Interdependence in rare earth element supply between China and the United States helps stabilize global supply chains

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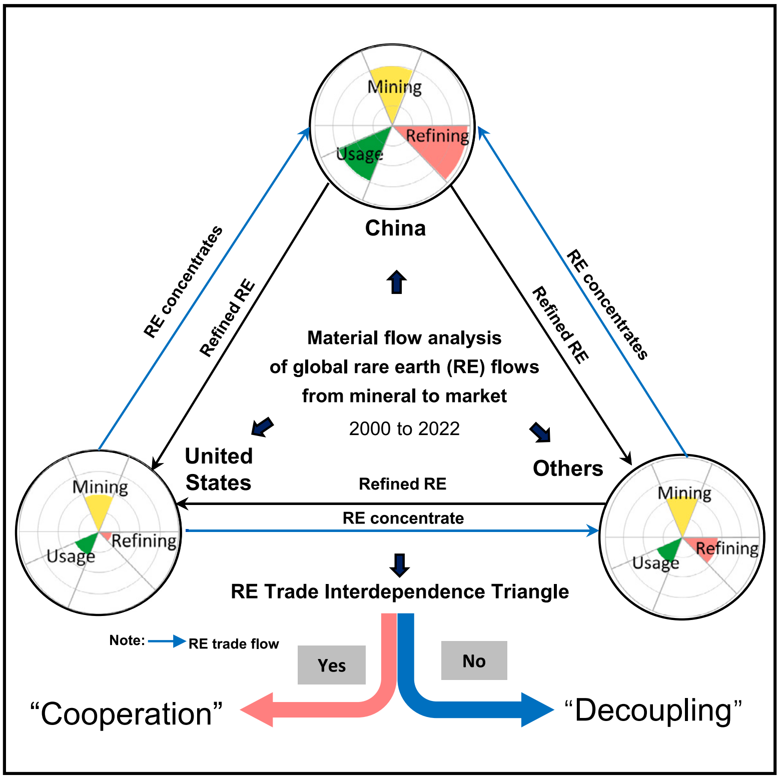
Graphical abstract



Highlights

- We mapped global REE flows from minerals to market annually from 2000 to 2022
- REE trade between China and the United States has grown increasingly intertwined
- Trade benefits all participating nations along global REE supply chains
- We suggest incorporating REE trade agreements into climate cooperation

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In brief

Soaring demand for rare earth elements (REEs)—key to many low-carbon technologies—has raised concerns due to the unvalidated perception that China dominates the REE supply. Countries such as the United States seek to reduce their dependence on importing REEs from China. However, the relationship between key participating countries on global REE supply chains remains unclear. Here, we explore global dynamic REE flows from mining to markets in 2000–2022 and reveal an increasing REE trade interdependence between China and the United States, with the United States becoming a net exporter and the largest REE supplier to China since 2018.

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Interdependence in rare earth element supply between China and the United States helps stabilize global supply chains

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SCIENCE FOR SOCIETY Rare earth elements (REEs) are strategic resources and vital components of many technologies, especially those key to the low-carbon energy transition (i.e., wind turbines and electric vehicles). There is an unvalidated perception that REE supply is heavily concentrated in a handful of nations, particularly China. This assumed threat to REE supply chain security has raised concerns, particularly in the United States, and has led to domestic resource exploitation and even national alliances, which could have undesirable socio-environmental ramifications. A dynamic material flow analysis, which can trace REE flows across global networks from resource mining to product sales, reveals that between the years 2000 and 2022, the United States has, in fact, become a net exporter of REEs, with China as its largest customer. The growing interdependence of REE trade between China and the United States has stabilized rather than disrupted global REE supply chains, benefiting both importer and exporter alike.

SUMMARY

Rare earth elements (REEs) are vital to the development of low-carbon technologies. There are rising concerns in the United States and elsewhere about REE supply chain stability and risks given the unvalidated perception in the heavy reliance of China, by far the largest REE supplier. However, the relationship between key countries at different stages of global REE supply chains remains unclear. Here, we use a dynamic flow analysis to explore supply dependence between the United States and China by tracing REE flows from mineral mining to market between 2000 and 2022. Our results indicate complementary and cooperative US–China interactions, especially after 2018 when the United States became a net exporter of REE and China's largest supplier, and China became the largest importer of the US REEs and manufacturer of REE-enabled low-carbon technologies. This intensifying interdependence stabilizes REE supply chains and highlights the importance of cooperative REE trade networks.

INTRODUCTION

Rare earths (REs) are a group of 17 elements with distinctive and versatile functions that are critical to key technologies for a global sustainable transition.[1–4] Products like mobile telephones, wind turbines, electric cars, and military hardware[5] are heavily REs dependent. REs also play a crucial role in the innovation and development of emerging high-tech and green applications.[6] Consequently, there has been a dramatic increase in global production of REs,[7] and their future demand is expected to accelerate to match the global expansion of low-carbon technologies required by net-zero climate targets.[8–11] However, REs mineral deposits are not equally distributed from a geographical point of view, and in the past few decades, nearly all REs products have been supplied by China.[12] This situation, coupled with occasional disruptions in REs supply and trade flows,[13] has led to concerns regarding the supply chain stability of REs, including recently in the United States as emphasized in the Executive

Order 13817[14] and the following Executive Order 14017 for 100-day review on its critical supply chains.[15,16]

International trade helps to close the substantial imbalance between the supply and demand of critical minerals across nations. In the past decades, increasing mineral trade volumes and reductions in tariffs have led to improving resource availability for importing nations.[17] Nevertheless, the dependence of mineral trade is still viewed as a potential risk to national security,[18,19] especially for metals with a so-called "China-concentrated" supply chain.[20] The latter relates to the 2010 Chinese export embargo of REs to Japan, which is widely considered to have caused a price spike and global panic in manufacturing supply chains.[12]

Given the perception that the United States is heavily reliant on Chinese supply,[16] REs are at the frontline of the US–China trade disputes and other geopolitical developments such as recent "de-coupling" or "friend-shoring" strategies.[21] Despite the long-term trend toward globalized trade and resource availability, trade restrictions are still frequently applied by exporting nations.[22] Conversely, under the assumption that reliance undermines security, there have been growing efforts in the United States and elsewhere to reduce dependence on critical mineral imports by requiring product supply chains to rely on domestic resources or allied nations.[14,23] However, these efforts may risk reducing efficiency and boost extraction activities in some areas, which are both economic costly and environmentally damaging.[19] Friend-shoring on some emerging suppliers is also likely to fuel competition and bring new risks, such as the case of Indonesia to ban the export of nickel ore. Given the delay in opening new supply sources, this pattern ultimately jeopardizes the speed and cost[24] with which technologies crucial to the energy transition can be implemented at scale. Thus, it is imperative to have a comprehensive understanding of critical mineral flows across supply chains. Quantifying the interdependence among nations makes it possible to formulate policies that mitigate these risks to global sustainability.

