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Original Article

Investigating the Characteristics of Uranium Trade Flows and Trade Evolution along the Supply Chain

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Abstract:
Nuclear energy is essential for national energy security and clean energy transition, which has been defined as a critical mineral by many countries. However, the supply of nuclear fuel in the international market is complex. Currently, the trade flow and trade pattern characteristics of the uranium supply chain have not been clarified, and insufficient attention has been paid. To explore this issue, this paper constructs a multi-layer complex network model of uranium supply chain based on uranium product trade data from 2014 to 2023 through complex network methods. Then, we focus on the topological characteristics, trade flow, trade pattern evolution characteristics of the multi-layer trade supply chain network of uranium (MTCN), and the importance of major trading countries in the network. The results show: (1) international trade in the global uranium supply chain is of a "boom-to-fade" characterization, with the number of participating countries, trade relations and trade volumes decreasing, while the main hub countries are fixed. (2) The global uranium trade flow shows a significant centralized characterization, with the characteristic of large to small along the supply chain. Besides, the main trade is concentrated in the upstream natural uranium, and it has formed a "Kazakhstan-Canada" supply center and a "China-USA-France" demand center. (3) Importing countries, such as Russia and USA, show strong resource control in uranium supply chain trade. It expects that the findings of this paper will help countries involved in uranium trading to develop sustainable resource management policies.
Keywords: Uranium, Complex network, Multi-layer, Trade flow, Trade pattern, Importance

1. Introduction

Urgent climate crisis, volatile energy prices and the fragility of the fossil fuel supply chain have driven the resurgence of nuclear energy, and many countries are gradually realizing the importance of nuclear energy in ensuring energy security and clean energy transition[1]. Nevertheless, due to safety and waste of nuclear energy, countries such as Germany, Italy, Belgium, and Spain have announced plans to phase out nuclear power[2]. To the contrary, Britain, France, China, Poland and India have all announced new energy strategies to speed up the construction of nuclear reactors[3]. As the main raw material of nuclear fuel for nuclear reactors, uranium demand in nuclear reactors is expected to reach 130,000 tonnes by 2040, according to the World Nuclear Association (WNA) [4]. Moreover, because of the poor uranium resource endowment of the world's major nuclear power countries, trade is the main supply channel of uranium. Uranium supply can be characterized by two main categories: primary and secondary supply. Primary supply refers to uranium that is newly mined and processed, while secondary supply includes uranium received after reprocessing and returned back to the fuel cycle[5]. Uranium in the international market is mainly traded in these two forms, and forms a complex system of multi-layer trading products based on the supply chain.

However, amid geopolitical, anti-globalization and trade frictions, vulnerabilities in supply chains can pose significant economic risks[6], which threatens the stability of uranium trade. Although Russian uranium supply is not subject to ongoing sanctions imposed by Western and European entities during the Russia-Ukraine conflict. As the world's largest supplier of enriched uranium, Russia still faces geopolitical risks that pose important uncertainties to uranium supplies[7]. Specifically, the uranium supply chain has formed a multi-layer chain network structure. Significant demand pressure in the future and global trade fragility factors increase the risk of supply chain disruptions. Hence, clarifying the evolution of trade patterns, network topology characteristics and trade flows in MTCN is of great importance to ensuring the stable supply of global uranium, energy security and energy transition.

MTCN is a typical chain-network organizational structure, and the highly heterogeneous characteristics of the chain-network organizational structure cannot be explained by the traditional trade model[8]. Complex network theory can explain the impact of network structure on system functions by revealing the evolutionary characteristics of international trade, thereby analyzing the impact of supply changes on the international trade pattern and its interaction between products at different levels of the supply chain[9–11]. Complex network methods can reveal the complex relationships and structural patterns among various components by transforming complex systems into network structures of points and edges, which reveal many new characteristics and topological dynamics of international trade[12–14]. It has been widely used in the trade research of energy transition minerals such as lithium[15–17], cobalt[18,19], nickel[20] and rare earth[21].

At present, some scholars begin to pay attention to the trade issues of uranium. Lan et al. studied the trade pattern of natural uranium and believed that the evolution of the global natural uranium trade pattern was mainly affected by economics, politics and nuclear accidents[22]. Wang and Xing constructed the trade network of natural uranium and enriched uranium based on complex network methods and analyzed the evolution trend of network characteristics at the global, regional and national perspective[23]. Monirul Islam et al. investigated the impact of global, Russian, and USA geopolitical risks on USA nuclear energy consumption driven by Russian uranium exports from 1996 to 2019[7]. Furthermore, some scholars focus on the uranium trade issues of China, an emerging nuclear energy country[24–26].

Although previous research begun to pay attention to the trade characteristics of uranium, they have mainly focused on the changes in the trade pattern of single products, ignoring the evolution of the trade pattern and trade flow in the uranium supply chain. To fill this gap, this paper selects trade data from 2014 to 2023, constructs a complex network model of the supply chain of uranium ore-natural uranium-enriched uranium-depleted uranium based on the complex network method, and studies the topological characteristics, trade flow and trade pattern evolution characteristics of MTCN. The main contributions of this paper are: (1) exploring the flow between regions and within supply chains from a multi-layer supply chain network perspective; (2) determining the importance of major trading countries in the supply chain network. This paper expects to provide decision-making support for building a stable uranium supply system by studying the evolution characteristics of MTCN, analyzing the international trade pattern between upstream and downstream products and the impact of their interactions.

