (inclusive) with different settings for countries' capacity to withstand import reduction (namely, threshold γ is set to 0.1, 0.3, 0.5 and 0.7). The ratio of avalanched countries to total countries in the trade network is an indicator of the seed country's dynamic influence. Furthermore, the iterative count reflects the speed at which the shock spreads across the whole trade network.

[Table 2](#) shows the top 10 countries ranked by dynamic influence in 2020 with different threshold settings. It has been found that few countries contribute to systemic shocks to the international medical device trade and that export restrictions in most countries have a limited impact. [Table 2](#) indicates that the distribution of countries' dynamic impacts is skewed and heterogeneous. The results show that the list of critical countries with a high dynamic influence remained stable when the antirisk capabilities of countries were set at different levels. Combined with the results in [Table 1](#), the list shown in [Table 2](#) highlights that critical net export countries have strong dynamic impacts on the GMDTN. For instance, export restrictions in net export countries, such as the US, Germany, the Netherlands, Belgium, and Sweden, have a serious impact on the normal operations of the whole global trade system. In addition, the intricate trade relationships between countries amplify the influence of these net export countries on the trade network. The shock caused by a seed country not only directly affects its own partner countries but also propagates to other countries through the trade relationships of partner countries. Thus, an export restriction of 20% in the US leads to 98% of all countries being avalanched.

It is worth noting that some major net importing countries, such as China, India and Italy, have a great dynamic impact when limiting exports. In comparison, these three countries show different performances under different threshold settings. [Table 2](#) shows that China, with a low antirisk capability, has a greater dynamic impact than do India and Italy. When setting the threshold to more than 0.3, India is ranked higher than China and Italy. Based on the LT-based dynamic influence model proposed in [Subsection 3.2.2](#), the threshold represents the capacity of countries to withstand the shock caused by import reduction. For a country causing a high avalanched ratio with a low threshold setting, its influence has more breadth than depth when the avalanched ratio significantly decreases with a small increase in the threshold setting. In other words, when countries' capacity to withstand import reduction is improved slightly and the high avalanche ratio caused by export reduction by country i declines sharply, country i is said to have more breadth than depth. Conversely, the country's influence

is reflected in terms of depth when the increase in the threshold cannot lead to a significant drop in the avalanched ratio. Therefore, the influence of China on the GMDTN is reflected in terms of breadth. In contrast, the dynamic impact of India is shown in terms of depth. For instance, the export restriction of China has a limited impact on most countries, but that in India has a stronger dynamic influence on fewer countries. Unlike India and China, Italy has a dynamic impact that is balanced in terms of depth and breadth.

Table 2. Top 10 seed countries in 2020 with the threshold set to 0.1, 0.3, 0.5 and 0.7

$\gamma=0.1$				$\gamma=0.3$		
Rank	Country	Avalanched ratio	Iterative count	Country	Avalanched ratio	Iterative count
1	US	0.98	4	Germany	0.98	5
2	Germany	0.98	5	US	0.98	5
3	Netherlands	0.98	5	Netherlands	0.98	6
4	Sweden	0.98	5	China	0.98	6
5	Belgium	0.98	6	Sweden	0.24	5
6	Italy	0.98	6	Denmark	0.24	6
7	China	0.98	6	UK	0.19	5
8	Denmark	0.98	6	Belgium	0.18	5
9	Israel	0.98	7	Italy	0.11	4
10	UK	0.24	4	India	0.07	2
$\gamma=0.5$				$\gamma=0.7$		
Rank	Country	Avalanched ratio	Iterative count	Country	Avalanched ratio	Iterative count
1	Germany	0.98	7	US	0.22	3
2	US	0.98	10	Belgium	0.08	4
3	Belgium	0.09	4	India	0.05	2
4	UK	0.08	3	South Africa	0.03	2
5	India	0.05	2	Netherlands	0.03	2
6	Netherlands	0.04	2	Germany	0.03	2
7	Italy	0.04	3	Estonia	0.03	2
8	South Africa	0.03	2	Italy	0.02	2
9	Estonia	0.03	2	UK	0.01	2
10	Sweden	0.03	4	Spain/Denmark	0.01	2

Note: Seed countries are ranked in descending order by avalanched ratio and in ascending order by iterative count. The export restriction of a seed country with a high avalanched ratio and a small iterative count leads to this large-scale country avalanching at a rapid rate. γ reflects the threshold set in the shock propagation model.

