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The flow of embodied minerals between China's provinces and the world: A nested supply chain network perspective

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ABSTRACT

This paper explores the flow of embodied minerals of different provinces within China, and the characteristics of embodied mineral supply between the minerals sector of China's provinces and other countries or regions (outside of China) in the world by a nested multiregional input-output (Nested-MRIO) model. Besides, cascading failure is used to simulate the effect of key countries or regions of the nested embodied mineral supply chain network (NEMSCN). The results show that China's embodied mineral trade is mainly concentrated in the southeast and northeast. Association of Southeast Asian Nations (ASEAN), European Union (EU), and America are China's three closest trade partners. In NEMSCN, ASEAN, EU, India, USA, Chile, Liaoning, Mexico, Turkey, Anhui, and Brazil are key countries, regions and provinces (key nodes).By cascading failure analysis, we found that if the imports and exports of embodied minerals of these 10 countries, regions and provinces are changed, then the flow of embodied minerals in the entire NEMSCN will change significantly within a certain period of time. The practical significance of this paper is the provision of a theoretical basis and references for the formulation of the related resource and supply security policies.

1. Introduction

In the context of economic globalization and integration, international trade continues to increase, and the exchange of goods and services between countries is also increasing. On this basis, tangible resource accounting and tracking the flow of tangible resources have become popular topics. Most previous studies have focused on the analysis of trade issues such as energy (Papangelou et al., 2020; Gasim, 2015; Shi et al., 2017), exergy (Zhang et al., 2018) water (Tian et al., 2018), certain specific metals or other raw materials (Wiedmann et al., 2015; Niero and Kalbar, 2019; Jiang et al., 2019). However, minerals are also an essential material in the production process. Most industrial production uses the output of the mining sector directly or indirectly. Trade activities between countries and regions cannot be separated from the mineral trade. As long as the exchange of goods or services is involved, mineral flows will occur (Jiang et al., 2018). As one of the largest mineral producers and consumers in the world, China has a great influence on global mineral supply activities. Moreover, different provinces have different characteristics and thus have different effects on mineral supply activities, which are called heterogeneity characteristics. The research motivation of this paper is to quantify such characteristics and effects, and to provide theoretical guidance for the policy-making of mineral supply security, which is also the research question of this paper. Based on the above, this paper chooses the embodied mineral flow as the research object and constructs the nested embodied mineral supply chain network (NEMSCN).

This paper studies the supply and demand of embodied minerals between the minerals sector of different provinces in China by nested multiregional input-output (Nested-MRIO) and complex network, and uses the same method to analyze the supply and demand of embodied minerals between Chinese provinces and other countries or regions (outside of China) in the world. Through the above research, the

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embodied mineral flow within China and the import and export situation of different provinces in China can be understood. Previous studies have fully discussed most transfer flows (Zhang et al., 2020; Mi et al., 2017; Liu et al., 2020). On this basis, this paper explored the flow and impact of embodied minerals between China's provinces and foreign economies systematically.

The supply-demand relationship of mineral resources can reflect the trade relationship (Jiang et al., 2018). This paper can provide an academic reference for formulating corresponding trade policies based on this relationship. In addition, the key countries or regions of the NEMSCN have also been identified by the weighted degree of the network. Then, based on these key nodes, the cascading failure simulation is performed. The NEMSCN is a dynamic system with complex trade relations between countries and regions. When a supply risk occurs at a node, some or all countries in the network will face embodied mineral supply risk by the chain reaction (Heckmann et al., 2015), and cascading failure simulation can effectively quantify the risk and determine the corresponding solutions.

In summary, the research object of this paper is the embodied minerals of NEMSCN, and the main goal is to explore the flow and impact of embodied minerals between China's provinces and other countries or regions (outside of China) in the world. The contributions of this paper is to providing a quantitative basis and reference for serving trade contacts and dealing with the global mineral resource supply risk. The rest of this paper is organized as follows. Section 2 is the literature review. Section 3 introduces the data and methods for constructing a nested-MRIO model and a NEMSCN. Section 4 introduces the flow of embodied minerals and key nodes between the minerals of China's provinces and the world and conducts a cascading failure simulation. Finally, the findings are concluded in Section 5.

2. Literature review

The current research on minerals mainly focuses on two aspects. The first is direct mineral input in economic activities (Adibi and Ataee, 2015; Ebner, 2015). Direct minerals can only reflect instant mineral consumption at the user's site. Secondly, there are embodied minerals, which contain all historical and off-site information about the product during production, transportation and consumption. This indicates that embodied minerals include direct and indirect minerals (Jiang et al., 2018), which more comprehensively reflect the flow of minerals. In addition, embodied minerals contain the meaning of footprints (the flow relationship between different countries or regions is relatively obvious), and it is more suitable to use it to analyze the global mineral flow.

As far as the research methods of embodied minerals are concerned, input-output analysis has become an effective tool (Kucukvar et al., 2019), and the multiregional input-output (MRIO) model is usually used. The MRIO model generally studies a certain country (Shi et al., 2020; Jia et al., 2019; Chen and Chen, 2015) or analyzes the world (Yang et al., 2020; Zhang et al., 2020). Using the MRIO model in a global context, the focus of research is usually on the region (Li et al., 2020; Sun et al., 2018), and there are also sectors of different countries and regions (Shi et al., 2017; Liu et al., 2019; Guo et al., 2020). From another perspective, depicting the relationship between the various levels of the economic system is also very important to the global, national and regional economies. Therefore, a multiscale input-output analysis (multiscale IOA) is introduced to depict relationships at different scales (Liu et al., 2017; Han et al., 2015; Chen et al., 2013). Considering that it is suitable for measuring multiple impacts of different scales, multiscale analysis can effectively avoid the deviation of data at different scales between related economies and regions, but the same level of remote contact relationship may be restricted to a certain extent. So the research of combining multiscale and multiregional research has attracted increasing attention. Due to the ability to correlate economic activities and final demands of multiple regions and different scales, the Nested-MRIO model can be used to cope with the multiregional transfer flows at different scales in complex systems (Han et al., 2020). The Nested-MRIO model usually embeds the input-output model of a certain country into the world input-output model, and it is often combined with carbon emissions to study the relationship between China's provinces and cities and the world (Yang et al., 2020; Zhang et al., 2020; Mi et al.,2017, 2020). In addition, the model can also distinguish the influence of different countries/regions and provinces/cities (Liu et al., 2019; Han et al., 2019).