This paper is organized as follows: Section 2 is the data and method. Section 3 analyzes the basic characteristics of the network, trade flows and trade patterns. Section 4 is conclusions and policy implications.

2 Data and Methodology

2.1 Data Description

Based on the availability of data and the main supply system of uranium, this paper selects relevant trade products in the uranium supply chain to define the uranium commodities involved in this study, including uranium ore, natural uranium, enriched uranium, and depleted uranium. Besides, we convert all trade products into U235 content. Collecting relevant trade data from 2014 to 2023, and constructing directed-weighted complex network trade models with countries as nodes and trade relations as edges. The specific conversion coefficients and HS codes of commodities are shown in Table 1. In addition, according to the converted trade data, it is found that there are few countries involved in ore trade and the scale of trade is small. The largest trade volume is still less than 100kg. Therefore, this study ignores uranium ore trade.

The data in this paper is from the United Nations Commodity Trade Statistics Database (UN Comtrade). Because of the asymmetry of bilateral commodity trade, import data is often used to analyze the international trade pattern[27], so this paper uses import trade data for modeling and analysis. To reduce the impact of marginal trading countries on the global trade pattern, this paper eliminates edges with trade relations less than 100kg.

Table 1 HS code, description and U235 content of the major in-containing commodities.

Commodity	HS code	Description	U^{235} content
Uranium ores and concentrates	261210	Uranium ores and concentrates	0.03%
Natural uranium	284410	Uranium; natural uranium and its compounds, alloys, dispersions (including cermets), ceramic products and mixtures containing natural uranium or natural uranium compounds	0.71%
Enriched uranium products	284420	Uranium; enriched in U^{235}, plutonium, their compounds, alloys dispersions (including cermets), ceramic products and mixtures containing uranium enriched in U^{235}, plutonium or compounds of these products	3.5%
Depleted uranium products	284430	Uranium; depleted in U^{235}, thorium, their compounds, alloys, dispersions (including cermets), ceramic products and mixtures containing uranium depleted in U^{235}, thorium; compounds of these products	0.3%

Note: U^{235} content is from Lv[34].

2.2 Multi-layer Trade Network Model Construction

The international trade network model of uranium supply chain is *C*=(*V*,*E*), where *V* is the node set of MTCN, and *E* is the edge set between nodes. V_1, V_2, V_3 are the national nodes sets of natural uranium, enriched uranium, and depleted uranium, respectively. E_1, E_2, E_3 are the edges sets of natural uranium, enriched uranium, and depleted uranium, respectively. The sets *V* and *E* of nodes and edges in MTCN consisting of natural uranium, enriched uranium and depleted uranium are:

$$V = (V_1, V_2, V_3) \tag{1}$$

$$E = (E_1, E_2, E_3) \tag{2}$$

In this network, nodes are countries and the total number of nodes is the total number of countries. The edges are the trade relationship between countries. The direction of the edge is the flow direction of uranium and the weight of the edge is the trade volume.

This paper constructs a directed weighted complex network model of the multi-layer supply chain from 2014 to 2023. The MTCN is a matrix with *n* rows and *n* columns, which means that there are *n* countries involved in international trade. w_{ij} is the trade edge of country *i* exports to country *j*. The matrix of the complex network model is:

$$C = (V, E) = \begin{bmatrix} 0 & w_{12} & \cdots & w_{1i} \\ w_{21} & 0 & \cdots & w_{2i} \\ \vdots & \vdots & \ddots & \vdots \\ w_{i1} & w_{i2} & \cdots & 0 \end{bmatrix} \tag{3}$$

2.3 Node Centrality and Importance

(1) Degree Centrality

The degree centrality K refers to the total number of trade relations between the nodes, which is divided into in-degree k_i^{in} and out-degree k_i^{out}, representing the number of import relations and the number of export relations respectively. The higher the degree centrality, the more active a country is in participating in trade. The calculation method is as follows:

$$K = k_i^{in} + k_i^{out} \quad (4)$$

Where a_{ij} represents the actual number of trade relations between node *i* and node *j*.

(2) Closeness Centrality

The closeness centrality refers to the average shortest distance between a node and the rest of the nodes in the network, reflecting the overall trade closeness with other countries. The higher the closeness centrality, the closer the country is to other countries. $d(i,j)$ is the shortest path between node *i* and node *j*. The calculation formula is as follows:

$$\mathrm{CC}_i = \frac{n-1}{\sum_{j=1}^{n} d(i,j)} \quad (5)$$

(3) Betweenness Centrality

Betweenness centrality reflects the intermediary ability of a node as a network medium. It can assess whether a node in the network has an important intermediary role and how this affects the structure and connectivity of the entire network. The larger the betweenness centrality, the stronger the node's control over resources. The calculation formula is as follows:

$$\mathrm{BC}_i = \sum_{s \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}} \quad (6)$$

Where σ_{st} is the total number of topological shortest paths from node *s* to node *t*, and $\sigma_{st}(i)$ is the number of topological shortest paths from node *s* via node *i* to node *t*.