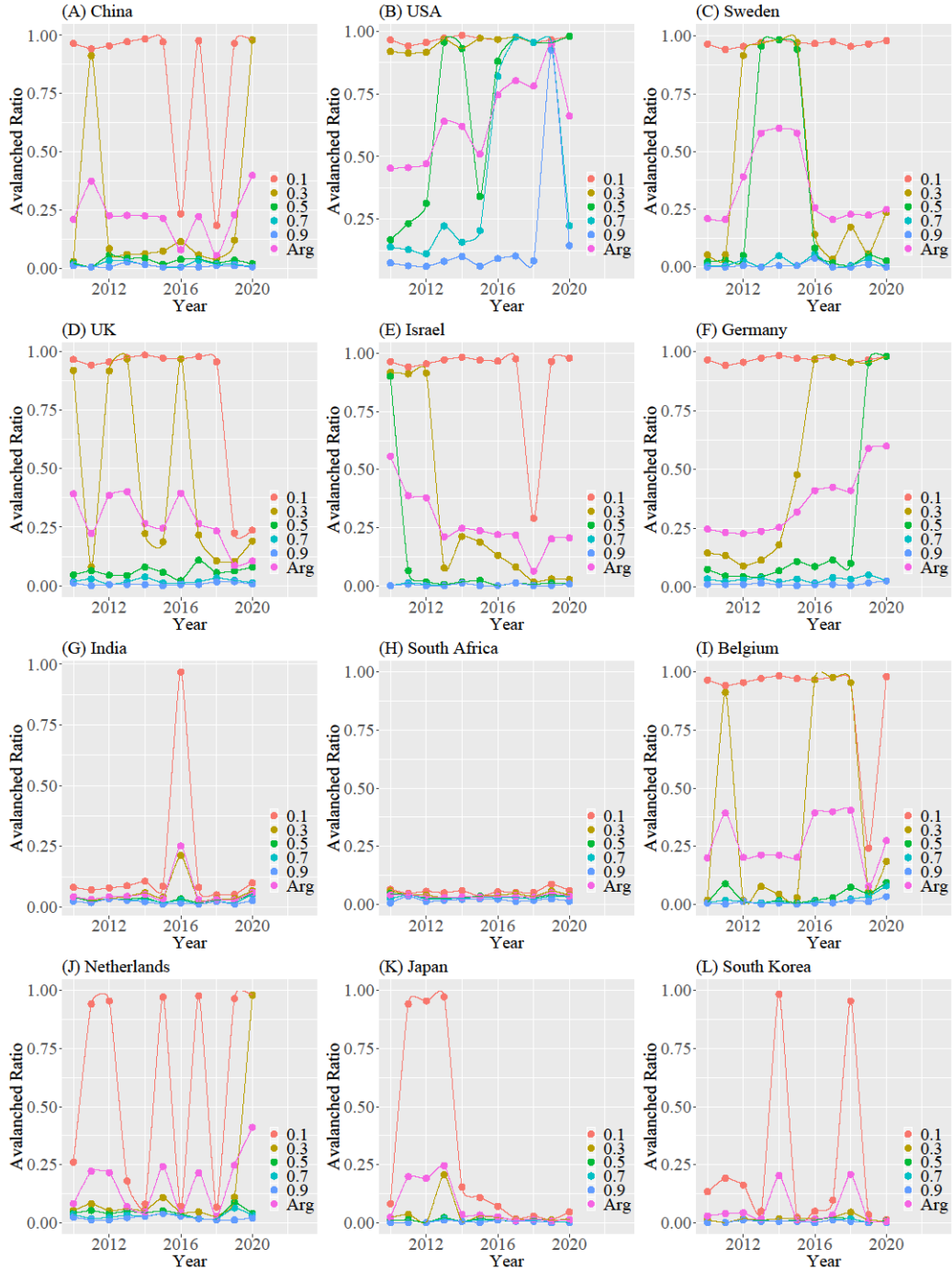
The above analyses provide a snapshot of countries' dynamic influence in 2020. Due to the continuous evolution of the GMDTN, countries' impact is always changing. Therefore, reviewing the variation trend of countries' impact in the past decade is necessary to anticipate the future influence of

countries in the global medical device trade market. In addition, analyzing the geographical distribution of avalanched countries caused by a seed country provides insights through which to understand the sphere of the seed country's influence. Finally, the detailed shock propagation paths provide detailed clues for understanding how the dynamic influence of a country is formed.

4.4 Variation tendency of countries' influence and geographical distribution

This subsection focuses on some key countries with which to analyze the variation tendency of a country's influence and geographical distribution under different settings of antirisk capacity from 2010 to 2020 and depicts the detailed propagation paths of countries' influence at some critical time points. As shown in [Figure 2](#), the trend of dynamic impacts in 12 critical countries from 2010 to 2020 is illustrated under different threshold settings. Countries have different variation tendencies of dynamic influence. Considering the reality of countries' low-risk resistance in the GMDTN, this study focuses mainly on the variation trend of the country's influence with a low threshold setting. Within this context, different patterns of sensitivity to countries' antirisk capacity ($\gamma=0.1$) are shown.

The first group of countries includes the US, Sweden, Germany, and South Africa, as shown in [Figure 2](#), which maintained a relatively stable dynamic influence from 2010 to 2020. In particular, the dominant positions of the US, Sweden and Germany in the GMDTN are clear. The second group of countries is represented by China, the UK, Israel and Belgium, the impacts of which were high in most years but changed drastically in certain years. For instance, the dynamic influence of Israel declined dramatically from 2017 to 2018. Similarly, China's dynamic influence in 2018 was far below that in other years. Unlike the second group of countries, the third group of countries includes India and Japan, where the dynamic influence was low in most years and increased significantly only at certain points in time. The fourth group of countries includes the Netherlands and South Korea, where their influence fluctuated severely from 2010 to 2020. To provide a better understanding of the dynamic influence in some critical countries, the breadth and depth of influence, the geographical spatial scope of the influence and the reasons for turning points in the dynamic influence tendency are explored in the following section.