By the weighted degree indicators, the key nodes on NEMSCN are discovered. Based on these key nodes, this paper uses the cascading failure method to simulate the supply risk. Cascading failure (also called a fault or an avalanche) is a dynamic process in which one or more nodes or edges in a network failure, which causes other nodes (edges) to fail due to coupling relationships between the nodes (edges), thus causing a chain reaction that eventually causes a significant portion or the entire network to crash (Watts, 2002). At present, simulations based on cascade failure have been widely applied in the dynamic research of networks. For example, graphite trade networks (Wang et al., 2018), food supply chain networks (Yan et al., 2010), and global economic systems (Lee et al., 2011). In addition, cascading failures have been found in many actual networks in nature (Chen et al., 2018; Huang et al., 2021). Based on this, the supply risk of embodied minerals can be appropriately quantified by the cascading failure method.

3. Methods and data

3.1. Construction of the Nested-MRIO model

Because the research goal of this paper is to explore the flow and impact of embodied minerals between Chinese provinces and other countries or regions (outside of China) in the world, a Nested-MRIO method is adopted.

We decompose the Chinese part of Eora into 31 provinces according to the China's MRIO model. According to Eora's original import and export ratio to China, the imports and exports of each province are adjusted by the remaining 189 countries/regions. We assume that the distribution ratio of a province's international exports (or imports) among all regions of the world is the same as that of China's total exports (or imports) (Yang et al., 2020; Mi et al., 2020). Therefore, the nesting is mainly divided into two steps. The first step is calculating the import and export ratio of the global input-output table, as formulas (1)-(4), and the second step is calculating the nested data (China's import and export data and the import and export ratio of the first step are correspondingly multiplied), as formulas (5)-(8). As shown in Fig. 1.

$$Im_{ratio} = \frac{ez_{ij}}{im_j} \tag{1}$$

$$Ex_{ratio} = \frac{ez_{ij}}{ex_i} \tag{2}$$

$$Yim_{ratio} = \frac{y_{ij}}{yim_j} \tag{3}$$

$$Yex_{ratio} = \frac{y_{ij}}{yex_i} \tag{4}$$

Im_{ratio}, Ex_{ratio}, Yim_{ratio} and Yex_{ratio} are the import and export ratio of intermediate use and the final demand in Eora's input-output table, respectively. ez_{ij} is the intermediate use of Eora, and y_{ij} is the final demand. im_j, ex_i, yim_j and yex_i are the import and export of intermediate use and the final demand in Eora's input-output table, respectively.

$$Nz_j = Im_{ratio} \times ci_j \tag{5}$$

$$Nz_i = Ex_{ratio} \times ce_i \tag{6}$$

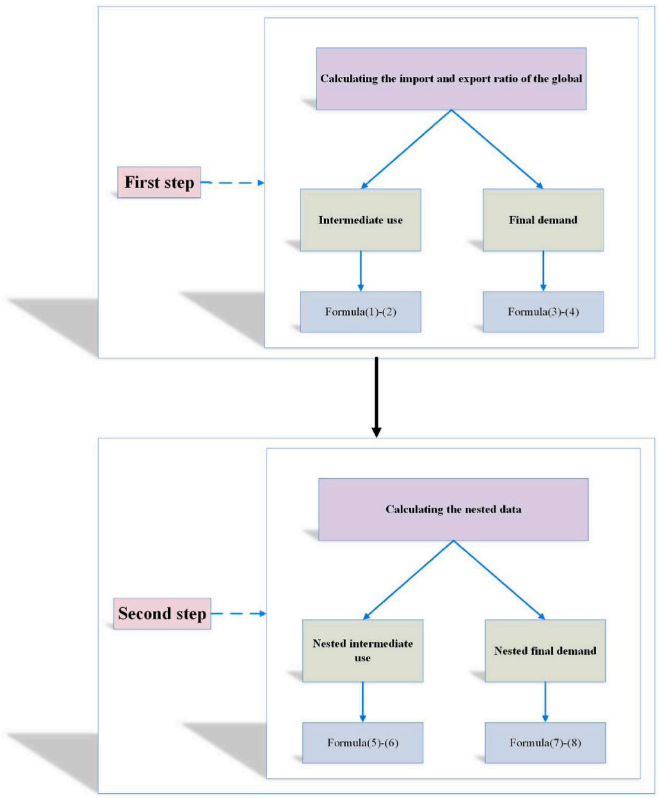


Fig. 1. Schematic diagram of nested steps.

$$Ny_j = Yim_{ratio} \times cy_j \tag{7}$$

$$Ny_i = Yex_{ratio} \times cy_i \tag{8}$$

Nz and *Ny* are nested intermediate uses and final demand, respectively. ci_j, ce_i, cy_j and cy_i are the import and export of intermediate use and the final demand in China's input-output table, respectively.

Thus, the China's MRIO model is nested into the world's MRIO model. A schematic diagram of the nesting is shown in Fig. 2. In general, the updated global MRIO model includes 155 countries and regions after merging 189 countries in the original Eora model and 31 provinces in China (the specific merger, abbreviations and full names are compared in the Supporting Information (SI)).

After the nesting is completed, we conduct the calculations of embodied minerals, and the research object becomes the minerals sector and non-minerals sector of 31 provinces in China and other countries and regions in the world. In this way, we can analyze two aspects: (1) we can study the flow of embodied minerals among the 31 provinces in China; and (2) we can study the flow of embodied minerals between China's provinces and other countries and regions in the world.