Previous criticality assessment studies[25] have provided a snapshot of the trade flows based on indicators such as net import reliance. One recent effort[26] highlighted that the United States is 100% reliant on foreign sources for 20 different minerals, including REs from China. Other studies have applied complex network approaches to probe the status and stability of REs supply.[27,28] However, those studies fail to systematically explore the dynamic interactions of nations along global REs supply chains.[29] In 2018, the US National Science and Technology Council emphasized the need for comprehensive analyses using material flow analysis (MFA).[30] However, as can be seen with some recent MFA efforts,[31–33] such analysis is still hampered by the lack of data transparency along supply chains. This is particularly true for REs supply chains, which are characterized by relatively extensive unregistered flows.[34,35]

Here, we map the global REs flows from minerals to metals across regional boundaries annually from 2000 to 2022 to better understand the degree to which regions are interdependent on one another. To address the reported issues in terms of data quality and availability (e.g., unregistered production, trade), we perform dynamic MFA that covers all potential flows, with specific efforts in the clarification of (1) supply chain routes, (2) the harmonization of trade records from different regions, (3) the estimation of unregistered flows, and the (4) collection of dispersed data on REs mining, refinery, and demand from various sources. Details for our approach and datasets can be found in the experimental procedures, supplemental information, and Database: https://zenodo.org/records/10396895. Building upon this foundation, we delve into the dynamics of disparities and linkages between China and the United States within the global REs supply chains over a period of rapid growth technologies that rely on these critical elements and further explore the need for international cooperation in boosting the critical mineral supply for a globally sustainable future. Our analysis reveals intensifying cooperative interactions between these two nations, as China emerges as the primary refinery center for the United States, leading to a notable increase in mineral imports from the United States. This evolving complementary pattern is accompanied by the formation of a more diversified and dynamic regional REs supply chain. Accordingly, this result urges us to reexamine the role of international trade and global cooperation in boosting the critical mineral supply for a globally sustainable future.

RESULTS

Global RE flows during 2000–2022

Global RE flows from minerals to metals in each year are mapped by Sankey diagrams (Figure 1 for 2022; for the rest of the years and cumulative results, see Figures S1–S23), all flows are measured by RE oxide (REO) equivalents in gigagrams (Gg) or thousand metric tons (kilotons, marked as kt in the following content). Overall, there were ~3,899 kt of REOs mined globally (Figure S23), and there exist 4 main supply chains (i.e., mining and beneficiation, roasting and leaching, separation and purification, and salt electrolysis; see Figure S24). As the main supplier, China (from both registered and unregistered sources) supplied 77% of global REOs (~2,996 kt), whereas its share declined dramatically from 97% in 2010 (Figure S11) to 60% in 2022 (Figure 1). Our results indicate dramatic changes in cross-border trade of REs products among nations. Before 2010, China acted as the main supplier of refined REs products to the United States and the rest of the world (RoW). Given various efforts made to diversify REs supply chains from the 2010's REs crisis,[36] when China suddenly halved its export quota (Figure S25) during its dispute with Japan,[37] 3 key changes can be observed during 2011–2022: first, the United States reopened its REs mining in Mountain Pass, California during 2012–2015 and from 2018 afterward; second, the RoW expanded its refinery process (mainly driven by Lynas Plant in Kuantan, Malaysia, or marked as LYnas Malaysia Plant [LYMP]) since 2012, and the plant-refined REs output has grown by 4-fold to 16 kt/year in 2022; third, according to the US Geological Survey (USGS) record,[38] the United States has fixed its domestic REs supply chain gap with refinery capacity since 2021 (0.3 kt/year in 2022 in Figure 1). Notably, China's role changed from an exporter to an importer of REs minerals and now as a refiner of minerals for the United States and the RoW via its dominant refining capacity (e.g., 278 kt/year or 83% of the global amount in 2022). Results indicate that most of the mined REs from other regions (i.e., 98% from the United States and 76% of the RoW in 2022) were shipped to China for refinery and separation, and then returned to meet their demand as processed RE products.