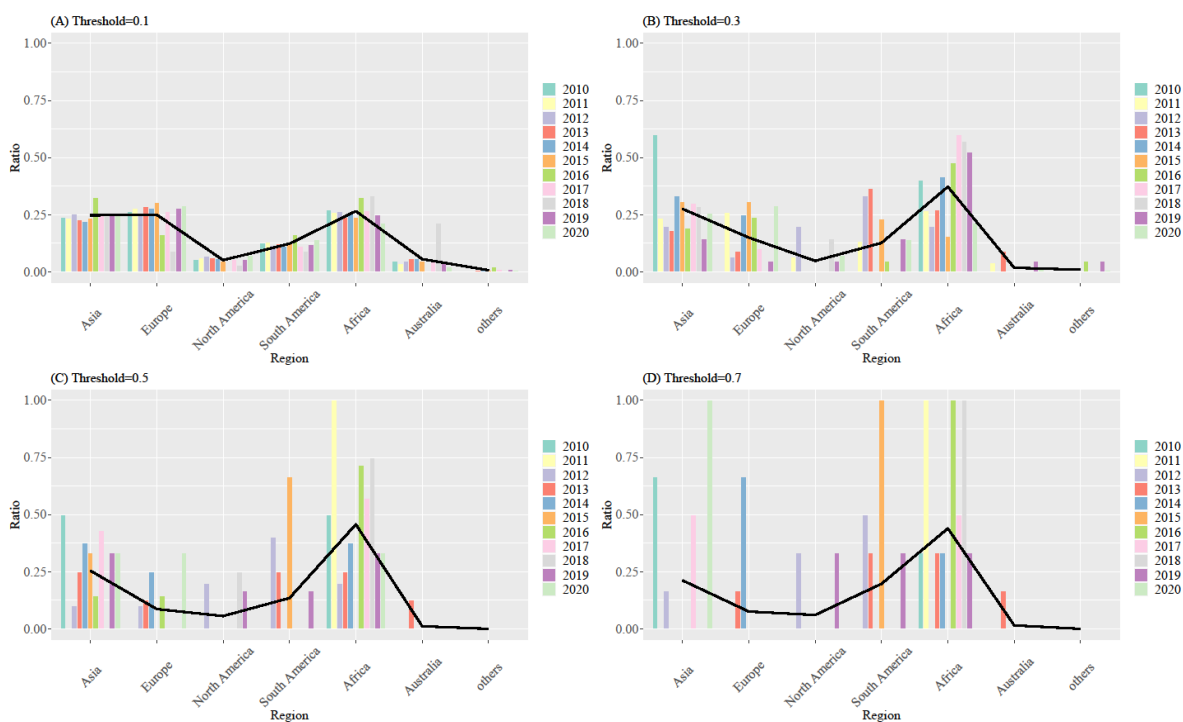
Note: The avalanched ratios caused by countries under different threshold settings are labeled with different colors. The average avalanched ratio at different thresholds in each year is marked in purple.

Figure 2. Variation tendency of countries' influence from 2010 to 2020 with different threshold settings.

(1) Leading country: China

As shown in Figure 2(A), China maintained a stable high impact on the international medical device trade in most years, with the exception of 2016 and 2018 ($\gamma=0.1$), in which its influence declined dramatically. Compared to the influence of the US illustrated in Figure 2(B), the influence of China

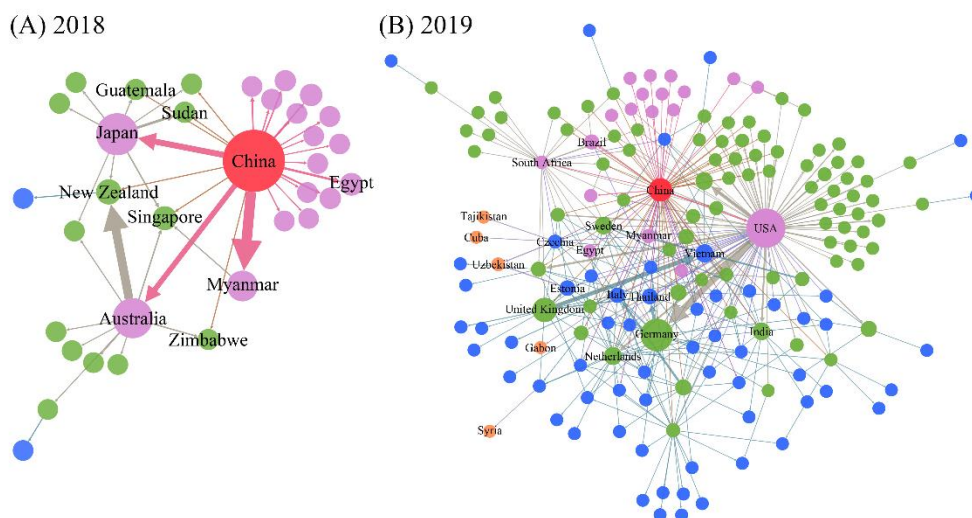
decreased when the antirisk capacity of other countries increased. Therefore, unlike that of the US, the influence of China in the GMDTN has breadth but lacks depth. Figure 3 depicts the geographical distribution of avalanched countries caused by China's export restrictions with different antirisk capacities from 2010 to 2020. The results show that China's sphere of influence is distributed mainly across Asia, Africa and Europe. Comparing the ratios of avalanched countries in the same region between different years reveals that China's influence on Asian and African countries remained nearly constant under the same threshold settings. In contrast, the impacts of China on European countries fluctuated significantly. For instance, its impact on European countries in 2018 was distinctly weaker than that in other years. With an increasing threshold, the average ratio of avalanched countries in Europe gradually declined, as shown by the black lines in Figure 3. This finding indicates that China's impacts on European countries were increasingly weakened as countries' antirisk capacity increased. In this context, the influence on Asian countries was not sensitive to antirisk capacity, but the impacts on African countries were stronger with greater antirisk capacity among countries. In summary, China's impacts on many European countries were wide, but its influence on African countries was deep.



