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The Ownership Network of Global Lithium Resource Supply Chain: How Company Ownership and Capital Ownership Reshape Lithium Geopolitics in the Energy Transition

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The Ownership Network of Global Lithium Resource Supply Chain: How Company Ownership and Capital Ownership Reshape Lithium Geopolitics in the Energy Transition

Abstract

Lithium has emerged as a pivotal factor in the geopolitics of global energy transition, and consequently, the competition for lithium resources among major economies is reshaping the global supply landscape. This study constructs ownership network of global lithium resource supply chain that includes supplying countries, companies, mines, and shareholders; and applies the GeoPolRisk methodology to assess the supply risk of global lithium resources based on company ownership and capital ownership, respectively. Within the global lithium supply system, the United States has consistently occupied a core supply actor, while the role of financial capital has been increasingly prominent since 2023. From a company ownership perspective, the equity production controlled by lithium consuming countries, particularly the United States and China, through investments in overseas mining projects, now surpasses that of the supplying countries. In terms of capital ownership, international financial capital has dramatically reshaped the global lithium resource and production landscape, shifting dominance to the United States and China. In both ownership categories, lithium supply risk has decreased in major consuming countries, with the United States experiencing the greatest reduction.

Key words

Lithium, Supply chain, Supply risk, Company ownership, Capital ownership

1. Introduction

Lithium has become more than a critical mineral, it has become a totemic material that is part of a much larger geopolitical transformation(Sanchez-Lopez, 2023). The widespread deployment of electric vehicles globally is driving significant demand for lithium (Zeng and Li, 2013; Yan et al., 2020). Although sodium-based batteries are under development, it is likely that lithium will remain the metal of choice for the foreseeable future as requirements are relatively independent of specific battery composition (IRENA, 2022). According to the STEPS Scenario, global lithium demand is projected to reach 1200 kt by 2050, marking a six-fold increase from current levels (IEA, 2024).

Recognized as a critical raw material in the clean energy transition, lithium has garnered attention from many countries and regions (EU, 2023; USGS, 2022; Australia,

2023) and become a focal point for various stakeholders. Currently, lithium consumption is concentrated in major economies like China, South Korea, and Japan, while its supply primarily comes from South America, Africa, and Oceania (USGS, 2024), creating an obvious imbalance between global production and consumption. To meet domestic demand, major consuming countries must secure resources through cross-border trade or overseas investment. As a result, the global lithium supply chain has evolved into a network involving countries, companies, shareholders, and mines as key actors. This raises the question: what changes have occurred in the characteristics of the global lithium supply chain ownership network in recent years, and how have the roles of the main supply actors evolved?

To maintain a leading position in the global clean energy transition, the competition for lithium resources among major economies has shifted from open competition to geopolitical rivalry. This intensified competition has driven a significant increase in mergers and acquisitions (M&A) of lithium projects worldwide. In 2020, there were 38 global lithium M&A projects valued at $202 million. By 2022, the number of projects surged to 297, with a total value of $925 million—representing a 682% increase in the number of projects and a 359% increase in value (S&P Global, 2024). Through overseas M&A in lithium mining projects, mining companies have strengthened their resource security, enhanced supply chain resilience, and reduced risks of supply disruptions due to political instability or market volatility in supplier countries. A key question worth exploring is how much these overseas investments have mitigated the supply risks of lithium resources in specific countries.

This study analyzes the characteristics of the global lithium supply chain ownership network using complex network theory, which enables the visualization of different participants within the supply chain. It also allows for the analysis of the overall network structure, community divisions, and the positions of nodes. While many scholars have studied the lithium resource network (Chen et al., 2020; Hu et al., 2021; Shao et al., 2021; Tian et al., 2021; Hao et al., 2023), their focus has generally been on trade patterns, competition dynamics, and the spread of trade risks. Unlike previous studies, this research constructs a global lithium supply chain ownership network based on complex network theory. It analyzes the evolution of the network structure and the changing roles of key supply actors, and discusses how ownership structures influence the global lithium resource landscape.

While the potential supply risks of lithium have been extensively discussed at the national and regional levels (Baars et al., 2021; Sun et al., 2021; Carrara et al., 2023), research at the company level (Tan and Keiding, 2024; Sun et al., 2024) and among company controlling shareholders remains limited. Several studies have addressed these risks using methods such as material flow analysis (Sun et al., 2019c; Song et al., 2019; Geng et al., 2021) , criticality assessments (Nansai et al., 2015; Sun et al., 2019a; Xun et al., 2021), complex network analysis (Nuss et al., 2016; Van Den Brink et al., 2020; Li et al., 2023), and GeopolRisk (Siddhantakar et al., 2023; Cimprich et al., 2017; Cimprich et al., 2018; Santillán-Saldivar et al., 2021; Koyamparambath et al., 2022), among others. We select the GeopolRisk method for evaluating global lithium supply risks because it emphasizes the availability of raw materials rather than their long-term

sustainability. It also accounts for factors such as foreign dependence, political stability, and production concentration, and enables a comparative analysis of supply risks from the perspectives of geographic location, company ownership, and capital ownership.

This study maps the global lithium supply chain ownership network, including lithium mines, companies, controlling shareholders, and the countries associated with these actors from 2012 to 2023. It systematically analyzes the temporal and spatial evolution of the global lithium supply system, while quantitatively assessing the positions of various supply actors —including mines, companies, shareholders, and countries—within the network. The study assesses the position of all supply actors within the supply chain, including mines, companies, shareholders, and countries. We introduce a new perspective on company ownership and capital ownership in the global lithium supply chain and examine the supply risks for major lithium consuming regions such as China, the United States, the European Union, Japan, and South Korea, then compare it with the traditional geographic supply risk. Furthermore, introducing a dual perspective of company ownership and capital ownership for the first time, this research measures the supply risk faced by major lithium-consuming economies—such as China, the United States, the European Union, Japan, and South Korea—under different ownership dimensions. These findings are compared with traditional geographically based supply risk assessments, revealing the significant impact of ownership structures on supply chain resilience.

This study broadens the theoretical connotation of the global lithium resource supply chain by introducing the key actor of corporate controlling shareholders, highlighting the increasingly important role of capital ownership in supply chains. It constructs a dual-dimensional analytical perspective based on company ownership and capital ownership, revealing significant differences in supply risks under different ownership structures. The findings can provide theoretical foundations and decision-making references for lithium resource supply chain management and the formulation of strategies to mitigate risks for importing countries.

2. Methods and data

2.1 Methods

2.1.1 Complex network model

Using complex network theory, this study constructs a global lithium supply chain ownership network (GLON) (Li et al., 2023). The ownership network model consists of a set of nodes (V) and edges (E), represented as GLON = (V, E). Here, nodes V = {vi: i = 1, 2, 3, ..., n} represent the supply actors, while edges E = {ek: k = 1, 2, 3, ..., m} represent the relationships between these actors. The matrix representation of the global lithium supply chain ownership network is as follows:

$$\mathrm{GLON} = (V, E) = \begin{bmatrix} 0 & \omega_{MF} & \omega_{MS} & \omega_{MC} \\ \omega_{FM} & 0 & \omega_{FS} & \omega_{FC} \\ \omega_{SM} & \omega_{SF} & 0 & \omega_{SC} \\ \omega_{CM} & \omega_{CF} & \omega_{CS} & 0 \end{bmatrix} \quad (1)$$

In the model, LM represents global lithium mines, LF represents lithium

producing companies, LS represents shareholders of lithium producing companies, and LC represents countries, which constitute the four types of nodes in the network. Here, ω_{MF} and ω_{FM} represent the edges connecting mines and firms, ω_{MS} and ω_{SM} represent the edges between mines and company shareholders, ω_{MC} and ω_{CM} represent the edges between mines and countries, ω_{FC} and ω_{CF} represent the edges connecting firms and countries, ω_{SF} and ω_{FS} represent the edges between firms and company shareholders, ω_{CS} and ω_{SC} represent countries and company shareholders.

A schematic diagram of the GLON is shown in Figure 1. The weight of each edge is determined by the production of the connected lithium mines. Node size reflects the production capacity of the supply actors, with larger nodes indicating higher production. The width of the edges corresponds to the production scale, with thicker edges representing larger production volumes between connected supply actors.