(4) Node Importance

Centrality is an important indicator for evaluating the importance of nodes in complex networks[28]. Degree centrality can measure the importance of a node to a certain extent. However, nodes with the same degree centrality may play different roles in a complex network[29]. Nodes with high closeness centrality and betweenness centrality usually play a critical role in maintaining effective connections between nodes in the network[30]. Hence, this paper measures the importance of a country in the network through degree centrality, closeness centrality, and betweenness centrality. The specific formula is as follows:

$$N_{imp} = \sqrt{N_k + N_{cc} + N_{BC}} \quad (7)$$

Where N_{imp} represents the importance of node *i* in the network, N_k, N_{cc} and N_{BC} are the normalized degree centrality, closeness centrality and betweenness centrality of node *i* respectively.

3. Results

3.1 Trade Patterns Evolution of the MTCN

Figure 1 is the network topology of the MTCN in 2014 and 2023. In the past decade, international trade of the uranium supply chain shows a "boom-to-fade" characterization, with the number of participating countries, trade relations and trade volumes decreasing. The reason is that after the Fukushima nuclear accident in 2011, the safety instability of nuclear power has led many governments around the world to cut nuclear energy, such as Japan, USA, the United Kingdom, South Korea and France[2]. Nevertheless, the main hub countries remain fixed, such as Kazakhstan, China, Canada, USA, France, and Russia. Besides, MTCN is a scale-free network, which the minority countries control the majority trade resource. This is because the countries that uranium demander are mainly concentrated in countries with nuclear power.

In the natural uranium trade network, the exporting countries are mainly concentrated in Kazakhstan and Canada, and the importing countries are mainly China, France, Germany, the United States, etc. The most significant trade flow is Kazakhstan-China, with exports to China reaching 81.1tU in 2023, accounting for 20.4% of the world's total trade volume. Regarding enriched uranium, trade relations are mainly concentrated in countries with nuclear fuel conversion and enrichment capabilities, such as France, Germany, the United Kingdom, and Russia. Although trade relationships have fallen from 72 in 2014 to 40 in 2023, the core countries have not changed. Regarding depleted uranium, the biggest feature is that trade is basically concentrated among a few countries. In 2014, Netherlands-France and Portugal-Spain trade flows were 11.7tU, accounting for 62.9% of total trade. In 2023, it will be concentrated in Spain-Portugal and Slovakia-Hungary, with a trade volume of 9.9tU, accounting for 64.3% of the total. Interestingly, the import-export relationship between Portugal and Spain has shifted over the past decade.

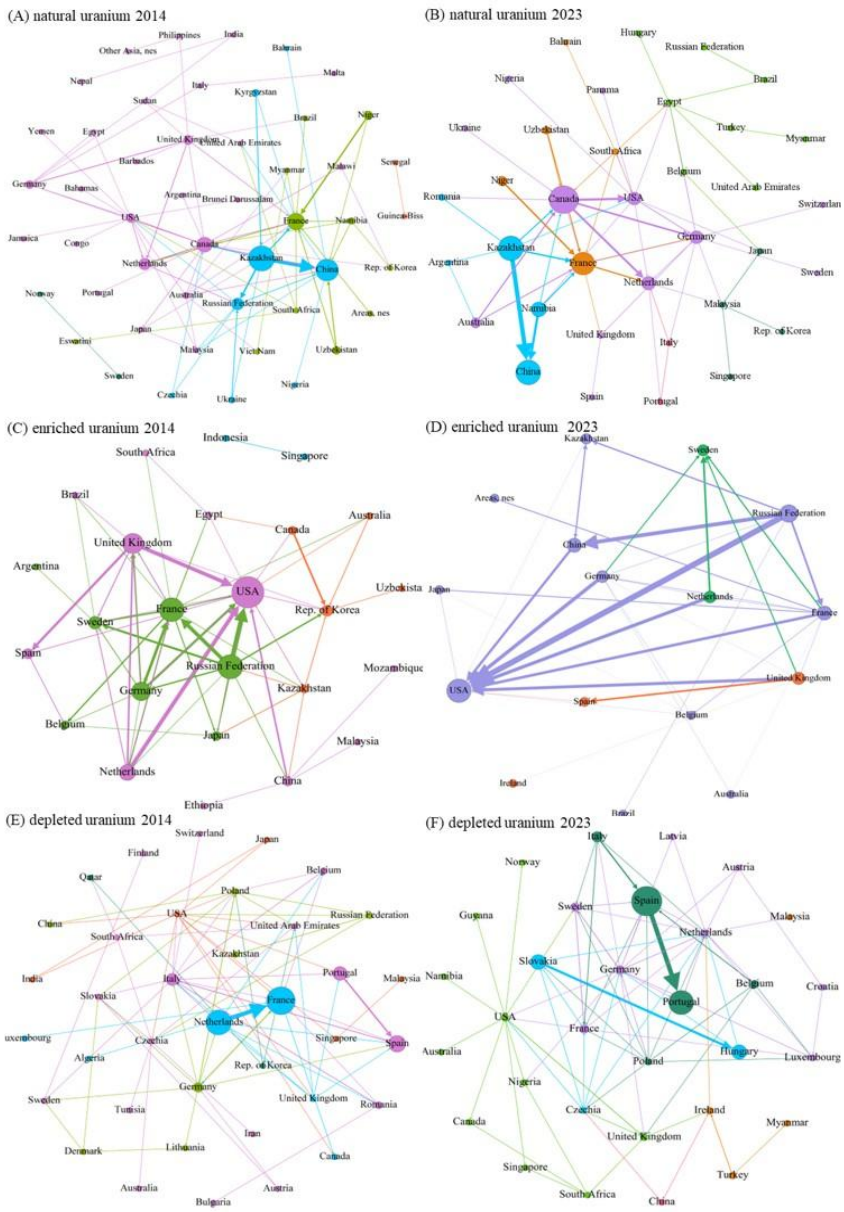

Figure 1 Uranium supply chain trade network in 2014 and 2023. (Note: countries with the same color are in the same community.)