3.2. Construction of the complex network model

3.2.1. Constructing a NEMSCN

The global NEMSCN model is represented by the set N=(R,EM), where the minerals sector of region $R = (r_1, r_2, \cdots r_n)$ is regarded as the network node, and the embodied mineral flow represented by EM will be the edge of the network

$$EM = \{em_{ij}\} = D(I - A)^{-1}Y \tag{9}$$

In addition, em_{ij} represents the embodied mineral flow from node *i* to node *j*, D represents the direct mineral intensity matrix, it is the ratio of mineral consumption data to total output. Y represents the final demand matrix, and $(I - A)^{-1}$ is the Leontief inverse matrix (Jiang et al., 2018; Chen et al., 2018).

Based on this, we constructed the NEMSCN model, as shown in Fig. 3. The China's provinces and the rest of the world are nested to analyze the embodied mineral flow between them and the heterogeneity characteristics of China's provinces are also found. Then, the key nodes in the network are found through the weighted degree, and the effect of their supply interruption is analyzed.

Based on the NEMSCN, the paper first analyzes the flow of embodied minerals among China's provinces and then studies the flow of embodied minerals between China's provinces and other countries and regions in the world. In addition, the embodied minerals in this paper mainly include ferrous metal flow, nonferrous metal flow, and nonmetal flow.

$$em_{ij} = nm_{ij} + nfm_{ij} + fm_{ij} \tag{10}$$

where nm_{ij} represents the embodied nonmetal flow from node *i* to node *j*, nfm_{ij} represents the embodied nonferrous metal flow from node *i* to node *j*, and fm_{ij} represents the embodied ferrous metal flow from node *i* to node *j*. Based on equation (11), we can analyze the proportions of the three mineral types in the embodied mineral flow.

We select the top five countries, because they are representative and include provinces of various characteristics (Hussain et al., 2020). This

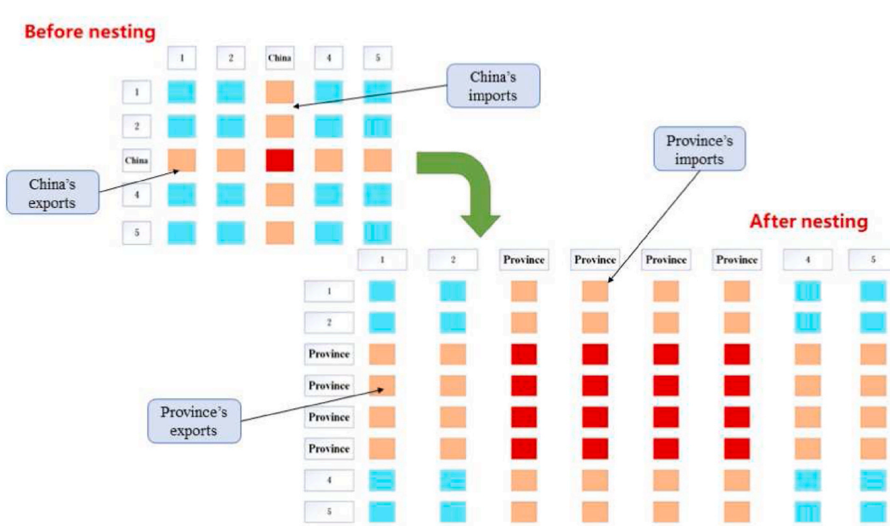


Fig. 2. Schematic diagram of the nested-MRIO model.

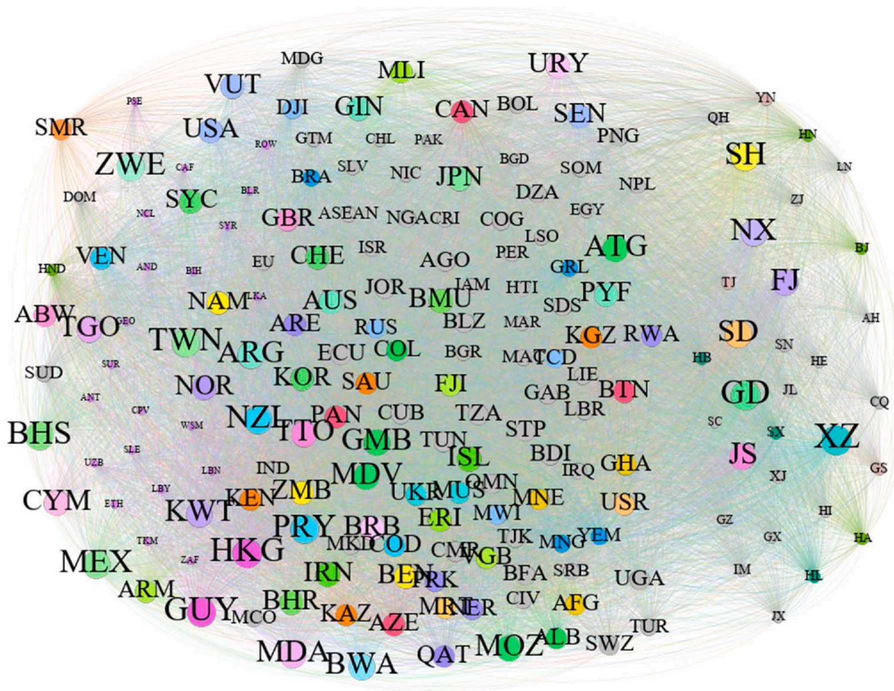


Fig. 3. Nested embodied mineral supply chain network (NEMSCN).

paper can idenfy the embodied mineral supply relationships in the network by analyzing countries, regions and provinces with embodied mineral flows.

3.2.2. The key nodes of NEMSCN

We express the weighted in-degree I_i of node i as the sum of embodied minerals from node j to node i, as shown in equation (12) (Ren et al., 2022):

$$I_i = \sum_{j=1} em_{ji} \tag{11}$$

where em_{ji} represents the embodied minerals flow from node j to node i.

Similarly, we use the weighted out-degree O_i, which is the sum of the embodied minerals from node i to node j, as in equation (13) (Ren et al., 2022):

$$O_i = \sum_{j=1} em_{ij} \tag{12}$$

where em_{ij} represents the embodied minerals flow from node i to node j.

The weighted degree is calculated as follows:

$$W_i = O_i + I_i \tag{13}$$

In this article, we take the top ten nodes by weighted degree as key nodes of the network.