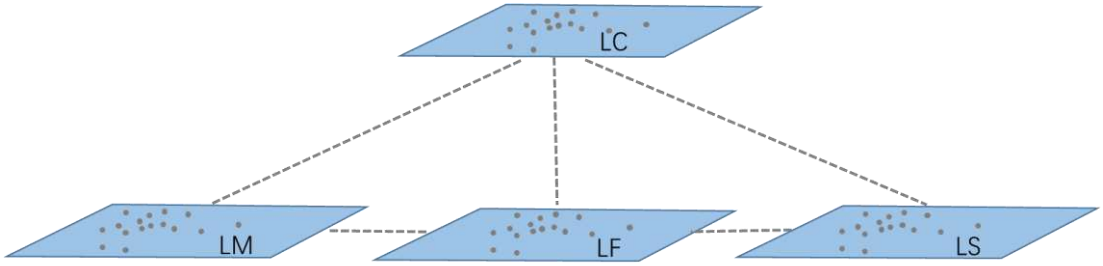


Fig.1. Schematic of the global lithium supply subordinate network（GLON）

2.1.2 Overall network characterization indicators

(1) Community

Networks are divided into communities based on the degree of connectivity and cohesiveness, with the independence between communities measured by modularity. A higher modularity value indicates greater differentiation within the network, while a lower value suggests less differentiation. Modularity values range from -1 to 1. The formula for calculating modularity is shown below.

$$Q = \frac{1}{2m}\sum_{ij}\left[w_{ij} - \frac{w_i w_j}{2m}\right]\delta(c_i, c_j) \tag{2}$$

$$m = \frac{1}{2}\sum_{ij} w_{ij} \tag{3}$$

$$w_i = \sum_{i} w_{ij} \tag{4}$$

Here, w_{ij} denotes the weight of the edge between nodes v_i and v_j; w_i represents the weighted degree of node v_i; c_i is the community assigned to node v_i; $\delta(c_i,c_j)=1$ means that nodes v_i and v_j are in the same community, while $\delta(ci,cj)=0$ is the opposite.

2.1.3 Core-periphery model

The global lithium supply chain ownership network consists of closely interconnected core supply actors and peripheral supply actors, with the latter being

influenced and controlled by the core supply actors. The flows within the global lithium supply chain exhibit a core-periphery structure. To quantify this structure, we use several metrics—coreness, degree centrality, weighted degree, betweenness centrality, and closeness centrality—to assess the importance of supply actors in the network. These indicators are normalized and K-Means cluster analysis is performed to construct a core-periphery model, identifying the role of each supply actor in the lithium supply chain. The calculation for each indicator is as follows:

(1) Coreness

Coreness measures the position of a node within the network. It ranges from 0 to 1, with nodes consistently positioned in the core having higher coreness values. In this study, the coreness of each supply actor in the lithium supply chain is calculated using the "Core/Periphery-continuous" index from the core-periphery model provided by UCINET software.

(2) Degree Centrality

Degree centrality indicates that the more edges a node is connected to, the greater its direct influence and importance within the network. It is the most straightforward measure of a node's significance. The degree centrality of node i is calculated as follows:

$$C_i = \frac{k_i}{2(N-1)} \tag{5}$$

where C_i is the degree centrality of node i, k_i is the degree of the node, and N is the total number of nodes in the network.

(3) Weighted Degree

Weighted degree reflects the production of a node. A higher weighted degree indicates greater production by the supply actor and a more important position within the ownership network.

$$D_i(t) = \sum_{j=1}^{N(t)} w_{ij}(\mathrm{t}) \tag{6}$$

Where $w_{ij}(\mathrm{t})$ represents the weight of the edge from node i to node j, and $N(t)$ is the total number of nodes in the lithium ownership network in year t.

(4) Betweenness Centrality

Betweenness centrality measures the probability that a node lies on the shortest path between two other nodes, reflecting its ability to control the flow of resources in the network. The higher the value, the greater the node's betweenness centrality and its control over the network. The betweenness centrality of node i is calculated as follows:

$$C_{(b)i} = \frac{2}{(n-1)(n-2)} \sum_{p=1}^{n} \sum_{q=1}^{n} g_{pg(i)} / g_{pq} \tag{7}$$

Where g_{pg} is the shortest path between nodes p to q.

(5) Closeness Centrality

Closeness centrality indicates the central position of a node in the network. The more centrally located a supply actor is, the shorter its total distance to all other nodes. A higher value indicates greater closeness centrality and a more central position within the network. The formula for the closeness centrality of node i is:

$$\mathrm{CC}_i = \frac{n-1}{\sum_{j=1}^{n} d(i,j)} \tag{8}$$

Where $d(i,j)$ denotes the shortest path between node i and node j.

Then, we clustered each supply actor by K-means clustering algorithm in SPSS, and got the clustering results of core supply actors, main supply actors, and periphery supply actors respectively.

2.1.4 Indicators for evaluating the importance of nodes in the network

(1) Eigencentrality

Eigencentrality reflects the importance of a node based on the number and significance of its neighboring nodes. The node with the highest eigencentrality in the network is typically regarded as having the greatest indirect influence. The eigencentrality of node i is calculated as follows:

$$E_i = \frac{1}{\lambda}\sum_{j=1}^{n} A_{ij}x_j \tag{9}$$

Where E_i is the eigencentrality of node i, λ is a constant, A_{ij} is the adjacency matrix of edge weights between node i and node j, x_j is the eigencentrality of node j, and n is the total number of nodes in the network.

(2) Indicators of node importance

The importance of a node, as defined in this study, is calculated based on three metrics: degree centrality, betweenness centrality, and eigencentrality:

$$NS_i = \sqrt[3]{NC_i \times NC_{(b)i} \times NE_i} \tag{10}$$

Where NS_i represents the importance of node i in the network; NC_i, $NC_{(b)i}$, and NE_i are the degree centrality, betweenness centrality, and eigencentrality of node i after normalization. The formulas for normalizing these three metrics are as follows:

$$NC_i = \frac{C_i - \min(C)}{\max(C) - \min(C)} \tag{11}$$

$$NC_{(b)i} = \frac{C_{(b)i} - \min(C_{(b)})}{\max\left(C_{(b)}\right) - \min(C_{(b)})} \tag{12}$$

$$NE_i = \frac{E_i - \min(E)}{\max(E) - \min(E)} \tag{13}$$

where C, $C_{(b)}$, E represent degree centrality, betweenness centrality, and eigencentrality of all nodes in the network, respectively.

2.1.5 Geopolitical Supply Risk Evaluation

We use the Geopolitical Supply Risk (GeopolRisk) method to evaluate the supply risk of lithium minerals and lithium primary products for five economies, China, Japan, South Korea, the United States and the European Union, for the typical years 2012,

2016, 2020 and 2023 during the period 2012 to 2023. These five economies account for over 90% of global lithium consumption and are all net importers of lithium resources. The study maps the global flows of lithium minerals and primary products and evaluates the supply risk for these importing economies.

The GeoPolRisk method is designed to quantify the supply risk of raw materials to a country, region, or group of countries. It measures supply risk from the perspective of a country, region, or company importing a resource from various supply actors in a given year. The method calculates supply risk as a function of global production concentration and the import shares of trade partners, weighted by their political instability. Production concentration is assessed using the normalized Herfindahl-Hirschman Index (HHI) (ranging from 0 to 1) for raw material extraction or processing, while political instability is measured using the Political Stability and Absence of Violence dimension from the Worldwide Governance Indicators (WGI-PV) (Kaufmann and Kraay, 2024) . Later, domestic production was incorporated into the GeoPolRisk formula to account for local production in the supply requirements (Helbig et al., 2016). The formula for calculating GeoPolRisk for material "A" in a given year from the perspective of country "c" is as follows:

$$GeopolRisk_{Ac} = HHI_A \times \sum_i \frac{G_i \times f_{Aic}}{P_{Ac} + F_{Ac}} \tag{14}$$

Where $HHI_A$is the Herfindahl-Hirschman index of mineral A, G_i represents the geopolitical stability of country i, f_{Aic} denotes the imports of commodity A from country i to country c, P_{Ac} represents the production of commodity A in country c, and F_{Ac} represents the total imports of commodity A from country c.