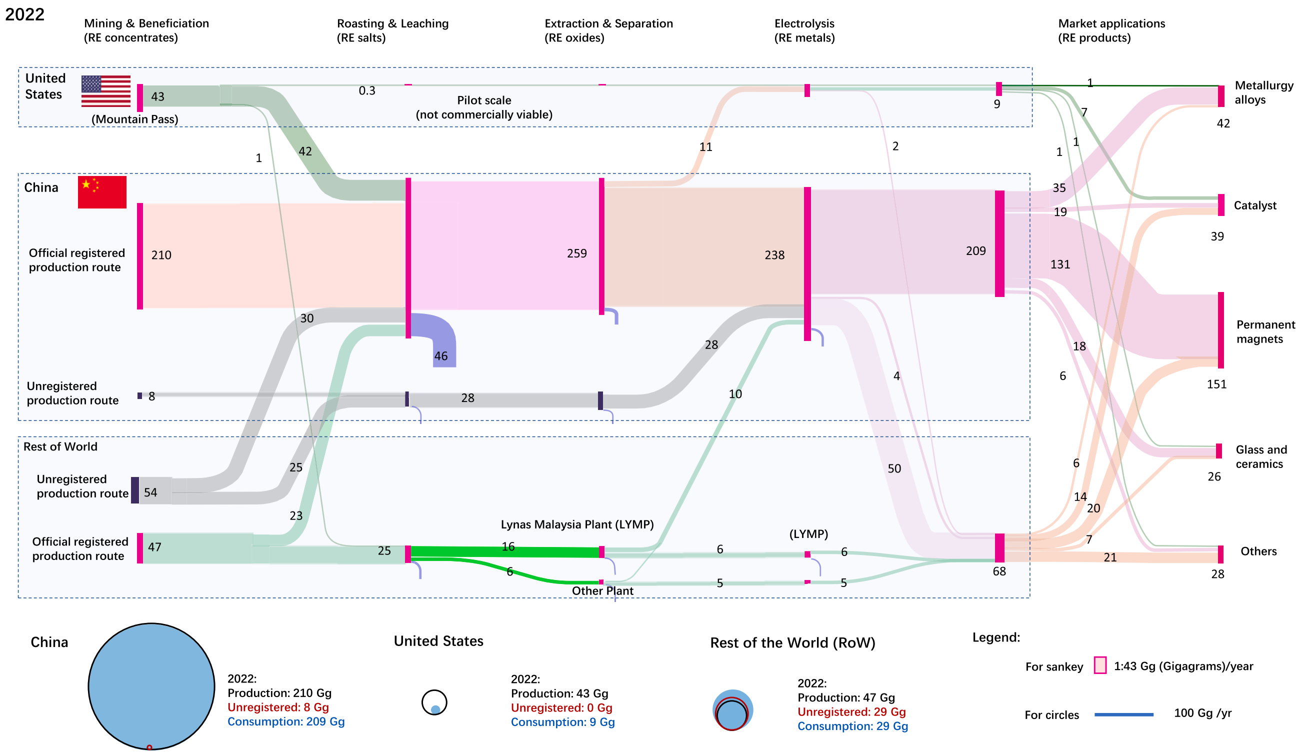

Figure 1. Global RE production and trade flows from mining, leaching, extraction, and electrolysis, through to market in 2022

Values are in estimated rounded amounts per year, in gigagrams per year (Gg/year) or thousand metric tons per year (kt/year) in REO content; there are two unregistered production routes (one in China and the other in the RoW). For the rest of the years during 2000–2021 and the cumulative results, see Figures S1–S24.

There are also substantial unregistered (illegal or without record) production and trade activities in the global production chain (marked as gray in Figure 1). Based on mass balance (see experimental procedures), we quantify and present the annual changes of these unregistered mining productions in Table S1. It is estimated that ∼15% of mining products (573 kt of REOs in total) were unregistered, ∼64% of which occurred in China (369 kt) during the studied period (Figure S23). The unregistered mining activities in the RoW were reported mainly in Southeast Asia (e.g., Myanmar, Vietnam, Thailand[39]), the amount of which is estimated as 204 kt in total, mainly occurring in the past 5 years. During the same period, China's unregistered mining production dropped quickly from 45 kt/year in 2017 to 8 kt/year in 2022 (Figure 1) due to the government's strong effort in combating illegal REs mining.[40] However, there is some evidence[41] indicating that some unregistered mining production in the RoW may be originally mined in China and then shipped to these nations to obtain official refinery quota permission (e.g., ∼56% of the RoW unregistered flows in 2022). Thus, the unregistered mining activities in China could be even higher than our estimates. Similar to those registered mining flows, nearly all of those unregistered mined products were shipped to China for further processing and refinery. As shown in Table S1, there are also some unregistered refinery activities beyond China's refinery quota to process those mined REs ores, the share of which rose from 9% in 2015 to 23% in 2018 and then declined to 11% in 2022.

RE applications differ among regions

We measure the regional consumption of the studied REs products as apparent consumption of REs raw material in Figure 2, following the same definition and boundary of the USGS in its REs mineral yearbook.[38] From 2000 to 2022, the world consumption of REs products increased by 3.7 times, from 78 to 286 kt/year (Figure 2A), with a compound annual growth rate of 6.1%. This corresponds to a cumulative consumption of ∼3,046 kt (Figure S23). Although China's share in global mining has declined as mentioned before, its share in global consumption has increased from 25% in 2000 to over 70% in the period 2018–2022. The permanent magnet, which is an indispensable component in many clean and sustainable technologies (e.g., wind turbines, electric traction motors), is the largest end-use application, accounting for 52% or 1,597 kt of the global total demand. The second-largest end-use application is petroleum catalyst, which consumed ∼454 kt of REOs. This is followed by the application in metallurgy (14%), and glass and ceramics (10%). It is worth noting that all other applications, including military applications, account for ∼8% of the total final demand for RE products. However, the demand for specific scarce REs elements (REEs) in these applications could still be significant (further analysis is limited by the lack of data).

Figures 2B and 2C illustrate the annual trend of apparent REs consumption for China and the United States, respectively. Results indicate that China's domestic demand for REs has increased by ∼10.8-fold, from 19 kt/year in 2000 to 209 kt/year