Note: The ratio of avalanched countries in a certain region to all avalanched countries in different years is shown by the bars labeled with different colors. The black lines show the average ratio of avalanched countries in a certain region to all avalanched countries from 2010 to 2020.

Figure 3. Geographical distribution of countries avalanched as a result of Chinese export restrictions

As mentioned above, there was a turning point in China's influence in 2018. To identify the reason for the change in China's impact on the global medical device trade, the detailed propagation paths of China's influence in 2018 and 2019, depicted in Figure 4, are compared. As shown in Figure 4(A), most countries were avalanched by China in the first round, colored pink in the figure, in 2018. Although some important countries, such as Japan, Australia, and Myanmar, were avalanched in the first round, they did not further expand the sphere of China's influence in the subsequent transmission. The detailed influence propagation path in 2019 was significantly different from that in 2018, as shown in Figure 4(B). In the first round, the number of avalanched countries caused by China in 2019 was similar to that in 2018, labeled with pink nodes. In this context, the critical point is that an important country, the US, was avalanched in the first round in 2019, which is different from that in 2018. Due to the avalanche status of the US, a large number of countries were avalanched in the third iterative round, labeled in green in the figure, including some important countries such as Germany and the UK. Under the combined results of the US, Germany and the UK, China's influence further propagated to more countries, as shown by the blue nodes in the figure. The US, as a critical intermediate node in the propagation path of China's influence, plays a significant role in China's influence. The influence propagation path of China in 2020 displayed the same patterns as that in 2019. Therefore, maintaining and enhancing its solid and close trade relationship with the US is important for China to preserve its interests and influence the GMDTN.



Note: (A) Influence propagation path of China in 2018. (B) Influence propagation path of China in 2019. The

nodes in the schematic diagram represent countries avalanched as a result of China's export restrictions. The size of the nodes indicates the trade value of countries in the GMDTN. The directed edges show the paths of influence propagation, and the weight of the edges reflects the trade flow from export country to import country. Different colored nodes indicate the sequential order of the avalanching of the countries. Specifically, the seed country, China, is labeled in red. The countries avalanched in different rounds are labeled in pink, green, blue, orange, gray and dark green in order of when they were avalanched. The top 5 countries in terms of trade value, avalanched in each iterative round, are labeled with their country name.

Figure 4. China's influence propagation paths in 2018 and 2019

(2) Leading country: US

Figure 2(B) shows that the avalanched ratio caused by the US was at a stable high level from 2010 to 2020 when the threshold was set to 0.1 and 0.3. This finding indicates that the US maintained a stable high impact on the international medical device trade under low levels of antirisk capacity. When countries' antirisk capacity was higher, the influence of the US was lower but had increased volatility before 2020. This result indicates that the US has had an increasingly deep influence on the international medical device trade. Regarding the geographical distribution of the US's sphere of influence, Figure 5 shows that the US has critical impacts on countries in Europe, Asia and Africa and is more influential in Europe than elsewhere. Unlike that of China, the geographical distribution of the US's sphere of influence was stable from 2010 to 2020. In addition, the ratio of avalanched countries in Africa/Asia caused by the US's export restriction decreased slightly with an increasing threshold. Unlike Africa and Asia, the ratio of avalanched countries in Europe remained stable at approximately 25%. It is worth noting that the ratio of avalanched countries to all countries increased as the threshold increased. Overall, the US plays an important role in the breadth and depth of countries in different regions.