Since negative values cannot be accommodated in the GeoPolRisk method, the WGI-PV is normalized mathematically with the following formula:

$$NG_i = \frac{G_i - \min(G)}{\max(G) - \min(G)} \tag{15}$$

Where G_i represents the geopolitical stability of country i.

The standardized values range from 0 to 1, with a higher score indicating lower political stability in the country.

In this study, P_{Ac} is calculated for three scenarios: the production of commodity A within country c, the production of commodity A by companies based in country c both domestically and through overseas investments, and the production of commodity A by shareholder companies associated with country c. The GeoPolRisk values range from 0 to 1, where 0 represents an ideal situation with no risk, and 1 indicates a high risk of supply disruption, representing the proportion of imported raw materials at risk of supply disruption.

2.2 Data

The research subjects in the global lithium supply chain ownership network include lithium mines in production, lithium mining companies, shareholders of these companies, and the countries associated with these supply actors. Specifically, the country of the lithium mining company and the country of the company's shareholders are defined based on the headquarters of the company or shareholders. Production data

for lithium mines, lithium mining companies, and shareholders of lithium companies, as well as information about the company to which a lithium mine belongs, the country of the mine, the country of the company, the company's shareholders, and the country of the shareholders, are sourced from S&P Global. Although there are slight differences between S&P Global's lithium production data and those from USGS, S&P Global remains the primary source for comprehensive production data on mines, companies, and shareholders. In this study, only lithium mines, lithium mining companies, their shareholders, and corresponding countries with production greater than 100 tons are included, excluding supply actors with smaller production. The political instability indicator (WGI-PV) is obtained from the World Bank (World Bank, 2024), which measures a country's governance on a scale from -2.5 to 2.5 (low to high) (Kaufmann and Kraay, 2024). Global lithium resource trade data is from UN Comtrade. The time frame for the data in this study spans from 2012 to 2023.

A company's shareholders may be from the same country or from other countries, and they may include the parent company or other entities such as asset management firms, hedge funds, venture capital firms, governments, and individuals. It is important to note that some asset management or investment companies may hold stakes in lithium mining companies purely for financial investment purposes, seeking returns without having the right to allocate equity resources volume and equity production. In this study, to compare the equity production of shareholders from different countries, it is assumed that all shareholders have access to the corresponding equity production based on their shareholding. If shareholder information for a lithium mining company is unavailable, we assume that 100% of the company's shareholders are from the country where the company is located. Additionally, since some shareholder information for Chinese lithium mining companies is not available, we assume that shareholders of these companies are primarily from China. As a result, Chinese shareholders are categorized under "China Firms," leading to higher equity production and influence for Chinese shareholders in the study.

3. Results and analysis

3.1 Evolution of global lithium supply chain ownership network pattern

3.1.1 Changes in the number of supply chain actors

The supply actors in the global lithium supply chain ownership network include lithium mines, lithium mining companies, shareholding shareholders of lithium mining companies, and the countries to which these supply actors belong. Fig. 2 illustrates the changes in supply actors within the GLON. From 2012 to 2023, the number of global lithium supply actors increased from 149 to 400. Specifically, the number of lithium mines in production rose from 15 to 38; the number of lithium mining companies grew from 14 to 35, dominated by Australia, China, the USA, and Chile; the number of shareholders in lithium mining companies expanded from 100 to 302, with a significant increase in investing companies; the number of lithium-producing countries increased from 8 to 9. Although the number of countries remained relatively stable, when considering both lithium mining companies and their shareholders, the total number of

countries involved in the global lithium supply chain rose from 15 to 26.

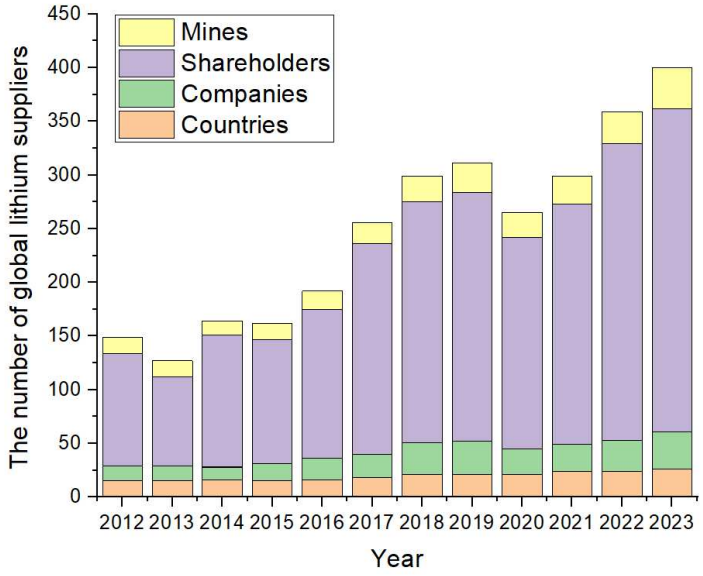


Fig.2. Changes in the number of global lithium supply chain actors in 2012-2023

3.1.2 Change in production of supply chain actors

From 2012 to 2023, global lithium production increased from 175 kt to 996 kt (LCE, the same hereafter), a rise of 469%. Fig. 3 compares lithium production by the country of the lithium mine, the country of the lithium mining company, and the country of the lithium mining company's shareholders in the GLON for the years 2012, 2016, 2020, and 2023, respectively.

The countries of global lithium mines reflects the geographic location of global lithium producers. As shown in Fig. 3, global lithium production has been dominated by Australia and Chile. Since 2013, Australia has replaced Chile as the world's largest lithium producer, which is due to the high quality of Australian spodumene and mature mining industry (Sun et al., 2019c), and the rapid expansion of spodumene mining business. Chile remains the second-largest producer, primarily extracting lithium from salt lakes. China's lithium resources are mainly located in Qinghai, Jiangxi, Sichuan, and other regions. However, due to high costs and environmental concerns, these resources have not been fully developed, and China ranks third in global lithium production.

The countries of global lithium mining companies reflects the company ownership of lithium mining project assets. As shown in Fig. 3 Australia, China, the United States, and Chile have consistently ranked among the top four producers at the company level, although this differs from the country of the mines. While the majority of the world's lithium mines are geographically located in countries such as Australia and Chile, American and Chinese companies have reshaped the global landscape through overseas investments. From 2012 to 2023, the share of lithium production controlled by domestic companies in Australia decreased from 100% to 45%, while in Chile, it fell from 42% to 18%. The United States made investments in Chile's Atacama Salt Lake in 1980 and Australia's Greenbushes mine in 2014, with 97% of its lithium production acquired through overseas investments by 2023. China began investing in overseas lithium mines

in 2013 to support the rapid growth of its domestic new energy vehicle industry. After a decade of development, about half of China's lithium production in 2023 will come from domestic sources, with the other half sourced from regions such as Australia and Zimbabwe.

The countries of shareholders in global lithium mining companies reflect the capital ownership of lithium project assets. As shown in Fig. 3, at the shareholder level, the top producers have shifted from the United States, China, Canada, and Chile to primarily the United States and China. This marks a significant difference when compared to the countries where the mines and companies are located. International financial capital has greatly altered the global lithium resources and production landscape. Although domestic lithium production in the United States accounts for less than 1% of global production, financial capital from firms such as BlackRock Inc. and Vanguard Group Inc. has invested not only in companies like Albemarle Corporation but also in large lithium mining operations in countries like Australia, Chile, and Argentina. As a result, the United States ranks first in terms of capital ownership. Unlike in the United States, about three-quarters of the production owned by Chinese lithium mining company shareholders comes from domestic companies, with only one-quarter derived from overseas equity investment firms.