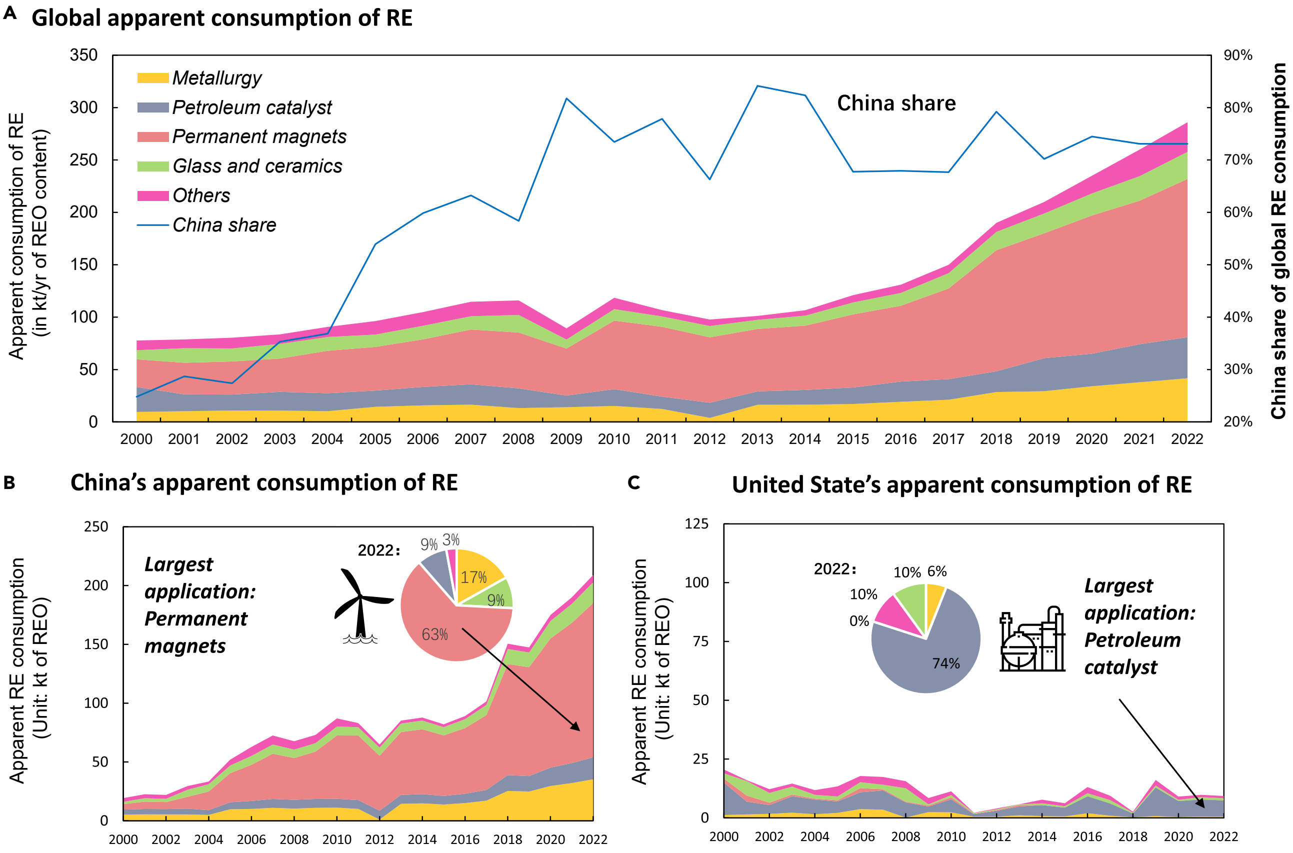

Figure 2. The apparent consumption of REs for global, China, and the United States by end-use applications from 2000 to 2022

(A) Changes in global consumption and China's share.

(B and C) Trend of apparent consumption of different REs applications in China and United States, respectively, in kt/year of REOs.

in 2022 (Figure 2B). Before the 2010 RE crisis, the United States had a relatively high REs consumption, ranging from 8 to 21 kt/year. Afterward, its REs consumption rapidly declined from 11 kt/year in 2010 to only 2 kt/year in 2011, and then remained stable at ~9–10 kt/year during 2020–2022, which is equivalent to only 4% of China's consumption level. Our analysis also reveals that permanent magnets with various emerging green energy applications, such as in wind turbines, were the major consumption sector for REs in China, totaling 1,195 kt during the period. The share of REs consumed by this sector increased dramatically from 24% in 2000 to over 62% after 2010. The remaining REs consumption in China was contributed by metallurgy (16%), petroleum (10%), glass and ceramics (9%), and other applications (5%). In comparison, the REs consumption in the United States was dominated by petroleum catalysts (by 74% in 2022). Given that its mining production is ~4.7 times higher than its consumption, the United States remains a major global supplier of REs minerals.

Trade flows among China, United States, and the RoW

Figures 3A and 3B present the annual REs trade net flows (import minus export) from China and the United States to the RoW, where we separated REs into concentrates, salts, oxides, and metals (based on customs records from both sides, all converted into REO value; for details on data harmonization, see Table S2). For a long period after the early 1990s, China was the world's largest REs exporter, whereas the United States was a net importer. However, this pattern changed rapidly during the past decade, particularly after the 2010s so-called REs crisis. In net terms, China's net export peaked at ~55 kt/year in 2003 and then decreased sharply to ~10 kt/year in 2010 (Figure 3A), partly owing to China's tightening export quota (i.e., from 45 kt/year in 2006 to 14 kt/year in 2011[42]). Meanwhile, China's REs imports doubled during this period, indicating strong growth in China's internal REs demand. Our estimates refine the previous observation that China emerged as a net importer of REs for the first time in 2018[43]; that is, China had already become a net importer in the 3 years (2011–2013) amid the 2010s REs crisis. Those trade policy changes also affected US import flows, which dropped from 20 kt/year during the 2000s to ~10 kt/year in 2010 (Figure 3B) and rebounded to 17 kt/year by 2013. With the reopening of the Mountain Pass mine, its net exports of all of the studied REs products have increased to ~25 kt/year (mainly in concentrates) in 2022, shifting the United States from being a net importer to a net exporter in the global REs market during 2018–2022.

The REs trade between China and the United States has grown increasingly intertwined (Figures 3C and 3D). Historically, the United States has been a small player (~20%) in China's global export market. In contrast, the United States relied heavily