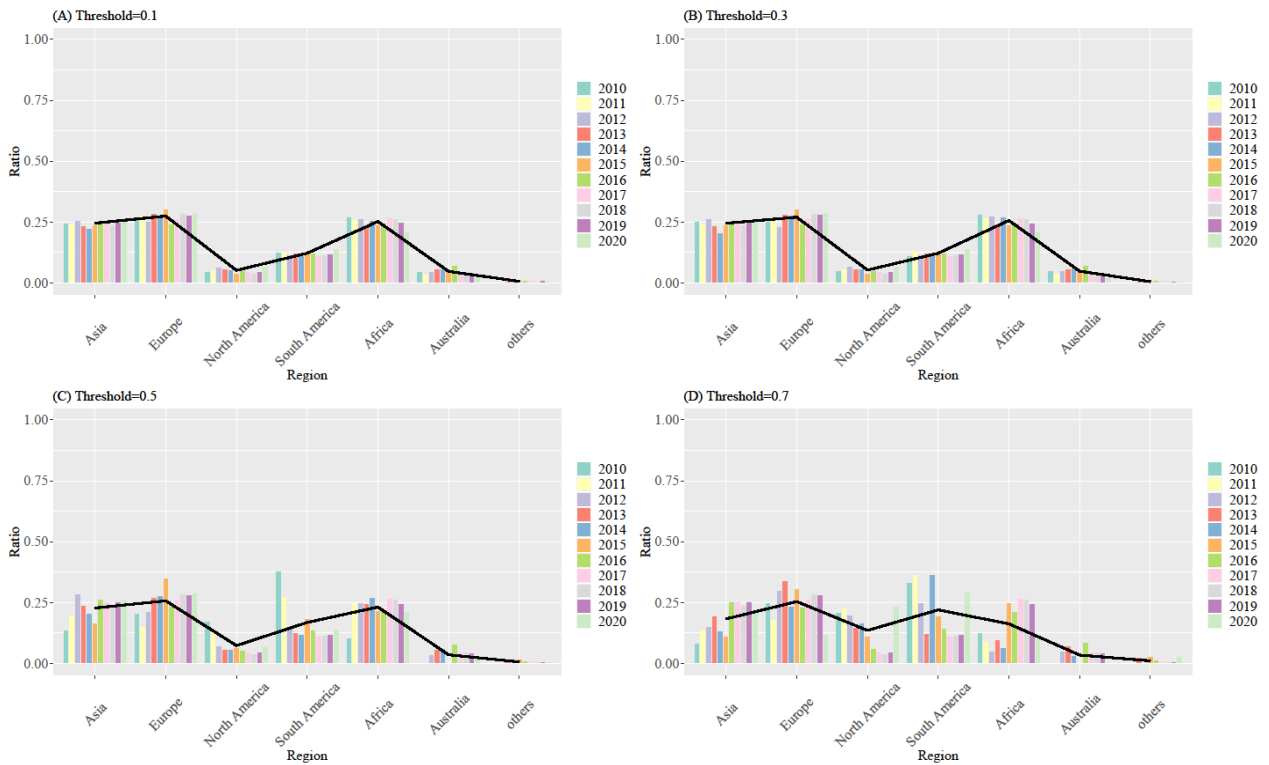
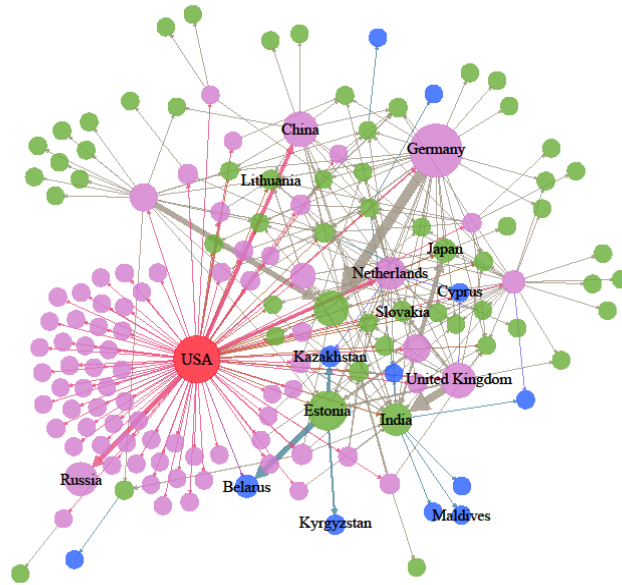


Figure 5. Geographical distribution of countries avalanched as a result of the US's export restrictions

Due to the stable impacts of the US on the international medical device trade, this study takes the influence propagation paths of the US in 2020 as an example to understand how its influence on other countries formed. As shown in Figure 6, most countries whose avalanching was caused by the export restrictions of the US were direct trading partners of the US. The US had a strong impact on many countries avalanched in the first iterative round, as shown by the pink nodes. Notably, as an important country in the GMDTN, Germany was avalanched in the first iterative round but did not play a prominent role in influence propagation. Unlike what is seen with the influence propagation path of China in 2019, shown in Figure 4(B), there were no critical intermediate countries to amplify the sphere of the US's influence. Therefore, this country's influence was formed mainly by its direct trading partners.



Note: The US, as the seed country, is labeled in red. The countries avalanched in the different rounds are labeled in pink, green, blue, orange and gray in order of when they are avalanched. The top 5 countries ranked by trade value avalanched in each iterative round are labeled with their country name.

Figure 6. The US's influence propagation paths in 2020

(3) Leading country: Israel

Figure 2(E) depicts the tendency of the avalanched ratio caused by Israel under different threshold settings from 2010 to 2020. Despite its turning point in 2018, Israel had a great dynamic impact on the GMDTN in other years. A comparison of the influence variation with different threshold settings indicates that the influence of Israel was sensitive to antirisk analysis capacity. Unlike with the US, the impact of Israel was greatly weakened as the threshold increased. From a global perspective, the influence of Israel had an advantage in terms of breadth but lacked an advantage in terms of depth.

