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Export restrictions and trade in critical mineral green products for clean energy transition[3]

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Co-funded by the European Union

Export restrictions and trade in critical mineral green products for clean energy transition

Abstract

Critical minerals are essential inputs in the production of green technologies that underpin the transition to sustainable energy. Export restrictions on these minerals raise global prices by constraining supply, reducing material availability, and disrupting international markets and supply chains. Using an event-study approach, we quantify the trade effects of export restrictions on critical mineral green products, drawing on the concept of product relationship stickiness. Our analysis covers export restrictions imposed between 2009 and 2022, combining data from the Global Trade Alert (GTA), ADB–WTO Trade in Critical Minerals (TiCM) database, and the CEPII - BACI trade database. We identify 242 products as green transition related for our analysis as per the TiCM database. On average, export restrictions reduce the quantity of critical mineral green product exports by about 11.8%. For high-stickiness raw materials, trade declines by roughly 30%, suggesting that restrictions on specialised raw materials are particularly disruptive to global supply chains.

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3. Kumuthini Sivathas and Meng Yu Ngov gratefully acknowledge the financial support from the Jean Monnet Centre of Excellence in Trade and Environment. The funding sources had no involvement in the writing of this paper nor the decision to submit it for publication.

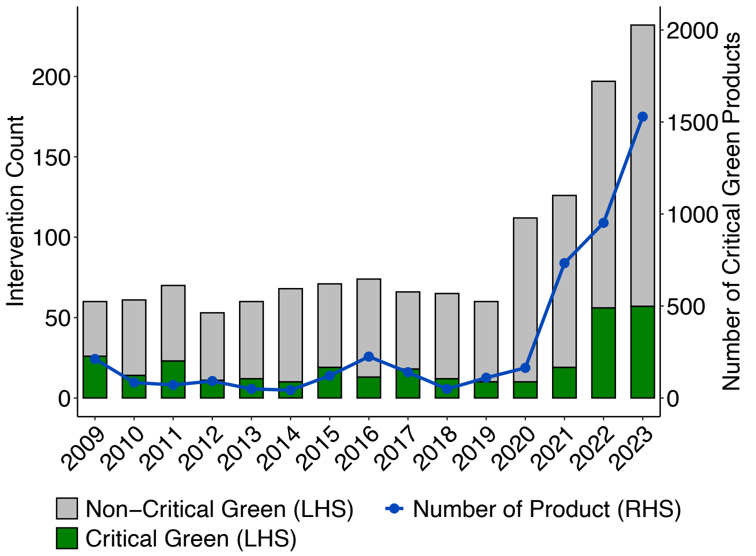
1. Introduction

Ensuring uninterrupted trade in critical minerals is crucial to achieving the green transition, as they form key components of low-carbon technologies (Pommeret et al., 2022; Cathles and Simon, 2024). The most widely used among them include copper, zinc, silicon, manganese, chromium, nickel, rare earth, and molybdenum (International Energy Agency, 2021). Moreover, it is estimated that achieving the Paris Agreement goal of keeping global temperatures well below 2°C will require over 3 billion tons of these minerals and metals (Hund et al., 2020).

Critical mineral reserves, however, are highly concentrated in a few countries (Ritchie and Rosado, 2024), making them susceptible to supply side risks, and prone to geostrategic considerations. This was evident during the COVID-19 crisis which exposed the vulnerabilities of global production and supply chains, and led to an increase in the use of industrial policy measures specifically targeting critical minerals. As a result, the volume of export restriction activities related to critical mineral products listed in GTA surged after 2020, with an estimated 569 of them subjected to export restrictions between 2020 and 2021 (Blue line in Figure 1).[1]

Moreover, for critical mineral green products in our sample, export ban stands out as the most widely used trade intervening measure. Export restrictions remain among the most commonly used measures for critical minerals. These restrictions affect trade either directly through export bans, quotas, and other quantitative limits—or indirectly through licensing requirements and other administrative barriers. Given the nature of critical minerals, such measures have significant implications for both exporting and importing countries.

Figure 1: Export restrictions and cross border trade of critical mineral green products



Source: Author's own calculations based on the data from Global Trade Alerts. The left-hand side (LHS) depicts the number of unique export restriction cases reported each year. The right-hand side (RHS) depicts the number of critical mineral green products subject to these restrictions.

Countries justify the use of export restrictions to achieve a number of different objectives, including with the intention to increase revenue, adjust domestic prices, encouraging local processing and value addition, ensuring adequate supply for domestic needs, and environmental reasons, among others. However, it is well established that industrial policies in the form of export restrictions have little to no long-term impact as a result of potential diversification of supply chains (U.S. Department of Energy, 2019).

A key concern is that such restrictions could disrupt trade, increase inflationary pressures on critical mineral related products, and hinder the green transition (Alvarez et al., 2023). The negative consequences of such measures is also well established in Korinek and Kim (2010), whereby the use of export restrictions in critical minerals had limited intended impact in achieving environmental protection targets, also posing increased risks for potential suppliers in making future investment decisions. Our finding reveal that export restrictions have a significant and negative impact on the trade flows of critical mineral green products, which are essential for the green transition. We find that, on average, export restrictions lead to a reduction of approximately 11.8% in the critical mineral green product exports.