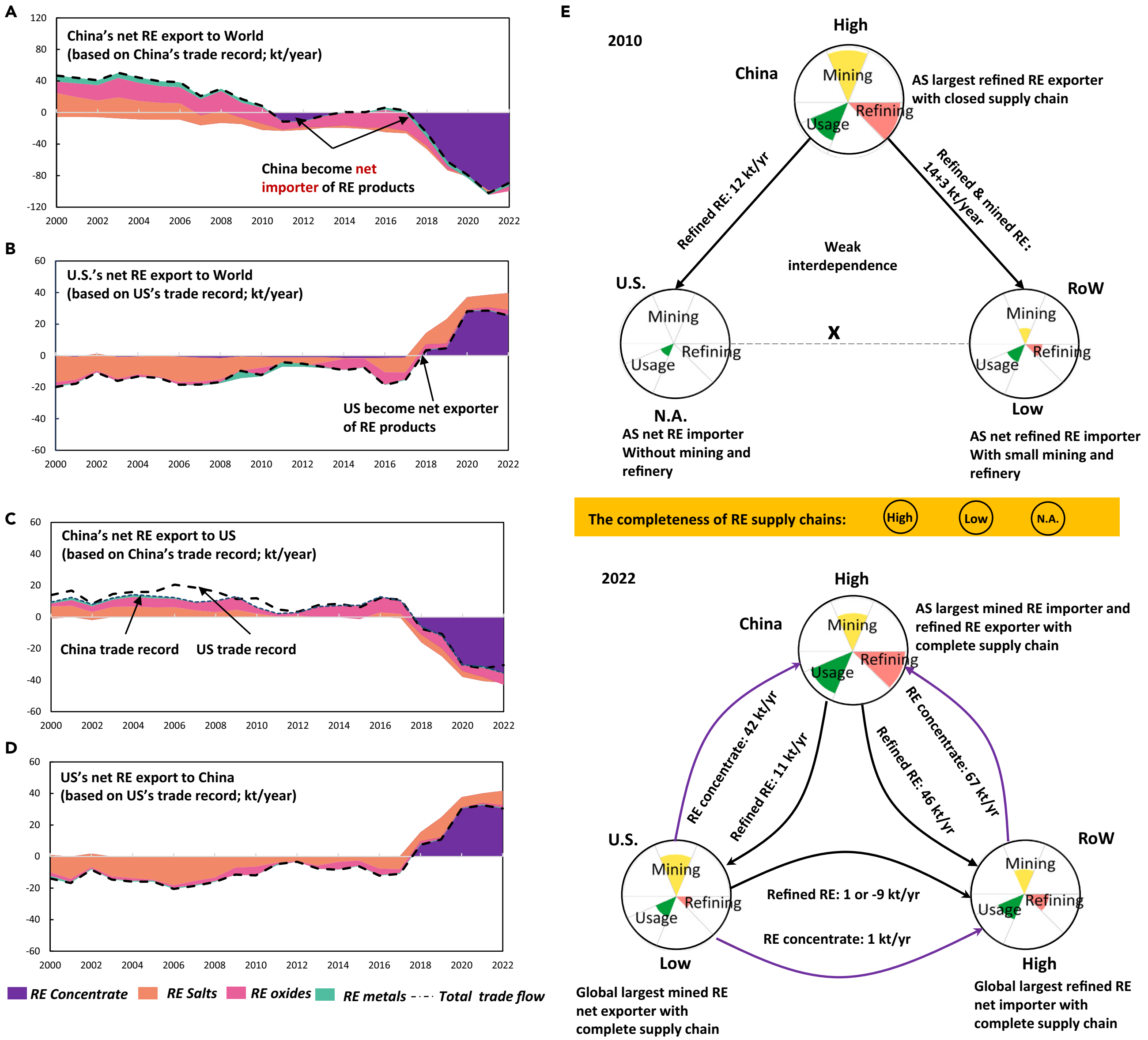

Figure 3. RE net export flows in and among China, the United States, and the RoW, in kt/year of REOs

(A and C) China's total net REs import to the RoW and the United States by REs mineral types.

(B and D) The United States' total net REs export to the RoW and China by REs mineral types.

(E) The changes of interdependences of RE trade between China, the United States, and Rest of world (ROW). For detailed values, see supplemental information).

(∼75%) on China's REs supply before 2018. Notably, there is a significant discrepancy in the customs records of each side—the United States net import record is ∼44% larger than China's export record. Part of this may be due to data reporting anomalies, but this figure also indicates that up to ∼50 kt of REs may have been smuggled from China to the United States during 2000–2022 (dotted lines in Figure 3C). In 2018, China shifted from being a net exporter to a net importer, whereas the United States became a net exporter to supply REs minerals to China. Such role changes were mainly driven by the US side rather than by China. The accelerating production of the Mountain Pass mine, with more potential mines coming, has reshaped the United States' role in the global REs market. China's dependence on the United States for its imported REs has risen dramatically from 5% in 2017 to 44% in 2022, making the United States China's largest external REs mineral supplier (Figure 3D). Still, the United States relies heavily on China's refined REs products (i.e., salts, oxides, and metal products).

A trade triangle form can be used to illustrate the dynamic changes in trade connection between China, the United States, and the RoW (Figure 3E). In 2010, both the United States and the RoW relied upon China for nearly all REs products, from concentrates to metals, whereas United States has nearly no mining and refinery capacity. This pattern has shifted to a more complementary one since 2018, when China became the largest REs net importer. Since 2020, the broken REs