It's worth noting that China has evolved into a major trading country in two links of the supply chain (natural uranium and enriched uranium). During the 13th Five-Year Plan period, China accelerated the construction of domestic nuclear power installed capacity, and by 2023, mainland of China has 55 operational reactors[31]. In addition, the community evolution of MTCN has obvious spatial characteristics. Countries join different trade communities according to their own trade preferences. Asian countries such as China and Kazakhstan are in the same community, while European and American countries are more likely to be in the same community.

3.2 Trade Flows of Uranium

3.2.1 Regional Trade Flows

Figure 2 shows the uranium trade flows of major countries in the world over the past decade, in tons. In the natural uranium network, Kazakhstan, Canada and Australia, as major suppliers, have close trade with several major nuclear power countries, especially China, USA and some European countries. As the largest exporter, Kazakhstan exports 1,503.4tU, mainly to China and Russia. Due to the strong momentum of nuclear power development, China has become the largest importer of natural uranium, with imports reaching 1,303.7tU. Overall, it forms the "Kazakhstan-Canada" supply center and the "China-US-France" demand center. In the uranium enrichment network, the suppliers are mainly Russia, Britain, Germany, France and other countries with nuclear fuel enrichment capabilities. Russia, the world's largest uranium enrichment center, is the biggest supplier of enriched uranium, exporting 513tU in the past decade, which accounts for 26.4% of the world's total exports. USA is the main importer in the enriched uranium market, importing 751.4tU, which accounts for 38.7% of the total imports. The trade in enriched uranium is characterized by centralization, forming a double-circle supply and demand center in Russia-USA. Regarding depleted uranium, the main trade flows are concentrated between Netherlands-France and Portugal-Spain, accounting for 63.3% of the total trade volume. Furthermore, compared with the natural uranium and enriched uranium networks, the trade scale of depleted uranium is significantly smaller than the former two, with a total trade volume of 404.7tU in the past decade.

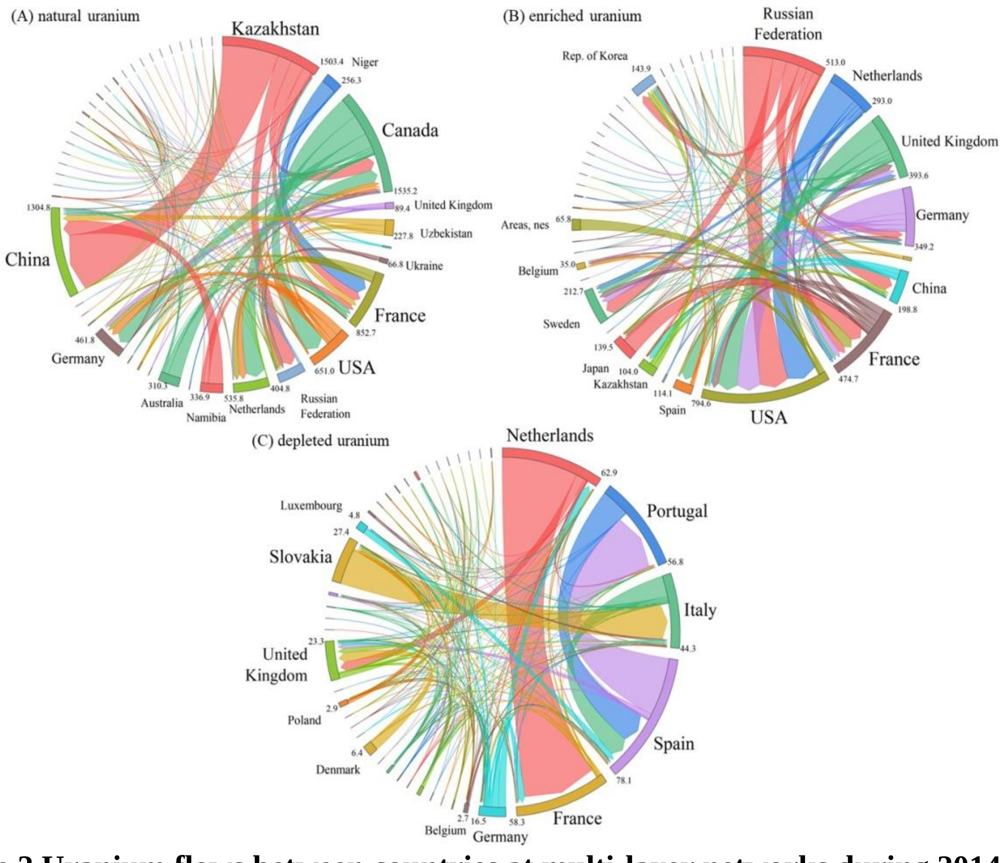

Figure 2 Uranium flows between countries at multi-layer networks during 2014-2023.