3.3. Cascading failure simulation

By using a network weighted degree, we can obtain the key nodes (TOP 10) in the network; that is, the node that has an important influence on the NEMSCN. Then, we simulate how these key nodes affect the network. How large is the impact? How large is the scale? Is it mainly a direct impact or an indirect impact? This work must be done by means of cascading failure simulation.

In a network, the cascade failure simulation model generally has three basic links: the load, distribution strategy, and failure rules. The load is the maximum load value that the nodes or edges in the network can currently bear. The distribution strategy refers to the process of recalculating the load throughout the entire network or local environment after the failure of the nodes. The failure rule indicates when the residual nodes are infected by failure when the current load exceeds the critical value of the maximum load (also called the threshold value), and then subsequent failure occurs (Wang et al., 2018). Based on the above ideas, this paper adopts the cascading failure model proposed by (Wang et al., 2018; Lee et al., 2011) to simulate the impact of the supply risk of key nodes on the entire nested embodied mineral supply chain network from a practical perspective. The process is as follows:

(a) Assume that no node is affected by the supply crisis. We define the initial state and define the load capacity of the node r_i as T_i; that is, the total amount of embodied minerals in the inflow and outflow of the node r_i. This paper selects a country's total import and export of embodied minerals as the country's ability to withstand the crisis, and the initial load from node r_i to node r_j is em_{ij} (Fig. 4a).
(b) Suppose that node r_i is the source of the crisis; that is, the country and region are infected by the crisis. (In our definition, if a node has a supply crisis, its total exports will decrease by a fraction α) (Fig. 4b).
(c) The weight em_{ij} of all edges that are exported by the infected country r_i is reduced by a fraction α. If the total reduction Δem_j in the volume of imports of any uninfected country r_j connected to an infected country exceeds the fraction β of its capacity T_j ($\Delta em_j > \beta T_j$), then the country r_j also becomes infected (for example, country k in Fig. 4c).
(d) Repeat step c until there are no newly affected countries in the network. Then, the simulation process terminates.

To determine the spreading range of a source in the network, we call the number of infected countries caused by that source of the crisis the avalanche size (A). Of course, the dynamic changes in the model's results depend on the ratio of α/β because α and β are both variable parameters. When α/β is too large, the scale of the crisis at any node is too large, which indicates that a crisis in any one country may cause large-scale cascading failures. In addition, when α/β is too small, there is no

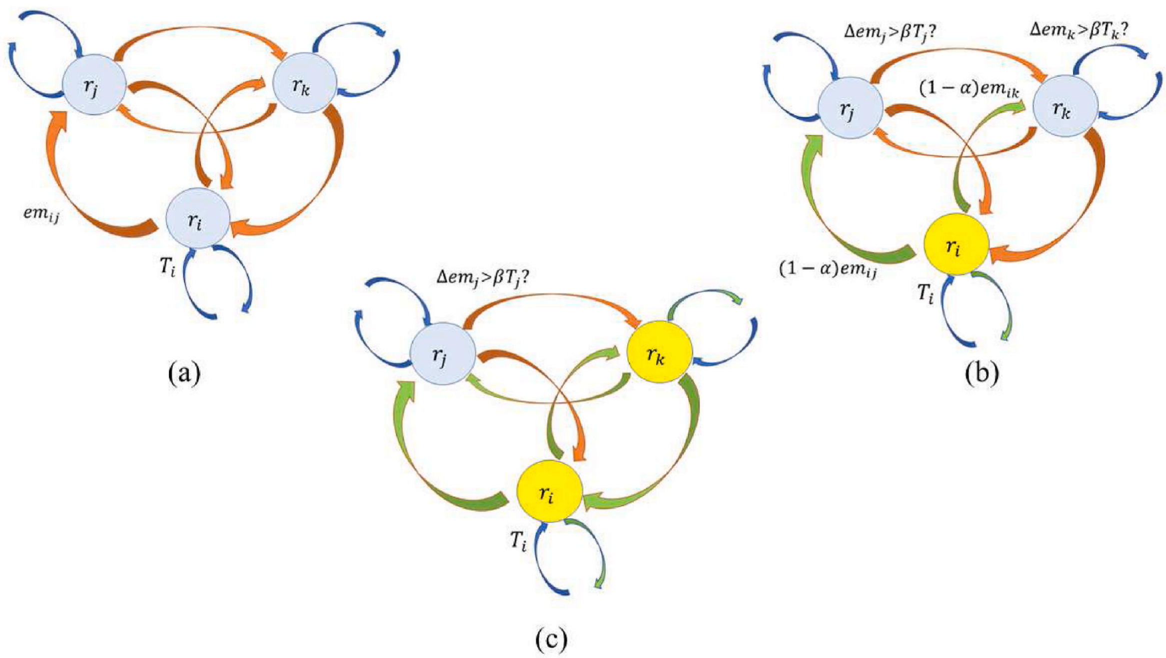


Fig. 4. Crisis spreading model (Note: the nodes r_i, r_j and r_k represent different nodes. If a node is affected by a supply crisis, the color of the country and the color of the arrow representing its exports will change. Both α and β are variable parameter).

large impact. The failure of any one country will not lead to the paralysis of other nodes, nor will it lead to effective circulation. We assume that ten key nodes are the root causes of the crisis, and by adjusting the ratio of α/β, we find that there is a critical point between the two; that is, $\alpha/\beta = 40$. As shown in Fig. 10, the horizontal coordinate of each point represents crisis scale A, and the vertical coordinates represent the cumulative count of the countries with the same or a greater crisis size than A. When $\alpha/\beta = 40$, the plot becomes straight with a slope of -1 (brown wire) on a logarithmic scale, indicating the power-law relation $P(A) \sim A^{-2}$. At this point, the accumulated count distribution of the crisis scale of each node obeys the power law distribution's characteristics. The distribution of nodes with different crisis scales is more uniform so that the differences between different nodes can be well-reflected. In addition, the size of the crisis of different nodes has the largest dispersion.