From a geographical perspective, Israel had a greater influence on countries in Europe, Africa, and Asia than on other countries, as shown in Figure 7. Under low antirisk capacity circumstances, the ratio of avalanched countries in the different regions changed slightly during the period from 2010 to 2020. As the threshold increased, the variation in impacts on countries in different regions became significantly noticeable from 2010 to 2020. In particular, the impacts on Europe increased when the threshold was less than 0.5 and decreased as the threshold increased to more than 0.5. Additionally, the influence on Asian countries showed a marked downward trend, which was more significant than the decline in the influence on African countries. Therefore, Israel's influence on European and African countries was broader and deeper than its influence on Asian countries, where it was somewhat lacking

in terms of depth.

As shown in Figure 8, there are no obvious differences between the propagation structure in the earlier stages in 2018 and 2019. In the first round, in both 2018 and 2019, the critical countries avalanched by export restrictions in Israel were China and Japan, as shown by the pink nodes. The difference between Israel’s influence path in 2018 and that in 2019 is due to the change in China in 2018, as illustrated in Figure 4. China’s low influence on the US in 2018 led to the propagation of Israel’s influence in the GMDTN. As shown in Figure 8(B), as a joint result of Israel and China, the US was avalanched in the second round of Israel’s influence propagation. Therefore, Israel’s influence was seriously affected by that of a critical country, i.e., China.

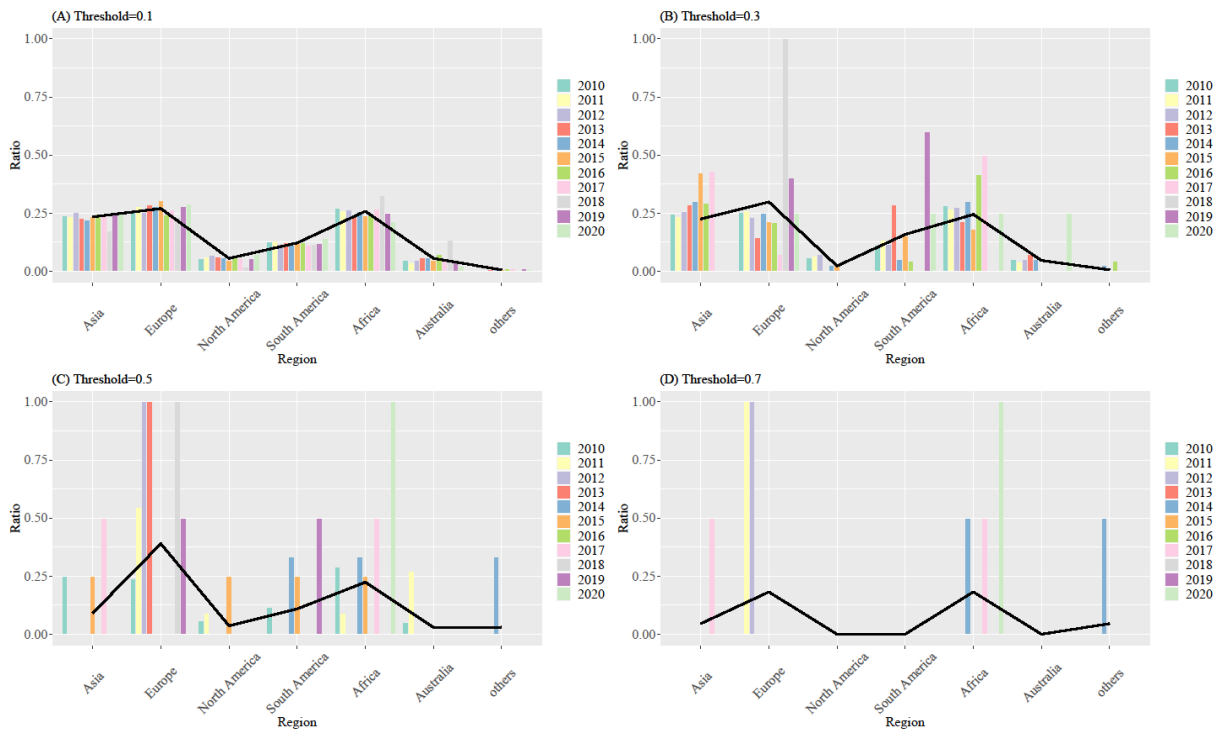
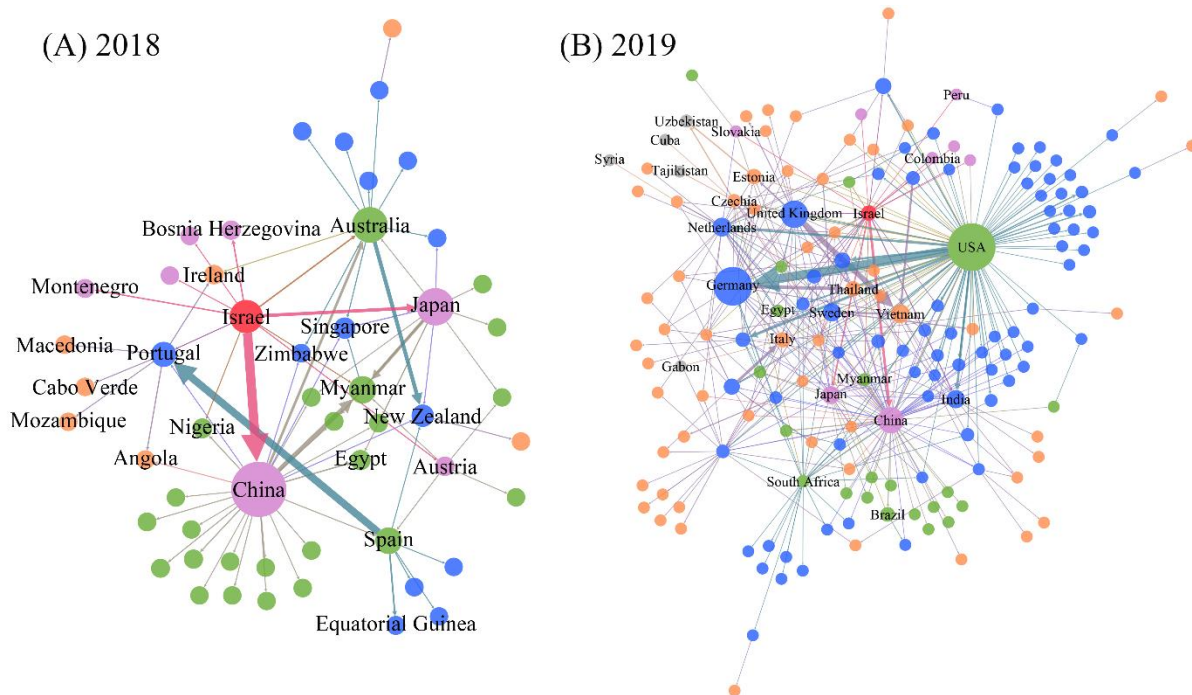