3.2.2 Trade Flows in the Industrial Chain

Figure 3 shows the trade flow of uranium along the industrial chain in 2014, 2019 and 2023. Due to the large number of trade relations, this study selects the main trade flows in the supply chain for analysis and filters out trade relations with smaller trade volumes. Generally speaking, the trade scale of uranium shows a trend from large to small along the supply chain with trade mainly concentrated in natural uranium in the upstream, indicating that uranium trade is mainly natural uranium, followed by enriched uranium and depleted uranium. Moreover, the uranium trade was at the highest level in 2014 and reached its lowest level in 2023. The COVID-19 pandemic and the decline in uranium prices had a huge impact on the uranium trading network. It's worth noting that the raw material (natural uranium) is mainly supplied by Kazakhstan and Canada, and flows to Russia, France, Germany, and France for conversion and enrichment, which exports the enriched uranium to major nuclear fuel-demanding countries such as USA and China. In the trade of depleted uranium, only Canada exported 28.9tU to Russia in 2019. After the COVID-19 pandemic, the trade scale of depleted uranium has dropped significantly. The international demand for mid and downstream products is not strong yet. Only certain countries have a high trade demand, and the overall trade level of mid and downstream products is low.

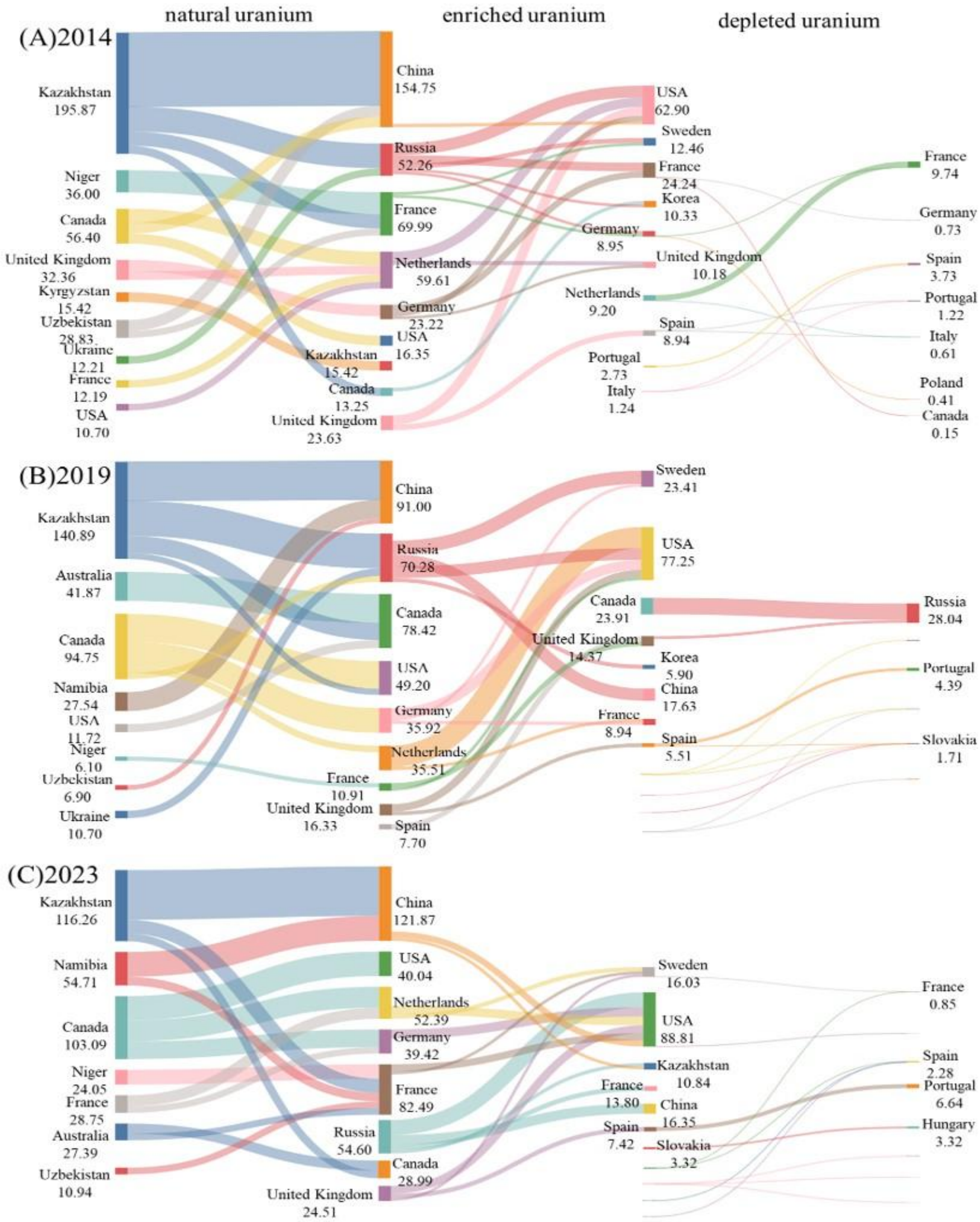

Figure 3 Trade flows of uranium along the industrial chain in 2014, 2019 and 2023.