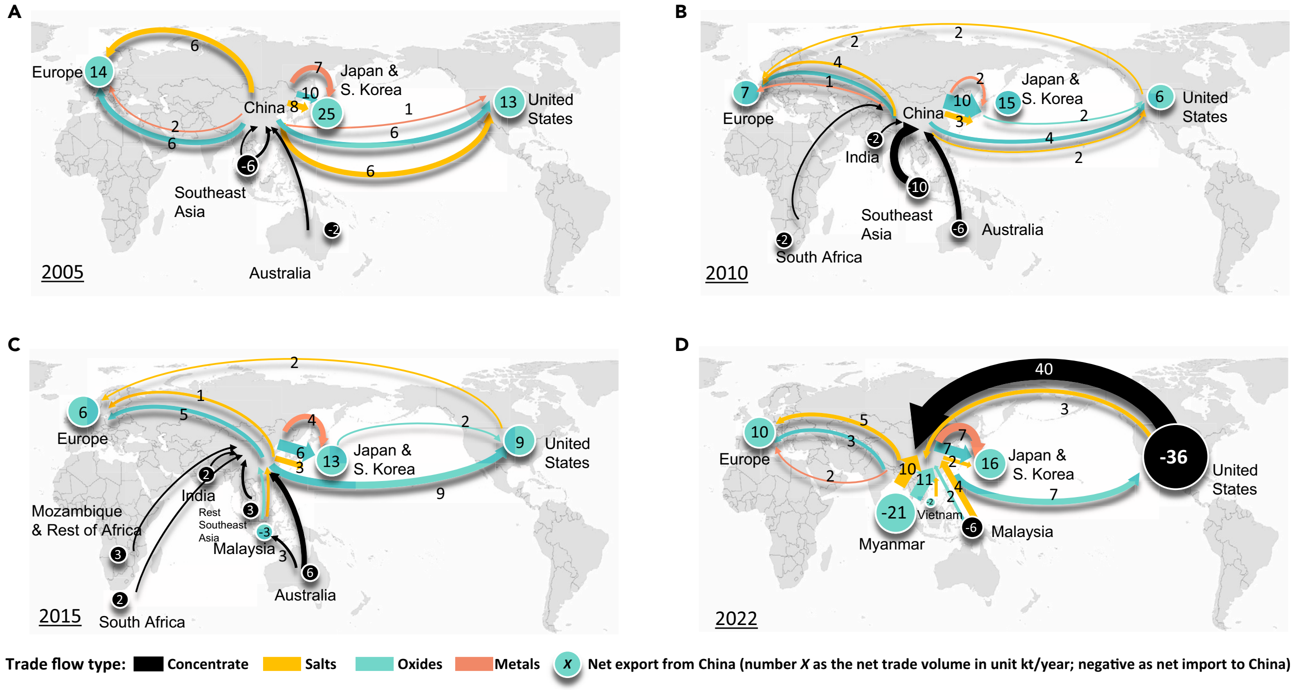

Figure 4. REs trade flows linking China and the United States to the RoW in kilotons of REOs

(A–D) Annual trade flows of 4 separate products are estimated based on their high-resolution trade records; the number in the circle indicates the REs net export of China to Europe, Africa, India, Southeast Asia, Japan, South Korea, and the United States in 2005 (A), 2010 (B), 2015 (C), and 2022 (D).

supply chain in United States has begun to be fixed, making this trade triangle more stable. Such trade complementariness, together with the completeness in REs supply chains, can benefit all regions. For instance, China imported ~42 kt/year of REs concentrates from the United States in 2022, over 25% of which (10 kt) were shipped back to the United States as refined products, and the remainder stayed in China, either to meet its domestic demand or to be exported to other nations. In other words, China can now be viewed as a refining center for US REs minerals, and the United States has become a major REs mineral supplier for China. This relationship also applies to China and the RoW.

Growing dependence on international market

The global trade flows linking China, the United States, and other specific nations are mapped in Figure 4. China, as the largest global consumer, is increasingly dependent on overseas REs minerals. With the expansion of US mine production, China's concentrate import has nearly doubled from 26 kt/year in 2017 to 81 kt/year in 2020, and further increased to 94 kt/year in 2022 from nearly all major mine producers in the world (Figure 4). Before 2018, Australia and Southeast Asia were the largest concentrate suppliers of China. Meanwhile, China's export of REs salts, oxides, and metals to Japan, Europe, and the United States were gradually declining from 2005 to 2015 (Figures 4A–4C). Since 2018, China expanded the import of all REs products, including concentrates, salts, oxides, and metals to meet its growing internal demand. In 2022, aside from the concentrate import from the United States, China also imported ~14 kt/year of REs salts from Myanmar and Malaysia. As predicted,[44,45] China will also have a growing REs demand with increasing import reliance on global REs minerals.

For the United States, its REs apparent consumption in 2022 was ~9 kt REOs, only 19% of its REs mine production. This indicates that the United States can be more than self-sufficient on its domestic REs supply. Despite the available refinery capacity since 2020, most of those minerals were processed and refined in China or the RoW to oxides or metals for downstream manufacturing. Notably, the Australian company Lynas operates a major REs refinery outside China (i.e., the LYMP plant in Malaysia), whose products were shipped mainly to China (Figure 5). Records show limited trade activities between the United States and Malaysia since 2018, despite the fact that LYMP's annual output (16 kt/year REO)[46] is approximately two times larger than US apparent consumption. Under the limited internal market, the continuing expansion of the United States in mining and refinery (as summarized in Note S1) may create an even larger REs surplus, some of which may be wasted or still exported to China (like the LYMP trade flow to China in Figure 4). This highlights the urgent need for the United States to expand and upgrade its internal REs market, especially in the emerging clean energy applications, just as China did in the past decade.

DISCUSSION

Through MFA, our analysis helps to fill the information gap related to global REs flows and trade with publicly available datasets. In general, we find a fundamental role reversal between China and United States in their bilateral trade. Such national interdependence will intensify given the growing efforts in

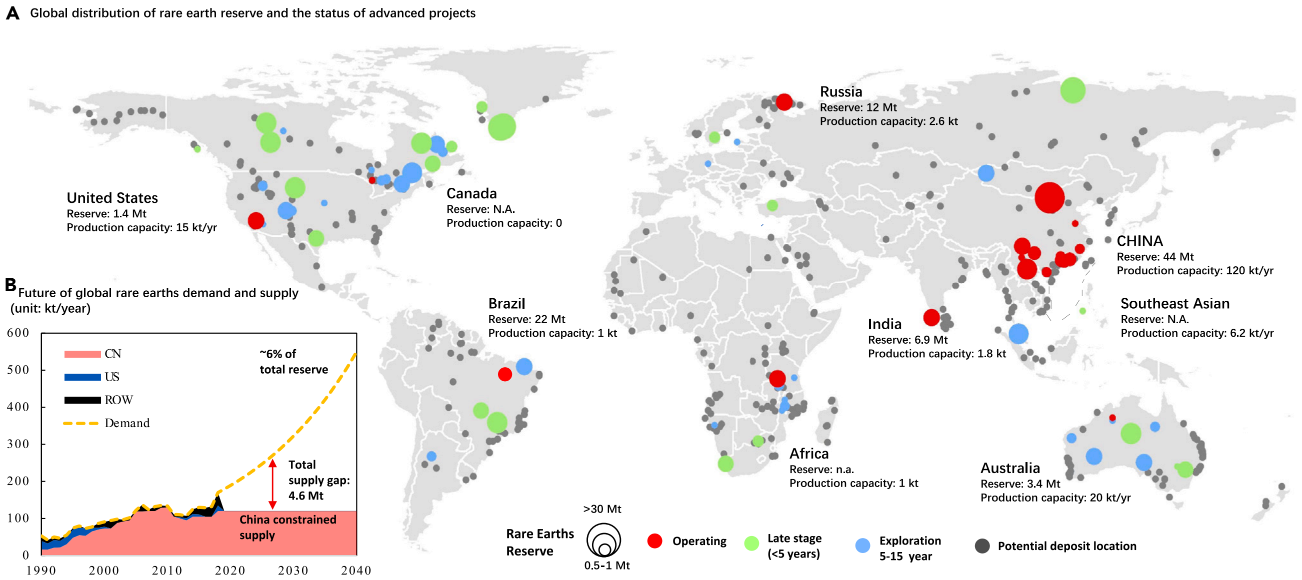

Figure 5. Global distribution of advanced REs projects, and future demand and supply