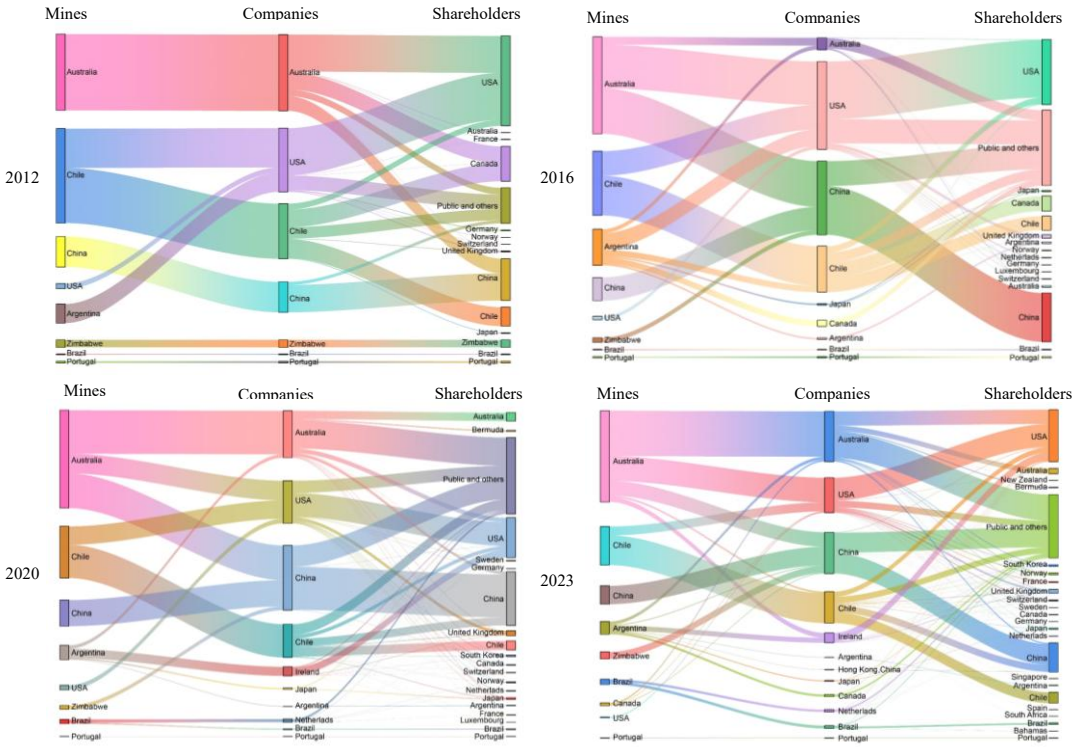


Fig.3. A comparison of global lithium production in 2012, 2016, 2020, and 2023 across the countries where lithium mines are located, where lithium mining companies are headquartered, and where the shareholders of lithium mining companies are based

3.1.3 Evolution of ownership network community

The global lithium supply chain ownership network exhibits clear community differentiation characteristics, typically forming 4 to 6 major communities. Fig. 4 illustrates the evolution of these communities in GLON from 2012, 2016, 2020, to 2023.

The evolution reflects a trend of gradual regionalization, starting with a single dominant community and evolving into multiple jointly-dominated communities. In 2012, the global lithium supply chain ownership network was primarily structured around a community dominated by the United States, with smaller communities representing major producers like Australia and Chile, and major consumers like China. After Chinese companies began investing in overseas lithium mines in 2013, a merger and reorganization of the communities occurred in 2016, resulting in a structure dominated by the United States, China-Australia, and Argentina. This shift was largely due to Tianqi Lithium's acquisition of a stake in Australia's Greenbushes mine, merging China and Australia into the second-largest community. By 2020, as the number of Chinese and Australian supply actors grew, China and Australia formed separate communities, with the global lithium supply chain now dominated by Australia, the US, and China. In 2023, the community structure will have further evolved, resulting in a regionalized supply pattern. Major lithium-producing and consuming countries will have formed their own communities, with the structure dominated by China, Argentina, the United States, Australia, and Chile.

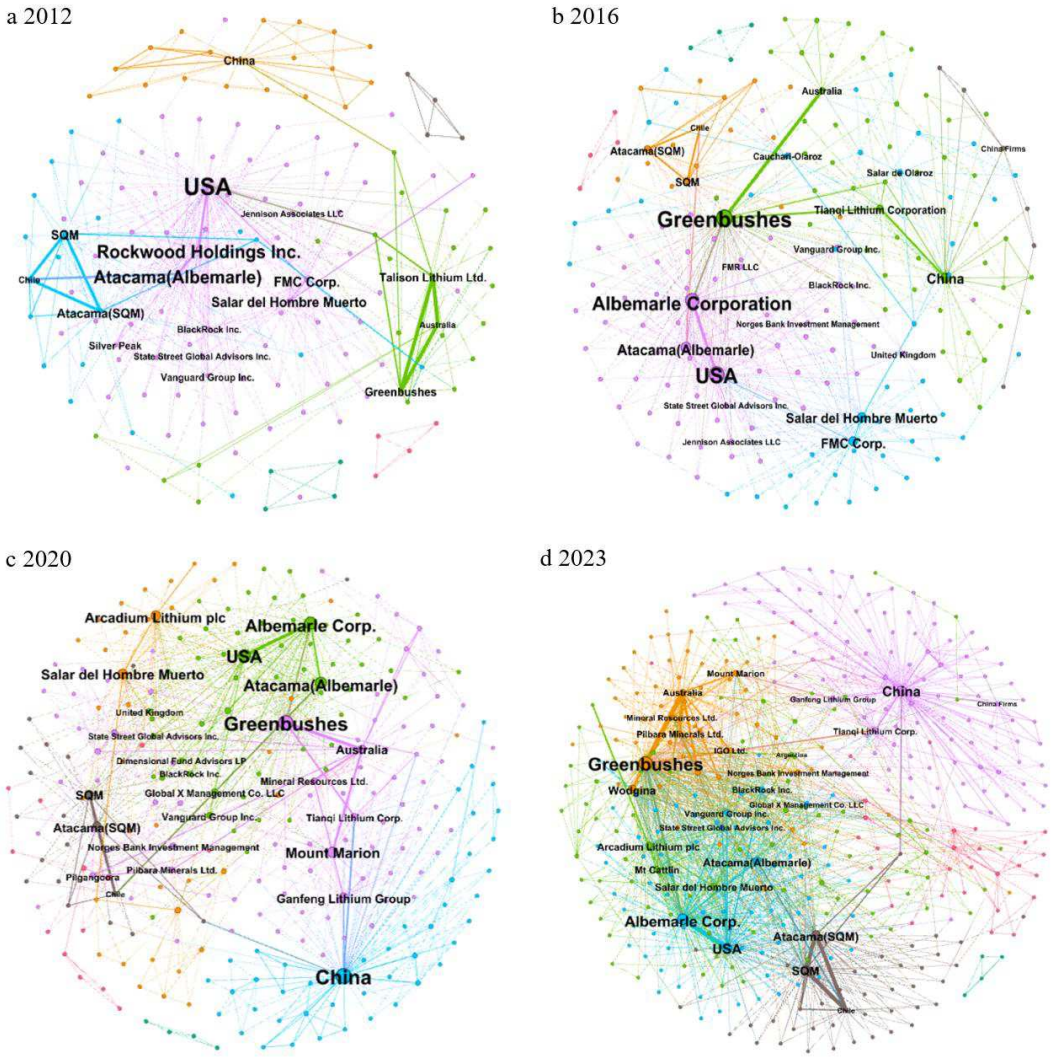


Fig.4. Evolution of the GLON community structure

3.2 Core-periphery structure of the GLON

3.2.1 Comparison of core-periphery supply actors structures

In the core-periphery model, we first calculate and normalize the coreness, degree centrality, weighted degree, betweenness centrality, and closeness centrality of each country from 2012 to 2023. Using the normalized indicators, we then apply the K-means clustering algorithm in SPSS to rank each supply actor, resulting in three clusters: Core, Major, and Periphery. Table 1 presents the coreness, degree centrality, weighted degree, closeness centrality, and betweenness centrality for each level in the core-periphery model.