In the natural uranium trade, Kazakhstan has always been the largest supplier, but the export volume has dropped from 195.9tU in 2014 to 116.3tU in 2023. In the early stage, it mainly flowed to China, Russia, Canada and France. After the Russia-Ukraine conflict, the uranium of Kazakhstan no longer flows to Russia in 2023. It causes that the overall oversupply of uranium in the past decade has resulted in a large amount of inventory, and Russia's uranium raw materials begin to consume domestic stocks. As a non-nuclear country with no conversion capability, Australia, the largest uranium reserves in the world and the fastest growing uranium supplier in East Asia, exports uranium to Canada for conversion[5]. In the trade of enriched uranium, global trade flows have remained basically unchanged. 85% of the world's nuclear fuel is provided by the top ten uranium producers who convert, enrich and manufacture uranium into fuel, and then they export to nuclear power nation[5]. These producers are mainly concentrated in countries such as Russia, France, Germany, Netherlands and the United Kingdom. In particular, Russia and France have monopolized the enriched uranium market since 2000[32].

3.3 Network Centrality

This paper chooses closeness centrality and betweenness centrality to reflect the position of nodes in the trade network and their control over resources. Figure 4 is a heat map of the closeness centrality and betweenness centrality of major trading countries in the uranium supply chain network from 2014 to 2023.

Regarding closeness centrality, countries such as China, Kazakhstan, Russia, Japan, South Korea and USA all have high closeness centrality in the natural uranium trade network, indicating that these countries are in a core position in the network and can trade quickly with other countries. Compared to the upstream network, in trade network, major exporting countries of enriched uranium such as France, Germany, and Russia have a higher closeness centrality, which means that exporting countries are in a core position in this network. In the depleted uranium network, countries such as the United Kingdom, Russia, Slovakia, and France have a high level of closeness centrality, indicating that they play an important role in the processing and reuse of depleted uranium.

Regarding betweenness centrality, Russia, Kazakhstan, France, USA, Netherlands, and Germany all show high betweenness centrality, indicating that developed countries in Europe and USA have a high control over uranium trade. USA has a strong betweenness centrality and plays an essential bridge role in the uranium enrichment trade. However, the mainly enriched uranium suppliers, such as France and Russia, is relatively weak in the control over resources. It is worth noting that China, as a rapidly developing nuclear power country, has poor control over resources in the uranium supply chain, which poses an instability to the construction of its domestic nuclear reactors and the security of uranium.

Generally speaking, Russia has the highest centrality in the three networks, an unmatched giant in the global uranium resource supply chain trade, which shows a critical position in the network. USA, China, and France show significant centrality, have strong control over resources in the network, which play an important hub role in the nuclear fuel supply chain.