3.4. Data sources

The data used in this study were downloaded from The Eora Global Supply Chain Database (www.worldmrio.com) on October 16, 2019, providing a complete set of world value input-output tables, including 189 countries and the 26 sectors in each country, and all remaining countries are aggregated into one area labeled ROW. To facilitate statistical calculations and subsequent analysis, we merged 190 countries into 156 countries and regions. See the Supporting Information (SI) for details. The multiregional input-output table (MRIO) of China's 31 provinces in 2015 was downloaded from China Emission Accounts & Datasets (www.ceads.net) on October 20, 2020. For China's MRIO model in 2015, 31 provinces were involved, and each province included 42 sectors. Since mineral data is mainly consumed by the mineral sector in China and globally, it is not consumed by other sectors, this paper consolidates all sectors in China and globally into mineral and non-mineral sectors, considering only the two sectors, the details are in SI. In addition, data on minerals consumed in other countries and regions in the world except China come from the Eora database, and data on minerals consumed in 31 provinces in China come from the Wind database. The mineral data only considers non-energy minerals. Due to data limitations, this paper assumes the mineral production data of each province as its consumption data. Besides, it is worth noting that the units of mineral data and input-output data in China and the world are not uniform, and we have to convert them. The mineral consumption data are all set in tons, and the input-output data are all set in US dollars (converted at 2015 US dollar exchange rates). The abbreviated list of China's provinces and countries in the world is in the SI.

4. Results

4.1. The analysis of a NEMSCN

This section will analyze the flow of embodied minerals between the minerals of provinces in China and between countries and regions in the world. In addition, embodied minerals can be subdivided into ferrous metals, nonferrous metals and nonmetals for research.

As shown in Fig. 5, for provinces in China, the minerals of LN, SC, AH, ZJ and JS provided more embodied minerals to other provinces, while GD, HA, HE, IM and CQ imported more embodied minerals from other provinces (embodied mineral traffic ranks of the top five). It shows that GD, HA, HE, IM and CQ consume more embodied minerals. In addition, we also found that China's embodied mineral trade mainly occurs in the southeast and northeast. For example, SC mainly provides embodied minerals to TJ, HE, IM, GD and SN; ZJ mainly provides embodied minerals to HE, TJ, JL, SN and IM.For three different types of embodied minerals, in China's 31 provinces, nonmetals account for the highest proportion, approximately 90%; ferrous metals account for approximately 9.3%; and nonferrous metals account for only approximately 0.7%. Therefore, among the main suppliers of embodied minerals in China, they are not only rich in mineral resources, but also have good economic development and developed trade. Among them, nonmetallic minerals should be paid attention to from a sustainable perspective.

As far as China is concerned, GD, SH, JS, SD and BJ are the five provinces with the most imports, showing that the final demand of these provinces consume a lot of embodied minerals from other countries and regions. These five provinces are the provinces with fast economic development. As shown in Fig. 6, GD, SH, JS, SD and BJ mainly import embodied minerals from ASEAN, EU, IND, USA and CHL. Among the

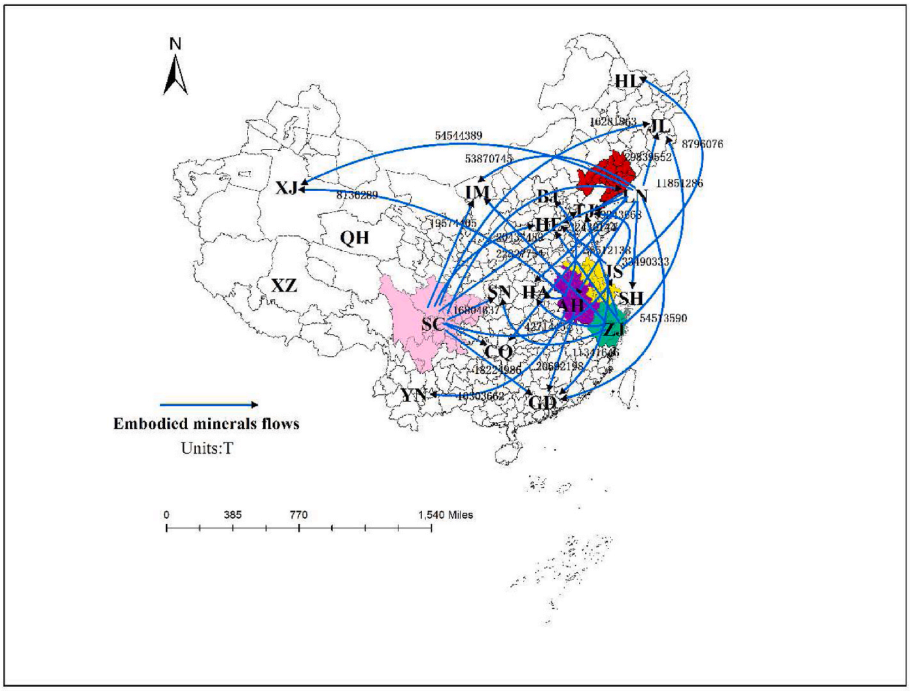


Fig. 5. China's minerals sector of top five provinces exporting embodied minerals (the direction of the arrow indicates the direction in which the five provinces mainly export embodied minerals, and the number on the arrow is the amount of embodied minerals exported).

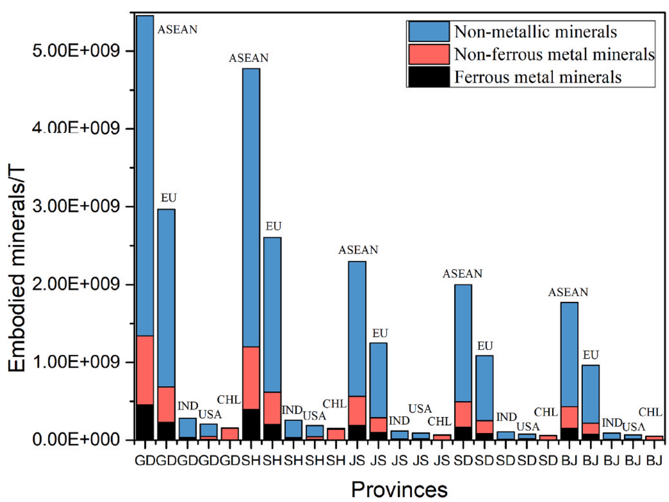


Fig. 6. The top five provinces of China's imports (final demand) of embodied minerals.