As shown in Table 1, core supply actors excel in coreness, degree centrality, weighted degree, and closeness centrality, indicating their dominant position in the network, high activity, and strong control. Major supply actors perform well in coreness, degree centrality, weighted degree, and betweenness centrality, demonstrating active connections with other supply actors and a certain level of control. Although peripheral supply actors show high closeness centrality in some years, their coreness, degree centrality, weighted degree, and betweenness centrality are generally low, reflecting their weak control in the ownership network. Closeness centrality and betweenness, as reference indicators in the core-periphery model, cannot independently determine the core status of supply actors.

Table 1 Statistical summary of five indicators at the core-periphery model

	Centrality	Coreness	Degree	Weighted Degree	Closeness	Betweenness
2012	Core	0.07	1.00	0.75	0.49	0.45
	Major	0.04	0.43	0.62	0.33	0.10
	Periphery	0.04	0.09	0.21	0.27	0.03
2016	Core	0.41	0.87	0.75	0.46	0.16
	Major	0.21	0.23	0.52	0.34	0.06
	Periphery	0.03	0.02	0.01	1.00	0.00
2020	Core	0.22	0.86	0.73	0.41	0.18
	Major	0.12	0.40	0.72	0.37	0.07
	Periphery	0.01	0.05	0.02	0.31	0.00
2023	Core	0.23	0.60	0.61	0.41	0.08
	Major	0.11	0.24	0.21	0.38	0.02
	Periphery	0.00	0.03	0.01	0.32	0.00

3.2.2 Evolution of the core-periphery structures

To further understand the evolutionary characteristics of the global lithium supply chain ownership network's core-periphery structure, this study selects 2012, 2016, 2020, and 2023 as representative years and maps the core-periphery structure for each of these years.

As shown in Fig. 5, although the core supply actors have shifted over the four years, the USA has consistently remained in the core position. In 2012, the USA was the sole core supply actor. However, by 2016, the core supply actors expanded to include the USA and Albemarle, following Albemarle Corporation's investment in the

Greenbushes mine in Australia in 2014. In 2020, the core actors diversified to include major lithium producers Chile and China, alongside the USA, Albemarle Corporation, and the Greenbushes mine. By 2023, the core supply actors included the USA, China, Australia, Albemarle Corporation, SQM, the Greenbushes mine, and the Atacama (SQM) mine. Although the United States is not the world's largest lithium producer, its investments in high-quality lithium mines worldwide, along with financial capital in major lithium mining companies, have established it as a core supply actor. Other core supply actors include Australia, Chile, China, and major producers such as Albemarle, SQM, the Greenbushes mine, and the Atacama mine (SQM).

Major supply actors in the global lithium supply chain primarily consist of lithium-producing countries, large mining companies, and major lithium mines. However, the inclusion of shareholders from lithium mining companies in 2023 highlights the growing influence of financial capital in the lithium supply chain. As shown in Fig. 6, in 2012, the major supply actors included three countries—Australia, Chile, and China—along with three companies: SQM, Rockwood Holdings Inc., and Talison Lithium Ltd., and three mines: Atacama (SQM), Atacama (Albemarle), and Greenbushes. In 2016 and 2020, the number of major supply actors adjusted to 10 and 9, respectively, though they were still dominated by major lithium-producing countries, mining companies, and mines. By 2023, the number of major supply actors increased to 18, with the inclusion of three American investment firms—BlackRock Inc., State Street Global Advisors Inc., and Vanguard Group Inc.—as well as SQM's largest shareholder, Chile’s Inversiones SQYA S.A. This shift demonstrates that while the USA remains a core supply actor, American financial capital's influence over the major supply actors has significantly increased.

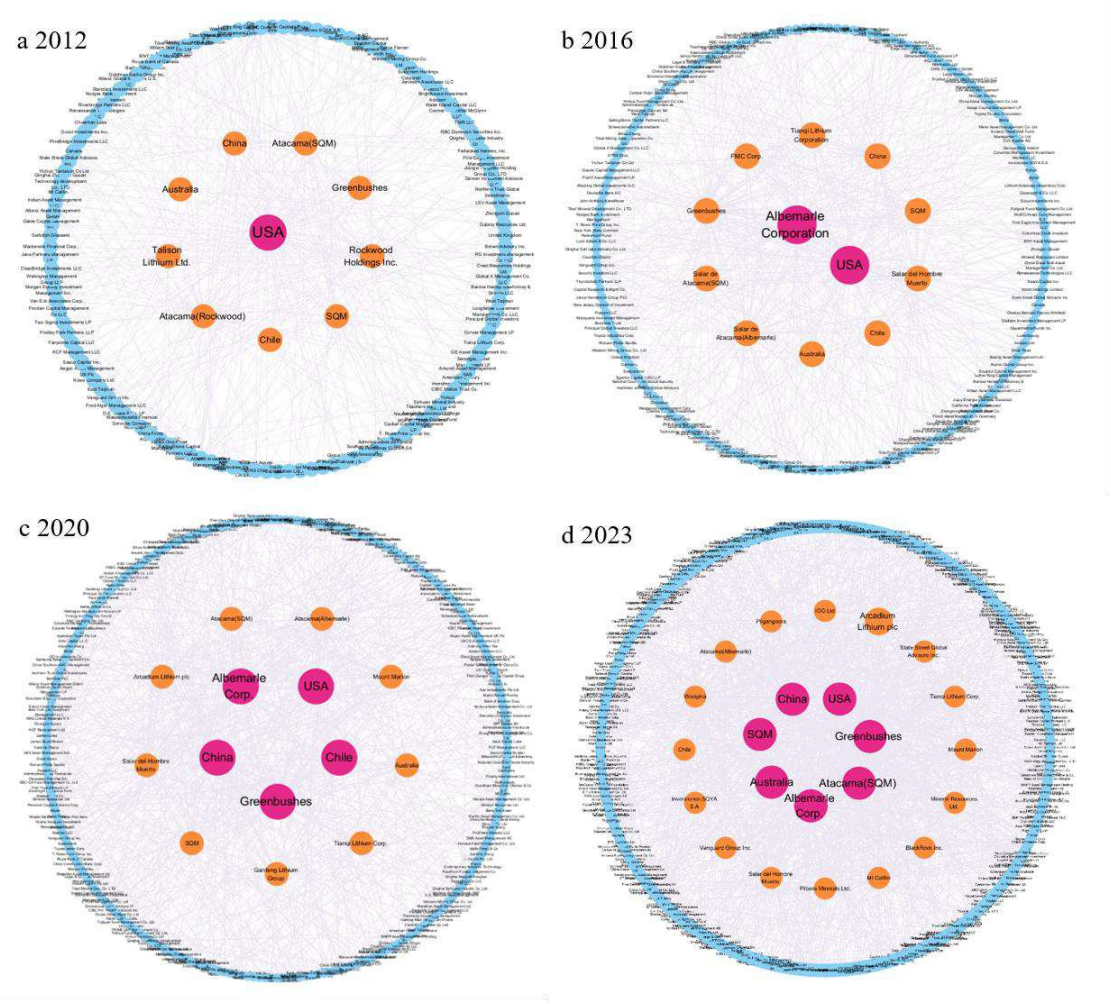


Fig.5. Comparison of core-periphery structures of GLON in 2012, 2016, 2020 and 2023

3.3 Identify important supply actors in the GLON

We further evaluate the position of global lithium mining companies, shareholders of lithium mining companies, and the countries of each supply actor in GLON.

3.3.1 Identify important lithium mining companies

From 2012 to 2023, a total of 60 lithium mining companies were involved in the GLON, including 31 Chinese companies, 12 Australian companies, 5 American companies, 2 companies each from Canada and Brazil, and one company each from Chile, Zimbabwe, Argentina, and other countries. Table 2 shows that the top five global lithium mining companies in terms of importance from 2012 to 2023 are predominantly from the United States, China, Australia, and Chile. These include U.S. companies Albemarle, Livent, and Rockwood; Chile's SQM; Chinese companies Tianqi, Ganfeng, and Salt Lake; and Australian companies Galaxy, Mineral Resources, and Pilbara.