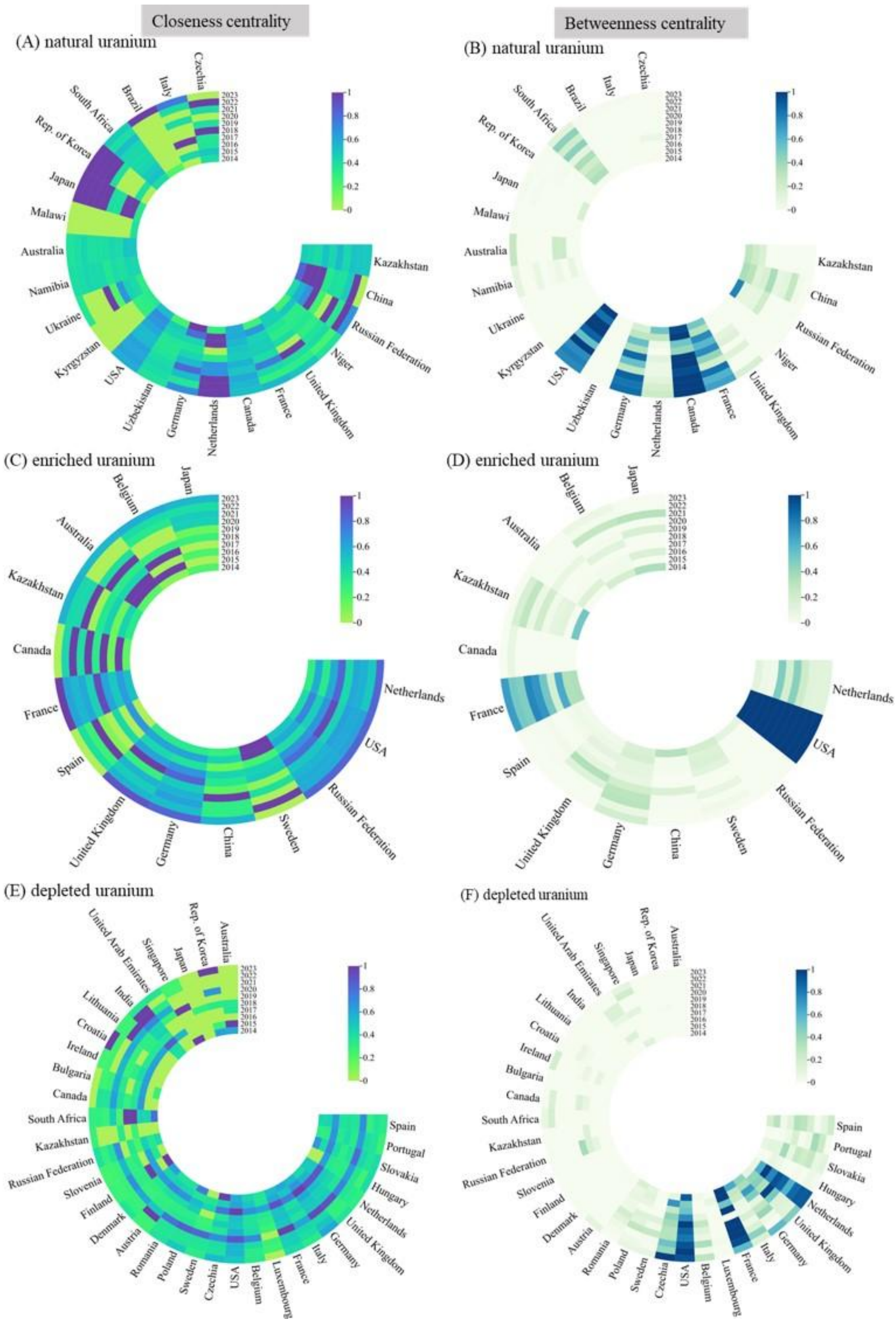

Figure 4 Nodes centrality of major trading countries from 2014 to 2023.

3.4 Node Importance

This paper determines the importance of nodes based on the trade relations (K), trade efficiency (CC) and resource control (BC) of countries in the network. Degree centrality reflects the number of connected edges of a node. Closeness centrality reflects the efficiency of a country in trading with other countries. Betweenness centrality indicates the ability of a node to act as an intermediary in the network, which means the frequency of playing the role of a "bridge" in trade flows. All of them determine the importance of countries in the uranium supply chain trade.

In the natural uranium trade, the node importance of importing countries such as USA, Germany, and France are in the first echelon, showing certain import and export capabilities and relatively strong intermediary capabilities. Kazakhstan, as the largest exporter, is of low importance, indicating that in the trade of raw materials importing countries have a higher control over resources. Interestingly, as China's demand for natural uranium increases, its importance is gradually decreasing. The reason is that China's participation in the natural uranium trade is low, which is concentrated in trade with Kazakhstan. However, Dependence on a single country or region is not conducive to the stability of resource supply.

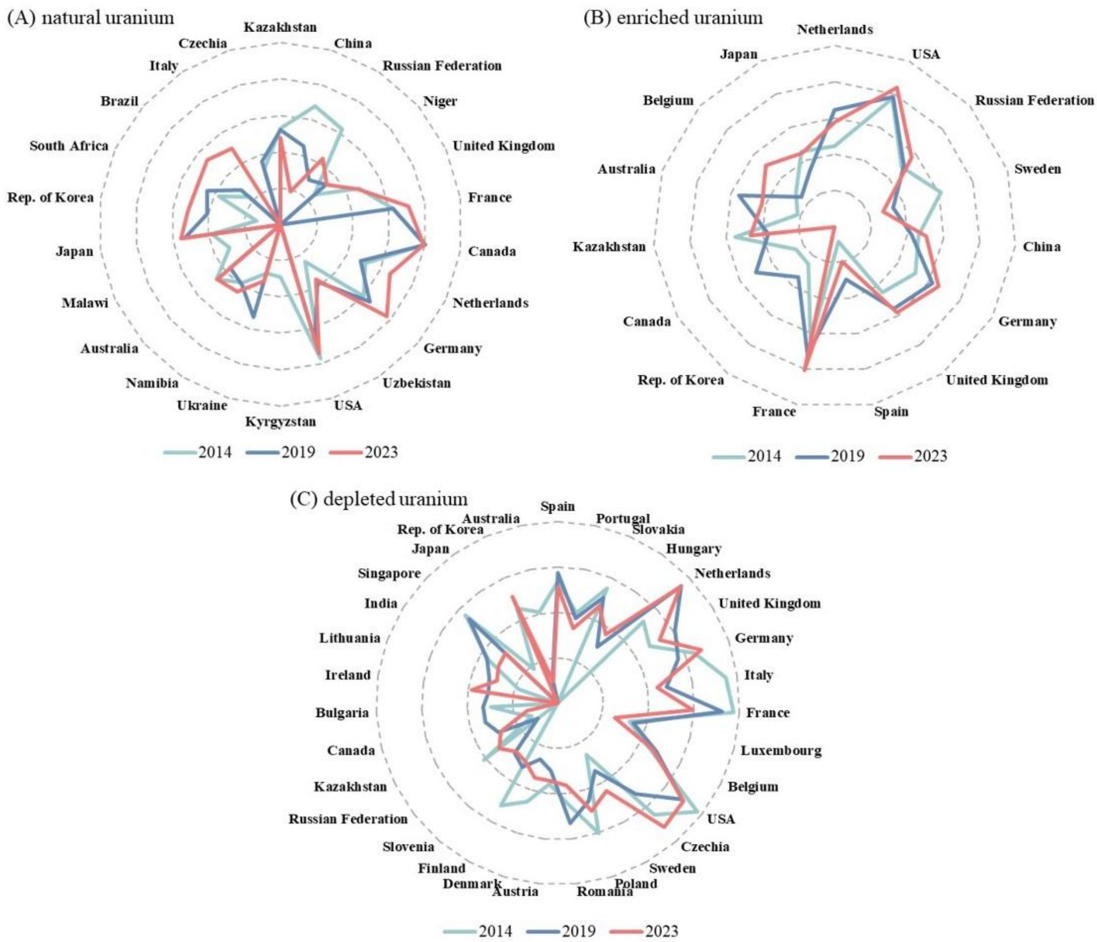

Figure 5 The nodes importance of major trading countries.