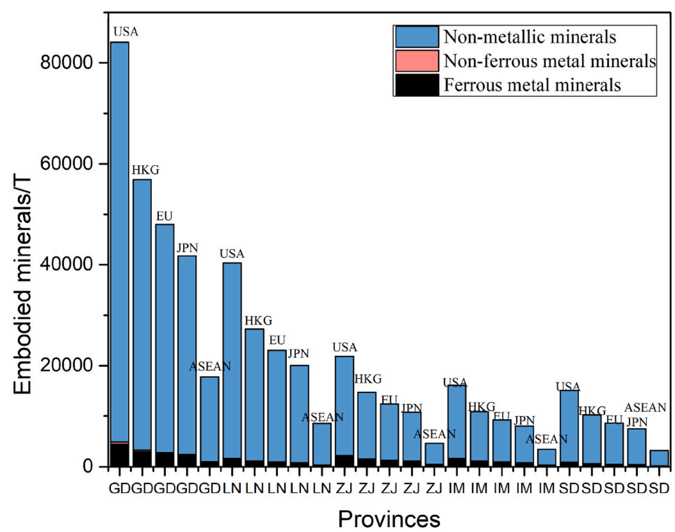


Fig. 7. The top five provinces of China's exports (minerals sectors) of embodied minerals.

embodied minerals imported to these five provinces and cities, nonmetallic minerals account for the largest proportion, followed by nonferrous metal minerals, and ferrous metal minerals account for the smallest proportion. It is worth noting that the embodied minerals imported from CHL to these five provinces are mainly nonferrous metal minerals.

GD, LN, ZJ, IM and SD are the five provinces with the most exports, showing that the minerals of these provinces provide a lot of embodied minerals to other countries and regions. LN and IM are rich in mineral resources and they are exported in large quantities, while GD, ZJ and SD are coastal cities with well-developed trade, and more embodied minerals are exported. As shown in Fig. 7, GD, LN, ZJ, IM, and SD mainly export embodied minerals to the USA, HKG, EU, JPN and ASEAN. Among the embodied minerals exported from these five provinces and cities, nonmetallic minerals account for the largest proportion, followed by ferrous metal minerals, and nonferrous metal minerals account for the smallest proportion.

4.2. The key nodes of the NEMSCN

Fig. 8 lists the key nodes in the supply chain network, and the minerals of ASEAN, EU, IND, USA, CHL, LN, MEX, TUR, AH, and BRA. ASEAN (25.6%) and EU (22.96%) far exceed other countries and regions. China has two provinces, LN (7.78%) and AH (3.64%); the two provinces are rich in mineral resources and the types are relatively complete. There is a large amount of embodied minerals flowing through them. The two provinces are rich in mineral resources, and each province also has a certain influence on the supply chain network. Its influence (direct influence and indirect influence) in the network is

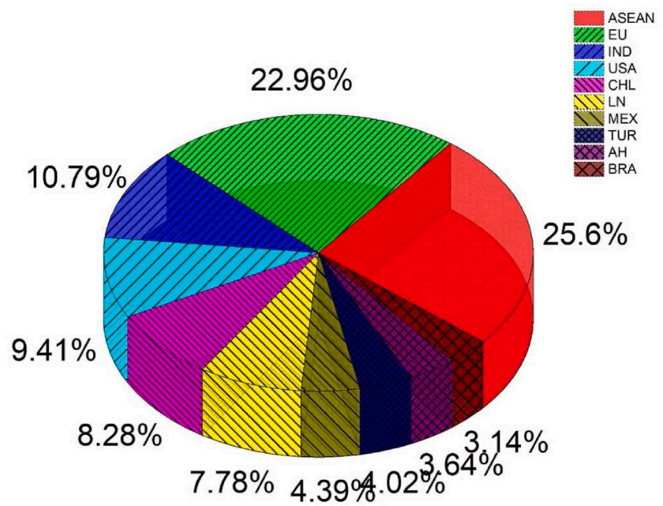


Fig. 8. The key nodes of the NEMSCN (the minerals sector of countries, regions and provinces).

greater. In other words, if there are supply risks at these nodes, the entire NEMSCN will be greatly affected. Therefore, to reduce the supply risk and ensure the security of supply, relevant countries and organizations should pay more attention to these countries and regions.

4.3. Cascading failure simulation

Based on the key nodes in the network. In the case of a given $\alpha/\beta = 40$ (Fig. 9), we obtain the size of the supply crisis of each source country (A) (the number of nodes affected by the source country of the crisis), the proportion of affected nodes (P) (the ratio of the number of affected nodes to the total number of nodes in the network), the duration of the crisis (T) (the number of steps the supply crisis has spread), and the number of affected countries in each period. The duration of the crisis in this paper is from T1 to T10, because the effect of cascading failure after T10 is not significant. Table 1 shows the supply crisis at the above key nodes (arranged according to the size of the supply crisis).

Among these countries, the mineral trade's influence of other countries on the NEMSCN is much smaller than that of ASEAN (95.6%) and EU (94.6%); moreover, the short duration of the supply risk between the two shows that they directly affect (T1) more countries and regions and indirectly affect (T2-T10) less. The scale of the supply risk for IND (60.7%), CHL (36.5%), MEX (36.5%), USA (25.2%), BRA (18.8%) and TUR (18.2%) decreased in order, and they directly affected fewer countries and regions and indirectly affected more. The risk in China's LN (15.5%) and AH (15.5%) provinces are relatively small, but the risk in LN and AH last longer, and their failure will also have a certain impact on the NEMSCN. LN directly affects more, while AH indirectly affects more.