(A) The location and status of active and potential REs projects; details can be found in Table S3. The historical production data in (B) were obtained from the USGS,[38] the future demand projection in (B) is based on Alonso et al.[9], and the production trend of China is based on Lee et al.[47]

seeking and operating new mineral sources worldwide. Indeed, REs reserve are neither "rare" nor "highly constrained" in China. Figure 5 shows our investigation (for details, see Table S3) on the status of 82 potential REs projects, showing that 27 additional projects in 12 nations outside China[48–50] could become economically extractable in the short term under preferable market conditions. In total, another 76 Mt of REO reserves could be brought into production phase. This could generate more complex trade relationships, as shown in historical changes indicated by the results of our MFA during 2018–2022. Thus, trade interdependence should be carefully considered by China, the United States, and other countries in their national strategies related to REs.

Similar to most MFA studies,[31–33] our approach has inherent limitations, primarily stemming from the quantification framework and data availability. The MFA framework (Figure S24) is a simplistic diagram of REs production processes, and some products with low-content REs are not covered. In addition, despite cross-checking with other sources, unregistered production and trade flows are our best estimates based on the mass balance principle, which should be treated as speculative rather than as actual numbers. It is important to note that our exclusion of REs stocks at processing plants may induce an overestimation of apparent consumption in certain years. However, the largest uncertainties in our results arise from the lack of adequate and harmonized data sources, emphasizing the need for more transparent data collection throughout the REs value chain on a global scale.

As the old saying goes, the Middle East has oil and China has REs. Before 2000, most of the mined REs (74% in 2000) in China were exported to other nations at low prices, and China quickly surpassed the United States as the world's dominant supplier. However, unregulated mining activities did cause severe damage to ecosystems and human health in China.[51] Partly because of this, China launched an export quota system to regulate its REs exports since 1999. In 2010, due to the geopolitical tensions between Japan and China, China reduced its trade quota to Japan dramatically (Figure S25). Because of China's dominant role in the one-way trade dependency pattern (Figure 3), this action led to broader and global effects on the REs supply, with an ~10-fold increase in REs price.[13] Thus, Japan, the United States, and the European Union (EU) jointly filed a complaint with the World Trade Organization (WTO). After the WTO reached a panel decision in 2014 (e.g., China's export quota was inconsistent with WTO regulations), China had to cease its export quotas since 2015.[52] Currently, the global REs supply chains are experiencing rapid and significant changes, driven by increasingly complex trade patterns, China's growing reliance on REs minerals (Figure 3), as well as the ongoing expansion of refining in the United States and the RoW. Those will significantly diminish the likelihood and potential effects of a second REs crisis resulting from export restrictions.

China's growing REs demand can be seen as a crucial factor in achieving a stable and secure REs supply chain. Since the mid-2010s, China has prioritized the development of its REs industry as part of its low-carbon and high-tech manufacturing base.[53] Considerable investments and efforts have been dedicated to research and development across the entire REs supply chain (Figure S28),[54] particularly in processing technology, material engineering, and market expansion for emerging applications. Thus, China has emerged as the largest global REs consumer and a world leader in the application of REs to green energy technologies. This surging demand[44,45] also exposes China to potential disruptions in the global REs supply chain. Thus, similar to that of the European Union and the United States, China would also strive for a more diversified and secure supply of REs in the future.

The United States was often characterized as a ‘‘net importing country’’ on REs, with a great dependence on China.[55] Thus, the US REs strategy primarily focuses on mitigating supply risks,[18] as well as diversifying global suppliers. For instance, various efforts by the US government, industry, and academia have been made to explore alternative domestic and overseas sources of REs (e.g., from Greenland, Mongolia). However, it is important to note that if the domestic demand market in the United States is not adequately cultivated, then the present US strategy at the supply side may create an even larger surplus. Thus, the experience of China's investment on final green application of REs should be seen as relevant to the present US REs strategy, particularly to support the ambitious US climate actions.[56] In fact, the United States owns significant REs resources (with a reported reserve of 2,300 kt REOs in 2022), which can sustain its present consumption for several hundred years. As summarized in Figure S26 and Note S1, with the operation of various new mining and refining projects[57] such as the Bear Lodge (Wyoming), Round Top (Texas), and others, the United States will continue to become the largest REs exporter. In this context, there is an urgent need for the United States to expand and upgrade its internal REs market and to enhance potential cooperation to expand the use of such mineral treasure in sustainable applications.

The present policies on critical elements tend to be focused on de-coupling from China and friend-shoring of minerals. By comparing with a counterfactual no-trade scenario in 2022 (assuming all trade flows are removed, and new flows are mapping in Figure S27), our results indicate a trade benefit to all of the participating nations. In particular, there would be a dramatic decrease in supply and demand across all regions and globally without trade, and the largest reduction would be attributed to permanent magnets, which support green energy applications such as wind turbines, electric vehicles, and energy-saving motors. Given this linkage of REs to climate mitigation, there is a need to incorporate global cooperation on REs trade into climate cooperation. Some key intergovernmental bodies such as the WTO, Group of 20 (G20), and the United Nations (UN) can play a pivotal role in promoting such mechanisms. For instance, the WTO can facilitate negotiations among member countries to eliminate trade barriers or develop trade agreements for secure global REs supply chain to address the climate crisis. Meanwhile, as our results indicate, the United States and China own the mutual benefits in obtaining REs flows from each other to support their ambitious climate targets. In light of this, the G20, which links the United States and China, can serve as a potential platform to explore the possibility in promoting critical mineral trade cooperation as part of climate cooperation negotiations.