Regarding enriched uranium, the most important nodes are also the United States, Germany, and France. As the world's largest supplier of enriched uranium, Russia's control over the enriched uranium market is relatively insufficient, and has basically not changed compared to before and after Russia-Ukraine conflict. Countries such as Germany and the United Kingdom are in the second tier of node importance, causing that these two countries are major suppliers of enriched uranium. It is worth noting that Kazakhstan is also an important country in the trade of enriched uranium. This is mainly because Kazakhstan's new nuclear industry development plan in 2010 has considered building small or large reactors[33]. Since Kazakhstan has no conversion or enrichment facilities, most of its natural uranium is converted and enriched in Russia, and then a certain amount of enriched uranium is returned to Kazakhstan.

In the depleted uranium trade, countries such as USA, Czechia, France, and Netherlands show strong importance, while the importance of other countries is relatively average. Nevertheless, Portugal and Spain, which have large trade volumes, are less important. This is because USA and Czechia have more trade relations in the depleted uranium network and are in a hub position in the network. The largest trade flow of Spain-Portugal has a high trade intensity but weak trade relations and intermediary capacity.

In summary, USA plays a relatively important role in the entire uranium supply chain network. Despite USA is a major importer, it is in a hub position and has strong control over resources. In addition, France, Germany and Netherlands, which have enrichment capabilities, also occupy important positions in the network and have demonstrated a certain voice in the uranium market. Although China's nuclear demand is gradually exaggerating and has occupied an important market share, it is still in a marginal position in the network and its node importance is poor.

4. Conclusions and Policy Implications

Based on the uranium product trade data from 2014 to 2023, this paper constructs a complex network model of natural uranium-enriched uranium-depleted uranium through complex network methods, and studies the topological characteristics, trade flow, and trade pattern evolution characteristics of the multi-layer chain network of uranium, as well as the importance of major trading countries in the network. The main findings are as follows:

(1) International trade in the global uranium supply chain is of a "boom-to-fade" characterization, with the number of participating countries, trade relations and trade volumes decreasing, while the main hub countries are fixed. China has emerged as an essential participant in the trade of natural and enriched uranium. The multi-layer network of the uranium supply chain is a scale-free network, which the minority countries control the majority trade resource. Meanwhile, the community evolution of MTCN has obvious spatial characteristics, such as China and Kazakhstan are in the same community, while European and American countries are more likely to connect.

(2) The global uranium trade flow shows a significant centralized characteristic, and the trade scale shows a trend from large to small along the supply chain with trade mainly concentrated in natural uranium in the upstream. Besides, it forms the "Kazakhstan-Canada" supply center and the "China-US-France" demand center. The trade in natural uranium has declined significantly, especially as exports from Kazakhstan to Russia were disrupted by Russia-Ukraine conflict. The trade demand for mid and downstream products is weak, and it forms a double-circle supply and demand center in Russia-USA. In contrast, the trade in depleted uranium is relatively small, concentrated between Netherlands-France and Portugal-Spain. Furthermore, the global nuclear fuel supply is highly concentrated in a few countries such as Russia and France.

(3) Russia and USA have demonstrated strong resource control in uranium supply chain trade. Russia occupies a central position in the global uranium market due to its strong enrichment capabilities. Although the United States is a major importer, its hub position in the network and its control over resources are extremely strong. Countries such as France, Germany and the Netherlands that have uranium conversion and enrichment capabilities also occupy an important position and have a certain voice. Meanwhile, despite its growing nuclear demand, China remains marginal in the uranium supply chain network and has limited influence in the global uranium market.

Based on the results, and taking into account the particularities of uranium and trade characteristics, the following recommendations are made for national trade in the uranium supply chain: firstly, as the global uranium trade flow has a significant centralized characteristic, it shows a certain monopoly pattern in both natural uranium and enriched uranium. It is recommended that major nuclear fuel demanding countries increase the diversification of import sources. Australia and Canada are important resource suppliers. In particular, as a non-nuclear country, Australia is a potential trading partner. Secondly, importing countries have greater control in the uranium supply chain trade. It is recommended that major exporting countries establish an intergovernmental organization similar to OPEC to jointly develop and promote a sustainable supply system for the uranium industry. Finally, Europe and north America have basically formed a supply pattern of the entire supply chain. It is recommended that China accelerate the development of mid and downstream product capabilities and enhance uranium enrichment capabilities so as to ensure a stable and secure supply of resources when the demand for nuclear fuel expands in the future.

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Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

Chunlei Cao: Writing–original draft, Methodology, Formal Analysis, Writing–review & editing; Guoliang Peng: Conceptualization, Methodology, Writing–review & editing.

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