In addition, we analyzed the mineral of China's provinces in which the ten key nodes directly affect (T1). For ASEAN and EU, most countries and regions are directly affected by them, and all 31 provinces in China are affected by them. There are 43 countries and regions directly affected by IND, of which 13 provinces are in China. As shown in Fig. 10a, the provinces with colors are the affected provinces. CHL, MEX, BRA and TUR directly affect fewer countries and regions, and there are no provinces in China. The USA directly affects 21 countries and regions, including nine provinces in China, as shown in Fig. 10b. The provinces with colors are the affected provinces. Most China's provinces affected by IND and the USA are provinces with developed coastal trade, and the others are provinces with high reserves of mineral resources. For LN and AH, the nodes directly affected by them are all provinces in China, as shown in Fig. 11a and b, and the provinces with colors are the affected provinces. AH mainly affects three provinces: GS, SN, and YN. LN affects 20 provinces in China, of which there are more inland provinces and fewer coastal provinces.

5. Discussion

There are three main types of embodied mineral import and export provinces: the first are provinces with higher GDP, such as BJ; the second is coastal provinces with developed trade, such as GD; and the third is provinces with rich mineral resources, such as LN. The most frequent trade in embodied minerals with China are the USA, EU, and ASEAN, which also reflects the close trade between China and them in 2015. In addition, China imports and exports more embodied non-ferrous metals, showing the importance of embodied non-metallic minerals in the embodied minerals trade.

The ASEAN, EU, IND, USA, CHL, LN, MEX, TUR, AH, and BRA are key nodes in the NEMSCN. In other words, these countries and regions should pay attention to the supply risks of minerals embodied in trade. In the context of economic globalization, supply cuts or restrictions in these countries and regions will have a greater impact on NEMSCN, which in turn will affect other trade activities. Because these key nodes have both direct and indirect influences on the network, the corresponding countries and regions have to formulate different policies according to the different proportions of direct and indirect influences.

ASEAN and EU have direct trade relations with most countries and regions, so their embodied mineral supply risk has a large impact and a

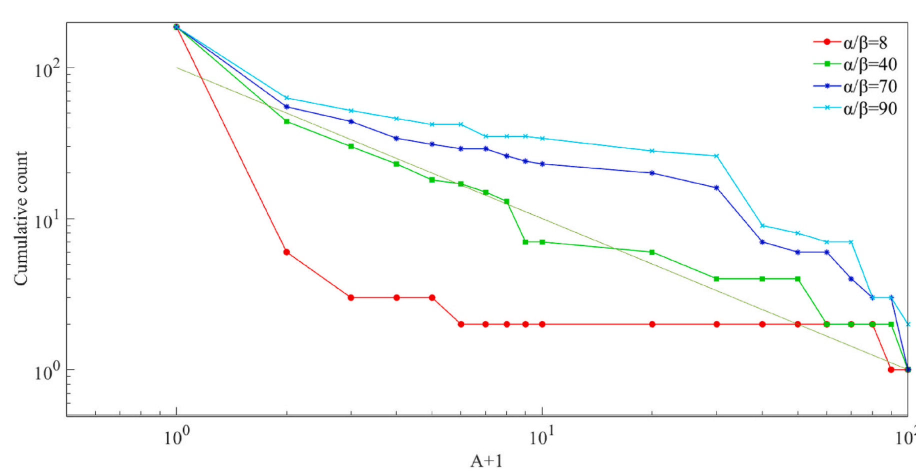
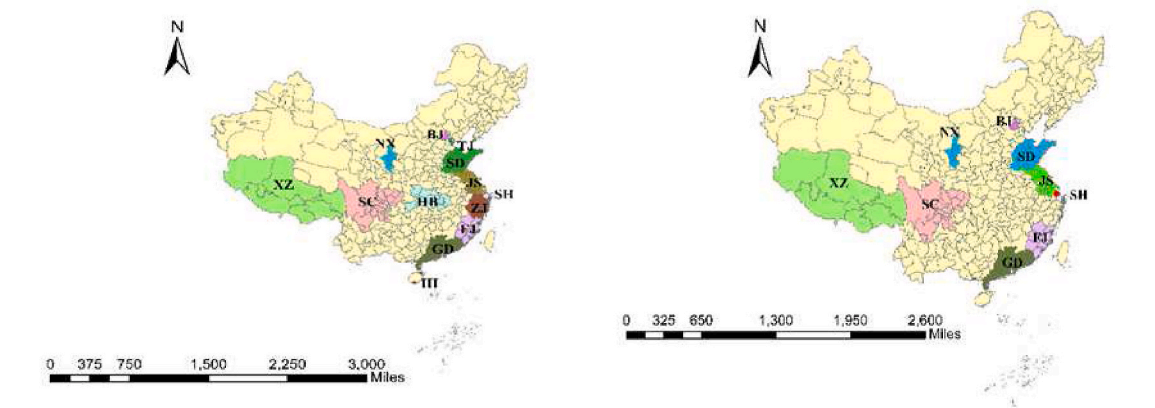


Fig. 9. Supply risk scale distribution (please note: plotting the cumulative count of countries with risk size equal to or greater than A, which behaves in the same way as the cumulative distribution of P(A), is plotted. The horizontal axis has been offset by one to plot the countries with A = 0 on a logarithmic scale).

Table 1
Top 10 nodes ranked according to the size of the supply risk (S represents the minerals sector of country or region where the risk originated).

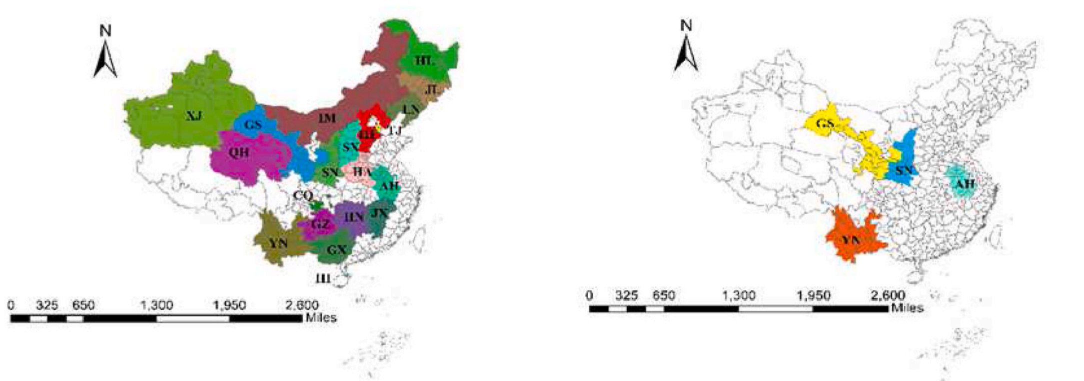
S	T	A	P	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
ASEAN	2	178	0.956	174	178								
EU	3	176	0.946	164	175	176							
IND	4	113	0.607	43	92	108	113						
CHL	5	68	0.365	6	16	35	46	68					
MEX	5	68	0.365	6	38	61	67	68					
USA	3	47	0.252	21	46	47							
BRA	5	35	0.188	5	8	18	32	35					
TUR	6	34	0.182	10	21	30	32	33	34				
LN	5	29	0.155	20	26	27	28	29					
AH	10	29	0.155	4	7	11	15	20	24	25	27	28	29