Figure 7. Geographical distribution of countries avalanched as a result of Israel’s export restrictions



Note: Israel is labeled in red. The countries avalanched in the different rounds are labeled pink, green, blue, orange and gray in order of when they were avalanched. The top five countries ranked by trade value, avalanched in each iterative round, are labeled with their country name.

Figure 8. Israel's influence propagation paths in 2018 and 2019

(4) Other leading countries

Germany, as one of the most important countries in the GMDTN, had a stable distribution of influence on countries in Asia, Europe and Africa from 2010 to 2020, as shown in Figure A2 in Appendix A4. In particular, its impacts on Asia and Europe were both deep and broad, but the depth of its influence on Africa was lower. This result is embodied by the high avalanched ratio in Asia and Europe and the decreasing avalanched ratio in Africa as the threshold increased, as shown in Figure A2. In addition, Figure A3 in Appendix A4 shows that the avalanched ratio in Asian countries maintained a high level as the threshold increased, but that in African countries presented a downward trend. Therefore, similar to Germany, Sweden had a deep and broad impact on Asian countries, deeper than its impact on African countries.

It is worth noting that the depth of Sweden's impact on European countries was weaker than that on Asian countries, although Sweden is a European country itself. In contrast, the UK and Belgium had deep and broad impacts on European countries, but their influence on Asian countries lacked depth, as shown in Figures A4-A5 in Appendix A4. In addition, the impact of the UK on countries in South

America was deep, unlike that of Belgium.

For the influence propagation paths, Germany and Sweden had a stable and similar pattern, similar to that of China, as shown in [Figure 4\(B\)](#). [Figures A6-A7](#) show that Germany and Sweden had a significant and direct influence on some critical countries, such as China and the US, which were avalanched directly as a result of the export restrictions of Germany/Sweden in the first iterative round. Furthermore, these critical countries further propagated this influence to their trading partners and thus expanded the sphere of Germany/Sweden's influence. Unlike the stable influence of Germany and Sweden from 2010 to 2020, the UK and Belgium maintained a high influence in most years and had a turning point with a low influence in 2018 and 2019, as shown in [Figure 2\(D\)](#) and [Figure 2\(I\)](#). In addition, the sharp decline in influence was not due to one or some key countries, such as China and Israel, but was the joint result of their diminished influence on their direct partners. As shown in [Figure A8](#), the joint results of the UK and its avalanched direct partners in 2019 caused a loss of influence of the UK on Belgium in the second iterative round and led to a loss of influence expansion caused by the US. Similarly, the joint effect of Belgium and its trading partners avalanched in the first round caused enough influence loss to cause the UK to collapse, as shown in [Figure A9](#), and the further loss of influence expansion opportunity for the US.