Based on the frequency of appearance of the top five companies, U.S. companies (including Arcadium Lithium) appeared 24 times; Chinese companies appeared 13 times; Chilean companies appeared 12 times; Australian companies appeared 11 times (including Arcadium Lithium); and Canadian companies appeared once. The top global lithium company in terms of importance is either Rockwood or Albemarle, indicating

that while there are fewer American lithium companies, they hold the most influence and control within the ownership network. In contrast, Tianqi, Ganfeng, and Salt Lake rank relatively low, suggesting that while China has the largest number of lithium mining companies globally, their company sizes are smaller compared to major players in the United States, Chile, and Australia. Additionally, their connections with various supply actors in the network are not as strong as those of American companies, and the actors they are connected to hold less importance and control.

Table 2 Ranking of the importance of lithium mining companies in 2012~2023

	1	2	3	4	5
2012	Rockwood (USA)	FMC (USA)	Talison (Australia)	SQM (Chile)	Galaxy (Australia)
2013	Rockwood (USA)	FMC (USA)	SQM (Chile)	Galaxy (Australia)	Salt Lake(China)
2014	Rockwood (USA)	FMC (USA)	Tianqi (China)	SQM (Chile)	Salt Lake(China)
2015	Albemarle (USA)	FMC (USA)	Tianqi (China)	SQM (Chile)	Lithium Americas(Canada)
2016	Albemarle (USA)	FMC (USA)	SQM (Chile)	Tianqi (China)	Allkem Limited (Australia)
2017	Albemarle (USA)	Mineral (Australia)	FMC (USA)	SQM (Chile)	Tianqi(China)
2018	Albemarle (USA)	FMC (USA)	SQM (Chile)	Mineral (Australia)	Tianqi(China)
2019	Albemarle (USA)	Arcadium (Ireland)	Tianqi (China)	SQM (Chile)	Galaxy(Australia)
2020	Albemarle (USA)	Arcadium (Ireland)	Ganfeng (China)	SQM (Chile)	Mineral(Australia)
2021	Albemarle (USA)	SQM (Chile)	Arcadium (Ireland)	Ganfeng (China)	Pilbara(Australia)
2022	Albemarle (USA)	SQM (Chile)	Livent (USA)	Tianqi (China)	Ganfeng (China)
2023	Albemarle (USA)	SQM (Chile)	Arcadium (Ireland)	Tianqi (China)	Pilbara(Australia)

Note: Livent Corporation was formerly known as FMC Corporation.

3.3.2 Identify important lithium mining companies's shareholders

Between 2012 and 2023, a total of 673 shareholders of lithium mining companies were involved in the GLON. These shareholders are primarily asset management firms and investment funds, but also include governments and individual investors. By country, the United States has the largest number of shareholders, with 286, followed by China with 131. Other notable investors come from Australia (73), the United Kingdom (45), Canada (25), Chile (21), France (13), and Japan (12), with fewer investors from other countries.

As shown in Table 3, from 2012 to 2023, the top ten shareholders in global lithium mining companies, ranked by importance, were predominantly American, with some shareholders from Norway, the UK, China, and South Korea. In terms of frequency, American capital companies or investment banks appeared 89 times, Norwegian companies 10 times, British companies 7 times, Chinese and South Korean companies 5 times each, German companies appeared twice, while Swiss, Swedish, French, and Bermudian companies each appeared once. Between 2012 and 2023, the most influential shareholder in global lithium mining companies was Vanguard Group Inc., ranking first for six years, followed by BlackRock Inc. for five years, and Norges Bank Investment Management for one year. The second-ranking shareholders included Vanguard Group Inc. (4 years), BlackRock Inc. (3 years), Global X Management Co. LLC (3 years), FMR LLC (1 year), and Norges Bank Investment Management (1 year). This indicates that American investment companies not only have the largest number

and control the highest share of lithium production but also hold absolute control within the lithium supply chain. The strong control of American investment firms reflects their extensive connections with numerous supply actors, their high influence on neighboring actors, and their ability to serve as bridges between other supply actors.

3.3.3 Identify important lithium producing countries

In the GLON, lithium mines, mining companies, and their shareholders are involved in a total of 30 countries and regions. As shown in Table 4, from 2012 to 2023, the United States ranked first in terms of the importance of global lithium supply actors for nine years, with China ranking first for three years. China ranked second for nine years, while the United States ranked second for three years. Australia and Chile, the world's leading lithium resource holders and producers, ranked next.

Although the United States has only one domestic lithium mine in production, its companies and shareholders play a significant role in the supply chain, giving it the strongest control among supply actor countries. In recent years, China has not only developed its domestic lithium resources but also invested in several overseas lithium mining projects, increasing its importance in the supply chain. While the United Kingdom has limited lithium resources and has not invested in overseas mining projects, British shareholders have invested heavily in lithium mining companies, placing the UK among the top five. This shows that, through overseas investments and equity holdings, lithium-consuming and investing countries have become more influential in the supply chain than resource and producer countries like Australia and Chile.

Table 4 Ranking of the importance of countries in global lithium supply actors in 2012~2023

	1	2	3	4	5
2012	USA	China	Chile	Canada	Australia
2013	USA	China	United Kingdom	Australia	Chile
2014	USA	China	United Kingdom	Chile	Canada
2015	USA	China	Argentina	Australia	Chile
2016	USA	China	Australia	United Kingdom	Chile
2017	USA	China	Australia	United Kingdom	Chile
2018	USA	China	Australia	United Kingdom	Chile
2019	USA	China	Australia	Chile	United Kingdom
2020	China	USA	Australia	United Kingdom	Chile
2021	China	USA	Australia	United Kingdom	Chile
2022	USA	China	Australia	United Kingdom	Chile
2023	China	USA	Australia	United Kingdom	Chile

Table 3 Ranking of the importance of global lithium mining company's shareholders in 2012-2023

	1	2	3	4	5	6	7	8	9	10
2012	Vanguard Group Inc.(USA)	BlackRock Inc.(USA)	Jennison Associates LLC(USA)	State Street Global Advisors Inc.(USA)	Morgan Stanley Investment Management Inc.(USA)	T. Rowe Price Group Inc.(USA)	Northern Trust Global Investments(United Kingdom)	William Blair Investment Management LLC(USA)	Columbia Wanger Asset Management LLC(USA)	Iridian Asset Management LLC(USA)
2013	Vanguard Group Inc.(USA)	BlackRock Inc.(USA)	China Firms(China)	Columbia Wanger Asset Management LLC.(USA)	Northern Trust Global Investments(United Kingdom)	First Eagle Investment Management LLC.(USA)	Iridian Asset Management LLC.(USA)	T. Rowe Price Group Inc..(USA)	BNY Asset Management.(USA)	FMR LLC.(USA)
2014	BlackRock Inc.(USA)	Vanguard Group Inc.(USA)	Norges Bank Investment Management(Norway)	Northern Trust Global Investments(United Kingdom)	Barrow Hanley Mewhinney & Strauss LLC(USA)	BNY Asset Management(USA)	Geode Capital Management LLC(USA)	State Street Global Advisors Inc.(USA)	Teachers Insurance and Annuity Association-College Retirement Equities Fund(USA)	BTG Pactual Global Asset Management Ltd.(Bermuda)
2015	BlackRock Inc.(USA)	FMR LLC(USA)	Vanguard Group Inc.(USA)	Norges Bank Investment Management(Norway)	Macquarie Investment Management Business Trust(USA)	Northern Trust Global Investments(United Kingdom)	Capital Research & Mgmt Co.(USA)	Columbia Management Investment Advisers LLC(USA)	State Street Global Advisors Inc.(USA)	BNY Asset Management(USA)