(a) The direct impact of IND on Chinese provinces

(b) The direct impact of USA on Chinese provinces

Fig. 10. The direct impact of IND, USA on China's provinces.



(a) The direct impact of LN on Chinese provinces

(b) The direct impact of AH on Chinese provinces

Fig. 11. The direct impact of LN and AH on China's provinces.

wide range (China's 31 provinces are affected by them). Special attention should be paid to their supply risk in the future. For other key nodes, they are all Asian or American countries, so they have one common feature: rich mineral resources and developed foreign trade. Therefore, their supply risk will directly or indirectly have a greater impact on the network. The supply risk in these countries and regions has been quantified, which also provides a basis for formulating relevant trade policies, supply security policies and even climate change policies. In particular, countries and regions that have a great direct impact should pay special attention, because their supply risks are too low in controllability, and they are fast and large in scope. In summary, for countries and regions that have a great direct impact, we must pay attention to their own trade imports, exports and reserves. While countries and regions that have a great indirect impact must not only pay attention to themselves but also the imports, exports and reserves of their neighbors.

6. Conclusions

From the perspective of the nested embodied mineral supply chain network (NEMSCN), this paper first studies the flow of embodied minerals between the China's provinces and the world, then the weighted degree indicator is used to determine the key nodes in the network. Finally, a cascade failure simulation is conducted based on the key nodes. The conclusions obtained are as follows.

As far as China's provinces are concerned, the provinces in the northeast and southeast should pay attention to the sustainable development and supply security of nonmetallic minerals and ferrous metal minerals. For China's embodied mineral import and export trade, the direct and indirect minerals embodied in the goods and services imported by China are mainly nonmetals and nonferrous metals. The direct and indirect minerals embodied in exported goods and services are mainly nonmetals and ferrous metals. This not only provides a reference and quantitative basis for China's mineral risk policy but also provides a reference for China's trade import and export policy. ASEAN (Association of Southeast Asian Nations), EU (European Union) and USA (America) are important countries and regions for China's mineral-containing trade. Therefore, China's trade relations, trade policies, and supply security issues with these three countries and regions should be focused on.

The import and export trade of embodied minerals in China's provinces is unbalanced. Due to this phenomenon, China should pay attention to the study of foreign trade dependence, establish and improve the foreign trade evaluation system as soon as possible, and make full use of the WTO's trade dispute settlement mechanism. In addition, China should actively respond to and optimize the settlement of mineral trade imbalances in an all-round and multifaceted manner, and safeguard China's resource and economic security. Compared with the nonmetals and ferrous metals exporter, China's provinces import a large number of nonmetals and nonferrous metals. Although China's nonferrous metal production has been the largest in the world for several consecutive years with the continuous rapid growth of China's economy, the consumption of nonferrous metal products has also continued to increase. However, due to the shortage of China's nonferrous metal mineral resources and the domestic supply is insufficient, there is a need to import much more from abroad. Furthermore, the import dependence of nonferrous metal raw materials has gradually increased, which has become a problem that cannot be ignored. In addition, the source countries for minerals are mainly the ASEAN, EU, IND, USA and CHL. This shows that China's embodied mineral suppliers are too concentrated, and it is necessary to prevent the impact of supply interruption on China's embodied mineral supply chain.

The ASEAN (Association of Southeast Asian Nations), EU (European Union), IND (India), USA (America), CHL (Chile), LN (Liaoning), MEX (Mexico), TUR (Turkey), AH (Anhui) and BRA (Brazil) are key nodes of the network because there are a large amount of embodied minerals flowing through them. Once they have problems such as a supply crisis, the network will be affected. The countries should be given priority when formulating mineral trade policies because their supply risks will have a greater impact on the network. For countries and regions with greater direct effects (ASEAN, EU, and LN), potential mineral resource substitute countries should be found to alleviate the impact of an outage on the network. Countries and regions with greater indirect impacts (IND, USA, CHL, MEX, TUR, AH and BRA) should be paid more attention, because these countries can only take precautions in advance. If they fail at a later period, they will have a large scope of spread, and the duration will also be long. In international trade, China should pay attention to its trade relations with IND and the USA, because if the two countries fail, it will have a greater impact on China. In China's internal provinces, LN is the most important province, and its failure would have the greatest impact on China. Therefore, China should pay special attention to the mineral sustainability of LN when formulating a national sustainable supply strategy for mineral resources.

In summary, for the provinces in the northeast and southeast, the China's government should formulate policies about the mineral supply risk, and for coastal provinces, it should mainly formulate mineral supply security policies and trade protection policies. In addition, for other important countries and regions, due to they have a greater impact on the network, the corresponding government sectors must take certain measures to deal with supply risks. Among them, for countries that have a greater direct impact, their own governments must formulate corresponding supply risk countermeasures and backup countermeasures. For countries with greater indirect influence, their own governments must formulate corresponding countermeasures to prepare for emergencies. This is the greatest practical significance of this article.

Because of the limited data, this paper only used the 2015 data to calculate the research, and it is based on two sectors (minerals sector and non-minerals sector) dimensions. Therefore, in subsequent research, we will collect data as much as possible to break down the sector in more detail. In addition, the mineral data analyzed in this paper are non-energy mineral data, due to the limitations of input-output data and mineral data, adding the energy mineral sector to the mineral sector when merging the sectors.

Author statement

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