5. Discussion and conclusions

Due to unexpected shocks to the international medical device trade in recent years, it has become necessary for policymakers to understand this global trade market and the most influential countries in this market, which can help them proactively prepare policies to respond to external shocks. However, studies that have focused on influential countries in the medical device trade in terms of intricate trade relationships are rare in the literature. In addition, most previous studies on the influential trade countries on other commodities have been based mainly on static indicators, ignoring the dynamic formation of the influence. The formation patterns due to the width or breadth indicate different crisis responses for other policymakers. To fill these two research gaps, this study investigates the evolution of the international medical device trade. The most influential countries in the international medical device trade are identified using a network-based approach from both static and dynamic perspectives. In particular, an LT model is proposed to describe the influence propagation process caused by export restrictions in a given country. Moreover, the geographical distribution of

influence, breadth/depth of influence, and detailed formation mode of influence for various countries are explored. The theoretical and policy implications derived from the research results and findings are discussed below. *First, the international medical device trade is export oriented and has outstanding heterogeneity.* As shown in [Figure 1](#), the competition among import channels between countries is moderate, but the monopoly of export channels between countries is high. In addition, most trade value is captured by only a few countries (the top 10 import countries accounted for 50-70% of imports, and the top 10 export countries accounted for 90% of exports), which reflects the technical threshold of the medical device industry in those countries. Therefore, to understand the patterns across the whole industry, countries need to focus on changes in critical export countries.

Second, influential countries have different impacts on different products and regions. The analyses of influential countries from a static perspective in [Subsection 4.2](#) show that the important net export countries are located mainly in Europe and North America (Sweden, the US, the UK and Germany), and the important net import countries are located in Asia (South Korea, China, Japan and India). In addition, countries' imports and exports are focused on different types of products, and countries with massive exports import a great deal as well. For instance, as a result of the existence of the entire industrial chain, inexpensive raw materials and low labor costs, China has advantages in terms of medium- to low-end medical devices and thus has a high level of exports. Conversely, China must import many high-end products to meet the needs of its large domestic population. In addition, the results reflect the highly differentiated roles of countries in the global medical device trade. Therefore, maintaining close cooperation among countries is important and contributes to having an intact global trading system.

Third, the US has a dominant position in the international medical device trade from a dynamic perspective. As shown in [Table 2](#) and [Figure 2\(B\)](#), the US has a stable high dynamic influence on the international medical device trade that is both broad and deep, reflecting the high avalanched ratio with different thresholds. In addition, the geographical distribution of influence in different regions, including Asia, Europe, and Africa, is almost even under the different antirisk capacities of countries, with an approximately 20-25% avalanched ratio, as shown in [Figure 5](#). The influence propagation path illustrated in [Figure 6](#) indicates that the impact of the US on its direct trading partners is key to its sphere of influence; the US has proactive influence and is not overly dependent on other countries.

Therefore, to understand the global medical device industry, countries must examine changes in the US.

Fourth, the high influence of certain countries on different regions may be due to the breadth or depth of countries' impact. As shown in [Figure 3](#), China's influence on European countries is broad but lacks depth, which fluctuates significantly with the increasing threshold. In contrast, China's influence on African countries is both broad and deep, remaining nearly constant under different threshold settings. For Israel, its influence on Asian countries lacks depth, as depicted in [Figure 8](#). It is interesting that Sweden, as a European country, has a greater influence on Asian countries than on European countries, with thresholds set to 0.3, 0.5 and 0.7, as shown in [Figure A3](#). Therefore, understanding the reason for the formation of this influence is helpful for countries in consolidating and expanding their influence on the global medical device trade. In particular, countries should strengthen the depth of their cooperation with other countries in regions where such depth is currently lacking. Similarly, they should establish more trade relationships with other countries in regions where their influence lacks breadth.

Finally, some countries are overly dependent on certain crucial countries with whom they may not even be direct trading partners but who are critical in the process of influence formation. As shown in the detailed influence propagation paths for China, Sweden and Germany in [Figure 4](#) and [A6-A7](#), the US is critical for their influence formation. In addition, the formation of influence in Israel, Belgium and the UK is closely tied with that in China and Belgium. It is interesting to note that Belgium plays a critical role in the diffusion process of the shock caused by the UK, but it was not avalanched in the first round. The influence of Israel, Belgium, and the UK is reactive and depends not only on their direct influence on their trading partners but also on their accumulation of the indirect influence caused by their other trading partners. In this context, the critical points may be occluded by analyses of these critical direct trading partners. Therefore, it is necessary to identify critical intermediate countries, remain vigilant about relevant changes there, and strengthen trade relationships with them.

This study analyzes the dynamic influence of countries with assumptions in terms of country antirisk capacity. Future works can further investigate the self-adaptive behaviors of countries under the influence of their trading partners and thus provide a more realistic assessment of countries'

dynamic influence. Furthermore, this study focuses on the export restrictions of countries to analyze the process of influence formation. In future works, the probability of export restrictions being implemented should be considered from economic, political and cultural perspectives to provide a comprehensive evaluation of countries' dynamic influence on the international medical device trade.

Appendix A. Supplementary data

[Appendix A1](#) presents the HS codes of the medical device commodities and the detailed preprocessing information for the data. [Appendix A2](#) introduces the basic metrics of the networks. [Appendix A3](#) presents the static analysis of the top influential countries. [Appendix A4](#) shows the dynamic analysis of the top influential countries.

Acknowledgments

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