The application of REs in green energy technologies can help to decarbonize the energy system at the demand side. However, on the supply side, the severe environmental consequences associated with REs production should be noticed, and the corresponding green energy processing technologies need to be quickly promoted along with the coming REs supply boom and expansion.[47,58] Before China's rise, the United States had dominated the global REs supply since the 1960s. However, the United States closed its mining operations from 1998 to 2010 due to the costly treatment related to radioactive waste, which may further limit US REs domestic mining expansion.[59] China is also suffering from significant environmental effects in mining sites.[60] The international trade of REs products will become more frequent and extensive under an increasingly diversified supply chain, which may shift the environmental burdens associated with REs production to developing nations such as in the case of LYMP in Malaysia.[46] Such a trade-linked burden shift will also increase the overall environmental effects, given that operations in developing countries tend to be less regulated.[61] Along with global efforts to diversify REs supplies, more production lines will be operated in the United States, Australia, Africa, and other countries.[62] This encourages more global cooperative and shared efforts in the support of the WTO and other international cooperation bodies to regulate REs trade toward a more sustainable supply.

In summary, our analysis emphasizes the necessity and urgency for major global players (particularly China and the United States), along with international cooperation bodies, to foster wider and deeper collaboration in global REs trade and supply chains. Through shared efforts in diversifying the resource supply, preventing the transfer of environmental burdens, promoting innovation in REs materials for green technologies, and so forth, this collaboration will be beneficial for all participating nations and can further secure a joint sustainable future for all.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for data should be directed to the lead contact, Peng Wang (pwang@iue.ac.cn).

Materials availability

This study generated no new materials.

Data and code availability

This paper analyzes existing and publicly available data. All of the data for MFA mapping and trade flow analysis are contained in the supporting data file deposited at https://zenodo.org/records/10396895. Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

MFA

The study traces the global REs flows from ore to end-use applications from 2000 to 2022. The system boundary of this study is illustrated in Figure S24. The system is categorized with four separated REs production routes from ore to metals, including three major ones in United States, China, and the RoW, and two unregistered ones in China and the RoW. Those production routes are interlinked with commodity trade between nations. In each route, there are four key industrial processes transferring REs from reserve to metals: mining and beneficiation, cracking and leaching, separation and purification, and salt electrolysis (Figure S24). Corresponding, this study divided REs products into four types: RE concentrates, RE salts, REOs, and RE metals. The details of these four major steps and product types are described in the following.

Mining and beneficiation

The REs production starts with the mining process. Depending on the form and location of the orebody, RE ores are mined by either open pit or underground methods. Afterward, these RE ores are processed with the beneficiation approach to remove gangue minerals and produce RE concentrates that are packaged and shipped for further processing.

Roasting and leaching

After mining and beneficiation, RE concentrates are further processed by cracking (roasting) and leaching processes to obtain RE salts, which include RE chlorides, fluorides, and more. Here, the concentrate cracking is a process in which the structure of an REE mineral is modified to dissolve REEs in a weak acid solution. This is accomplished through various techniques such as alkaline cracking and acid baking. The cracked concentrates are then leached to dissolve REEs in a solution and subsequently recover those via neutralization, precipitation, or solvent extraction methods.[63]

Separation and purification

Concentrates are typically roasted with sulfuric acid or hydrochloric acid, followed by leaching with water to obtain mixed RE chloride solutions ($RECl_3$). REs are recovered from leaching solutions by solvent extraction, in which REs are stripped by several groups and then separated into individual REEs. These compounds are further precipitated by using carbonic acid or oxalic acid, which are roasted again to produce individual REOs.

Salt electrolysis

RE metals are mainly prepared from REOs by salt electrolysis. In the molten salt electrolysis, RE metals or alloys with high purity can be manufactured by using RE fluoride as an electrolyte system.

We then apply MFA to quantify the RE production, consumption, loss, and trade flows throughout the previously designed system. MFA is a popular tool to quantify the flow and stocks of natural resources through industrial processes to intermediate or final products under the principle of mass balance.[64] All of the flows in this study are quantified in REO metallic equivalents by the use of mass balance principles on the basis of various publicly available statistics and reports. We report our data sources, equations, and results in a transparent and reproducible manner found in Table S4. In general, the mining production data are mainly from the USGS, and the apparent consumption is calculated as the sum of production and net import amount.

Unregistered RE flows estimation

The biggest challenge for global REs flow quantification is attributed to the existence of various unregistered (illegal) mining, smuggling, and processing activities in China[47,65] and the RoW.[39] Accordingly, we constructed two unregistered production routes to trace those unregistered flows: the one in China is widely considered to own an entire production chain from mining to final metal production,[47,65] whereas the one in the RoW is mainly limited to the mining and beneficiation stage due to the lack of processing capacity. The illegal mining production in China has been widely explored and estimated.[34,35] Accordingly, our calculation of the Chinese registered route is mainly production driven, which starts with the mining production estimate from Lee et al.[47] and quantifies the rest flows based on the mass balance principle. There is no estimate available for the unregistered RoW production route, and we follow a trade-driven approach (based on the gap from China's trade record and the RoW's production data) to quantify the flows along this route. We tried to provide the best estimates on those flows by cross-checking with various data sources under the mass balance principle. Still, more quantification tools such as the market dynamics model[34] are welcome to establish a more accurate base for our MFA.

International trade of RE mineral commodities

The trade data of REs minerals is critical to reveal the mineral interconnectedness of nations along the supply chain. Notably, most of the previous studies[27,28] relied on the UN Comtrade Database to obtain the trade data (i.e., imports and exports) of REs. However, the trade data for REs in the UN Comtrade Database is limited to only one general six-digit Harmonized Commodity Description and Coding System (HS) code, the resolution of which is not suitable for our study. Instead, we developed a high-resolution trade record of REs minerals from China and US customs records. All time-series records of REs minerals trade (i.e., ~57 eight-digit HS codes from China, and 18 ten-digit HS codes from the United States) have been collected (see Table S2). According to the domestic flow quantification, the trade records from both sides were merged and classified into four product groups: (1) ore and concentrates, (2) RE salts, (3) REOs, and (4) RE metals. All of the reported trade flows are measured with net physical weight value (in kilograms) and converted into REO content, with conversion factors described in Table S5.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.01.011.

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AUTHOR CONTRIBUTIONS

W.-Q.C. and P.W. designed the research. P.W. and W.C. analyzed the data. W.-Q.C., P.W., M.J.E., and B.S. interpreted the results. All of the authors contributed to the writing and editing of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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