2016	BlackRock Inc.(USA)	Vanguard Group Inc.(USA)	FMR LLC(USA)	Norges Bank Investment Management(Norway)	Capital Research & Mgmt Co.(USA)	Jennison Associates LLC(USA)	State Street Global Advisors Inc.(USA)	Adage Capital Management LP(USA)	Dimensional Fund Advisors LP(USA)	Macquarie Investment Management Business Trust(USA)
2017	Vanguard Group Inc.(USA)	Global X Management Co. LLC(USA)	BlackRock Inc.(USA)	Norges Bank Investment Management(Norway)	Dimensional Fund Advisors LP(USA)	State Street Global Advisors Inc.(USA)	Teachers Insurance and Annuity Association-College Retirement Equities Fund(USA)	Allianz Asset Management GmbH(Germany)	Janus Henderson Group PLC(United Kingdom)	BNY Asset Management(USA)
2018	Norges Bank Investment Management(Norway)	Global X Management Co. LLC(USA)	Vanguard Group Inc.(USA)	BlackRock Inc.(USA)	Teachers Insurance and Annuity Association-College Retirement Equities Fund(USA)	Dimensional Fund Advisors LP(USA)	BNY Asset Management(USA)	State Street Global Advisors Inc.(USA)	National Council for Social Security Fund(China)	Mirae Asset Global Investments Co. Ltd.(South Korea)
2019	Vanguard Group Inc.(USA)	BlackRock Inc.(USA)	Norges Bank Investment Management(Norway)	Global X Management Co. LLC(USA)	Dimensional Fund Advisors LP(USA)	BNY Asset Management(USA)	Van Eck Associates Corp.(USA)	National Council for Social Security Fund(China)	Mirae Asset Global Investments Co. Ltd.(South Korea)	State Street Global Advisors Inc.(USA)

2020	Vanguard Group Inc.(USA)	Global X Management Co. LLC(USA)	Norges Bank Investment Management(Norway)	Dimensional Fund Advisors LP(USA)	BlackRock Inc.(USA)	Handelsbanken Asset Management(Sweden)	State Street Global Advisors Inc.(USA)	BNY Asset Management(USA)	Van Eck Associates Corp.(USA)	GO ETF Solutions LLP(United Kingdom)
2021	Vanguard Group Inc.(USA)	Norges Bank Investment Management(Norway)	Mirae Asset Global Investments Co. Ltd.(South Korea)	BlackRock Inc.(USA)	Dimensional Fund Advisors LP(USA)	Van Eck Associates Corp.(USA)	Allianz Asset Management GmbH(Germany)	State Street Global Advisors Inc.(USA)	ICBC Credit Suisse Asset Management Co. Ltd.(China)	Teachers Insurance and Annuity Association-College Retirement Equities Fund(USA)
2022	BlackRock Inc.(USA)	Vanguard Group Inc.(USA)	Mirae Asset Global Investments Co. Ltd.(South Korea)	Norges Bank Investment Management(Norway)	State Street Global Advisors Inc.(USA)	Dimensional Fund Advisors LP(USA)	Van Eck Associates Corp.(USA)	Geode Capital Management LLC(USA)	Teachers Insurance and Annuity Association-College Retirement Equities Fund(USA)	UBS Asset Management AG(Switzerland)
2023	BlackRock Inc.(USA)	Vanguard Group Inc.(USA)	Global X Management Co. LLC.(USA)	State Street Global Advisors Inc.(USA)	Van Eck Associates Corp.(USA)	Norges Bank Investment Management(Norway)	Dimensional Fund Advisors LP.(USA)	Geode Capital Management LLC.(USA)	Legal & General Investment Management Ltd.(United Kingdom)	Amundi Asset Management SAS(France)

3.4 Evaluation of geopolitical supply risk in major global lithium consuming countries

Figure 6 shows the changes in trade flows and geopolitical supply risk of primary lithium products in China, the United States, the European Union, Japan, and South Korea for the years 2012, 2016, 2020, and 2023. It compares the supply risk based on the geographic location of lithium mines, company ownership, and capital ownership in these five countries. Global exports of primary lithium products are primarily sourced from Australia and Chile, which together account for over 70% of total exports. In this study, a country's overall supply risk is the average of the GeoPolRisk values for the country's mine geographic location, company ownership, and capital ownership. The GeoPolRisk values for primary lithium resources in China, the United States, the European Union, Japan, and South Korea range from 0.01 to 0.2, with the overall supply risk ranked in ascending order as follows: USA, China, European Union, Japan, and South Korea. From 2012 to 2023, the import volume of primary lithium products increased significantly in South Korea, China, Japan, and the United States, growing by 914%, 844%, 197%, and 22%, respectively. The import volume in the EU slightly decreased. However, GeoPolRisk varies by country, with overall supply risk increasing in China, Japan, and South Korea, and decreasing in the United States and the European Union.

The geographic location of lithium mines reflects a country's lithium resource endowment and supply capacity. The supply risk based on mine geographic location, in ascending order, is ranked as follows: China, the United States, the European Union, South Korea, and Japan. As shown in Fig. 4, a significant portion of global lithium production is controlled through overseas investments. Multinational corporations often expand operations across the entire lithium-ion battery (LIB) supply chain, which can significantly reshape national control (Tan and Keiding, 2024). Therefore, countries with higher overseas investments through company ownership and capital ownership may exert greater influence over production. Based on company ownership, in 2023, the United States, the EU, and China controlled 5618%, 3917%, and 210% of domestic lithium production, respectively. Japan also controlled a small portion, while South Korea had no lithium production. The supply risk, ranked from lowest to highest, is as follows: United States, China, European Union, Japan, and South Korea. The geopolitical risk from company ownership in all five economies is lower than that based on mine geographic location. Particularly in the United States, which has made significant investments in high-quality lithium mining projects worldwide, resulting in the largest reduction in geopolitical risk through company ownership. Based on capital ownership, lithium supply risk increases in the following order: United States, China, European Union, Japan, and South Korea. Although capital ownership does not guarantee full access to the corresponding equity production, assuming such access, the United States and China controlled 5870% and 156%, respectively, of global lithium production in 2023. Japan, the European Union, and South Korea also controlled small portions of lithium production. Geopolitical risk decreased in all five economies, with the United States experiencing the largest reduction in risk.

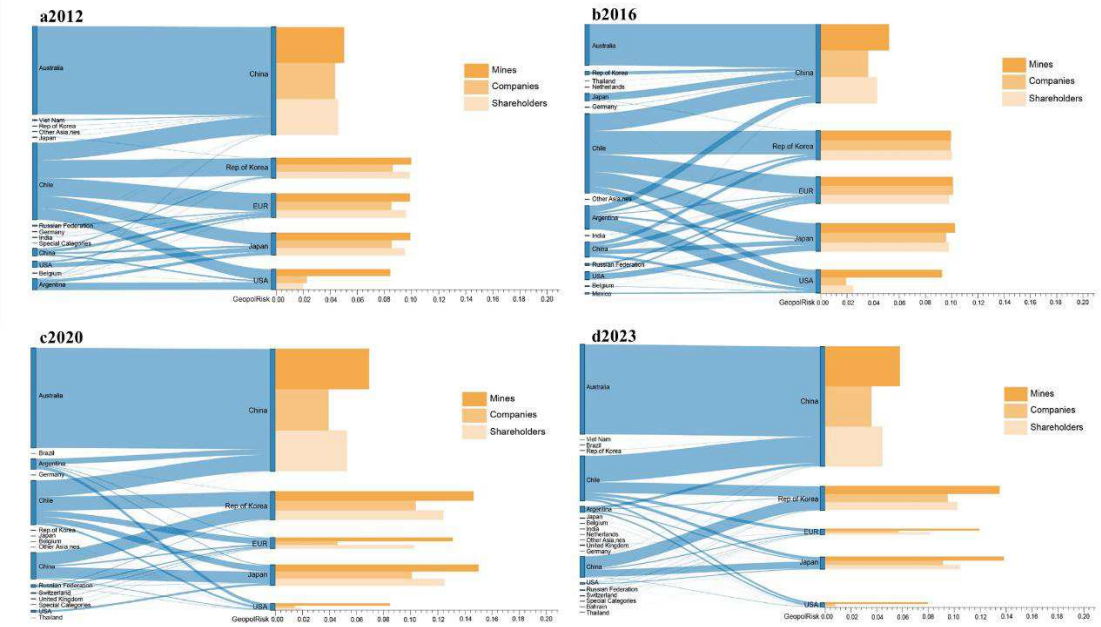


Fig.6. Changes in trade flows and geopolitical supply risks of primary lithium products in 2012, 2016, 2020, and 2023

4. Discussion

The competition for lithium resources among the world's major economies has increasingly shifted into a geopolitical competition driven by the transition to low-carbon energy. In response to this energy transition, governments are placing greater emphasis on securing critical raw materials, offering substantial financial support to enterprises involved in their extraction and processing (Kabeyi and Olanrewaju, 2022). By developing lithium resource strategies, fostering partnerships with resource-rich countries, and establishing resource alliances, major economies have effectively secured their supply chains and mitigated dependence on resource-exporting nations, thereby enhancing the stability of their lithium supply. This study diverges from traditional research, which primarily focuses on geographic factors within lithium supply chain analysis (Sun et al., 2017; Olivetti et al., 2017; Sun et al., 2019a; Bridge and Faigen, 2022). It broadens the analysis by incorporating shifts in company ownership (Tan and Keiding, 2024; Sun et al., 2024) and adding a capital ownership dimension, reflecting the growing influence of financial capital. Financial actors are pivotal in supporting the capital-intensive expansion of mineral extraction, particularly through equity investments, bank loans, and other debt instruments, all of which are critical for sustaining and expanding the resource extraction sector (Adams and Gilbert, 2019).

Lithium's status as a critical mineral has been steadily increasing, with the global lithium supply chain ownership network expanding to include more supply actors, leading to greater complexity. The projected global lithium supply gap has prompted the initiation of numerous new projects, bringing additional players into the mining sector and expanding the overall lithium supply system (Wojewska et al., 2024). Currently, the global lithium supply is concentrated in a few countries, but it is expected

that the industry will become more diversified in the future. Australia and Chile dominate lithium mining today, with production largely reflecting the distribution of reserves and resource endowments. However, this distribution can be reshaped through increased investment in exploration and advancements in mining technologies (Ali et al., 2017). The geographic diversity of global lithium resources is expected to improve as exploration efforts intensify and new mines in Africa, Europe, and North America come online (Silva E., 2023; Mining, 2021). Additionally, the global lithium mining sector is diversifying, with the rise of not only traditional mining companies but also chemical companies such as Albemarle. Since 2022, junior miners have increasingly turned to automakers and battery manufacturers for financing to support the final stages of major project development (Fitch Solutions, 2022).

We focus on studies of lithium supply risk based on company and capital ownership because the mismatch between the distribution of lithium resources and the company ownership and capital ownership is most pronounced in the lithium supply chain. From a company ownership perspective, which differs from lithium mining concentration, American and European companies play a significant role in lithium supply (IEA, 2024). In terms of capital ownership, American financial capital dominates the lithium supply landscape. In the absence of liquid derivative markets that allow direct exposure to lithium price movements, equity ownership has become a primary method for investing in lithium and benefiting from high prices (Wojewska et al., 2024). American financial capital has led investments in lithium mining companies even before the lithium boom, thereby indirectly controlling high-quality lithium mines globally and reaping the rewards of the recent surge in lithium prices. As for the refining stage, lithium production is primarily concentrated in China, Chile, and Argentina, but company ownership is mainly held by China, the United States, and Chile, with relatively low ownership mismatch due to overseas investments. In the cathode materials stage, ownership mismatch is minimal, while in the battery production stage, China's lithium battery manufacturing relies on investments from South Korea, Japan, and the United States (Tan and Keiding, 2024).

Facing limitations in natural and human resources domestically, many companies choose to transfer production capacity abroad through acquisitions and the establishment of overseas factories, thereby effectively reducing supply risk (Sun et al., 2019b; Xun et al., 2022). China, the United States, the European Union, and Japan have all mitigated supply risk to varying extents by investing in lithium mining projects overseas. Among them, the United States has seen the greatest reduction in supply risk. This is largely because the U.S. began mining lithium in the southern Atacama Salt Lake in 1980, and in 2014, Rockwood acquired a 49% stake in Windfield, the parent company of Talison Lithium. Currently, more than 90% of U.S. lithium mine production comes from overseas investments. Mineral capital ownership has received less attention in previous research (Li et al., 2023). This study finds that production based on capital ownership has also led to a decrease in supply risk for China, the United States, the European Union, Japan, and South Korea, with the U.S. benefiting the most from its dominant role in capital ownership. Major economies have implemented policies to support overseas resource development and safeguard resource security. For instance,

South Korea has reintroduced a tax credit incentive system for overseas resource investments and is strengthening cooperation with 30 mineral-rich countries (H. Yin, 2023). However, these overseas investments could limit the availability of raw materials for countries that lack the capacity for foreign investment. Thus, communication and cooperation among stakeholders at both the company and country levels are crucial to avoid or de-escalate geopolitical tensions that may disrupt the global green transition (X. Sun et al., 2024).

Increasing the recycling of lithium resources is crucial for alleviating potential supply pressures. In the NZE scenario, a combination of optimally sized EV batteries, adoption of alternative chemistries, and enhanced recycling could reduce lithium demand by 25% by 2030, with savings roughly equivalent to current production levels (IEA, 2024). Among major economies, China is expected to achieve full lithium recycling more than a decade ahead of Europe and the United States (J. Wesselkämper et al., 2023), meaning that the impact of lithium recycling on supply risk mitigation will be more apparent in China sooner. However, the effectiveness of resource recycling also depends on government policy support and improved business models.

However, this study does have limitations, which may also present opportunities for future research. In this study, the countries considered for company and shareholder location are based on where their headquarters are situated. However, there is ongoing debate about how accurately a company's headquarters can reflect a country's overall production. Since the global lithium recovery rate is currently only 2%, secondary recovery has not been included in the GeopolRisk calculations. As the recovery rate increases, it can be incorporated into future analyses. Additionally, while international financial capital invested in lithium mining companies may increase control over these companies, it is often more focused on investment returns, meaning it may not always correspond to the amount of equity production. Despite these limitations, this study offers a new perspective on capital ownership within supply chain research.

5. Conclusions

This study utilizes global lithium production data from 2012 to 2023 to construct a global lithium supply chain ownership network, applying complex network methodology. It investigates the spatial and temporal evolution, core-periphery structure, and dominant positions within the supply chain. Furthermore, the GeopolRisk method is employed to quantitatively assess the supply risk of five major economies—China, Japan, South Korea, the United States, and the European Union—considering the perspectives of mine geographic location, company ownership, and capital ownership.

The results reveal several key findings: (1) As lithium gains prominence as a low-carbon mineral, the global lithium supply chain ownership network is expanding, incorporating an increasing number of supply actors and growing more complex. This trend is expected to lead to greater diversification within the supply chain, ultimately fostering a more competitive and dynamic market. (2) When considering company ownership, overseas investments are reshaping the global lithium supply landscape. The lithium production obtained globally by the United States and China has surpassed that

of Chile, second only to Australia. American companies hold the greatest influence and strongest control within the network. The United States has been the biggest beneficiary of overseas lithium resource investments in recent years. (3) In terms of capital ownership, international financial capital has played a pivotal role in reshaping the resource and production landscape of global lithium mining, positioning the United States and China as the dominant suppliers. American shareholders hold dominant influence and controlling power within the network. (4) While the core supply actors in the GLON have evolved, the United States has consistently maintained a central position. The emergence of lithium mining company shareholders among major supply actors in 2023 highlights the increasing influence of financial capital in the lithium supply chain. (5) The control exerted by lithium-consuming countries is greater than that of supplying countries, with the United States holding the strongest influence at the company, shareholder, and national levels. (6) Both company and capital ownership indicate a decline in supply risk for China, Japan, South Korea, the United States, and the European Union compared to risks based on geographic location, with the most significant reduction observed in the United States. The study shows that overseas and equity investments in mineral resources effectively reduce a country's supply risk.

CRediT authorship contribution statement

Pengyuan Li: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Zhe Ma:** Writing – review & editing, Conceptualization. **Hongchang Hao:** Visualization, Methodology. **Jiangqiao Wei:** Visualization, Methodology. **Jianwu Li:** Writing – review & editing, Conceptualization, Funding acquisition. **Jinrong Tang:** Writing – review & editing, Conceptualization, Formal analysis. **Bin Zou:** Formal analysis, Data curation. **Xiaojing Yuan:** Formal analysis, Data curation.

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Data availability

The data that support the findings of this study are available from S&P Global Database and UN Comtrade. The raw and processed data for this study are available in the supplementary materials.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval

This article does not contain any studies with human participants performed by any of the authors.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

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