According to Graedel et al. (2012a), scarcity alone does not determine the criticality of a mineral. Instead, a number of interconnected risks associated with its supply, environmental implications, and its vulnerability to supply restriction determine its criticality. We draw on the ADB–WTO Trade in Critical Minerals (TiCM) database to define what constitutes a critical mineral green product.[2] Combining this with export restriction data from

1. 1In this paper, "critical mineral green products" is defined as a group of 242 HS6 critical minerals and related products (raw and semi-processed, intermediate, and finished critical mineral green products), that are relevant for the clean energy transition as defined by "Trade in Critical Min-erals Database" (TiCM database). Throughout the paper we refer to "raw and semi-processed critical mineral green products" as "raw materials", "intermediate critical mineral green products" as "intermediate products", and "finished critical mineral green products" as "finished products".

2. The TiCM provides a one-stop shop for up-to-date, publicly available critical minerals trade data and related policies, and maps trade networks and supply chains.

the Global Trade Alert (GTA) and trade data from CEPII–BACI, we employ an event-study approach following Rotunno and Ruta (2024) to quantify the effects of export-related restrictions on trade in critical mineral green products.

We find that export restrictions have a significant and negative impact on the trade flows of critical mineral green products, which are essential for the green transition. Our findings indicate that, on average, export restrictions lead to an approximate 11.8% reduction in the quantity of critical mineral green product exports. The effects of these trade barriers are not the same for all products and depends on how easy it is for a buyer to switch from one supplier to another. The analysis reveals that the negative trade impact is particularly strong for critical raw materials that have high supplier-switching costs. When a country restricts the export of critical raw materials, trade is disrupted because buyers cannot easily find alternative suppliers. This results in an approximately 30% decline in trade in critical raw materials. Our research identifies that for finished critical mineral green products, the impact of restrictions is felt immediately because they are traded in more competitive markets where buyers can quickly look for other options. For intermediate products, the impact of export restrictions was found to be statistically insignificant.

This paper contributes to two strands of literature. Firstly, it adds to the literature that quantifies the impacts of export restrictions on critical mineral trade. Solleder (2013) was one of the earliest works to establish a strong link between export restrictions and trade. The paper examined the impacts of export taxes on commodity prices using a structural gravity model estimation. Results found that a 1% increase in the rate of export taxes resulted in a 3.8% drop in export quantities, and a 2.8% decrease in total export value, resulting from export price increase. However, a major limitation of the study was the exclusion of export bans and quotas, which naturally result in bias. Felbermayr et al. (2019) make use of aggregate bilateral trade data and structural gravity framework to study the impact sanctions have on trade flows and welfare (real GDP change). Using the Global Sanctions Data Base (GSDB) between 1950-2015, they find that while the average and collective impact of sanctions on trade is insignificant, bilateral sanctions could reduce trade among trading partners by about 85% to 86%. Recently, Alvarez et al. (2023) construct a novel dataset which links bilateral trade flows and production for 48 commodities, including critical minerals. Their simple partial equilibrium trade model suggests that critical minerals are amongst the most vulnerable, with fragmentation leading to large differentials in commodity prices across trading blocs, resulting from supply-demand imbalances and commodities' elasticities of supply and demand.

The study by Caruso and Cipollina (2025) provide evidence for the impact of economic sanctions on mineral commodity trade, noting a 90% reduction in bilateral trade that intensifies over time, while sanctions appear effective only in the short run. Using a gravity model analysis for trade flows between 239 exporting countries and 38 OECD members from 2009-2020, the analysis reveals significant heterogeneity in the effectiveness of sanctions across regions and commodity types. North American countries appear better able to substitute sanctioned imports compared to European Union (EU) countries, and mineral fuels bear the most severe impact of the trade disruption, with 98% export reduction for target countries. Moreover, the countries introducing the sanctions experience reduced trade not only with target country, but also with third-party countries. Chen (2025) studies how mineral export restrictions affect industrial upgrading in developing countries. It finds that such policies reduce mineral exports and modestly boost low-complexity downstream production. The export ban fails to stimulate higher-value or technology-intensive industries, limiting their role in driving structural transformation. Lately, Alfaro et al. (2025) find that policies targeting critical minerals can have unintended consequences or spillovers. They construct an input-output table incorporating rare earth element (REE) use, and downstream innovation using patent data to study the effects of export restrictions imposed by China in 2010. Using difference-in-differences estimation, they conclude that China's protectionist policies spurred innovation, increased total factor productivity, and led to export growth of REE intensive downstream industries outside of China as a consequence of the resulting price shock.

International organizations, such as the Organization for Economic Co-operation and Development (OECD) have also been key contributors to some of the earliest exploratory work done in the area of critical minerals. Their annual publication *Inventory on Export Restrictions on Industrial Raw Materials*, using OECD members' self reported data on applied restrictions and verified data for other countries, has been providing detailed overview of the evolution and scope of export restrictions across 65 industrial commodities (including 58 minerals and metals) and 82 producing countries since 2009.

The most recent OECD (2025) edition of the report reveals that export restrictions on industrial raw minerals have seen an increase of more than five times between 2009 and 2023. According to this report, in 2023, over 500 new products had the incidence of at least one export restriction. In 2023, 7 countries namely China, Vietnam, Burundi, Russia, Congo, Zimbabwe, and Lao PDR, accounted for 94% of the global net increase in export restrictions. Most of these restrictions took the forms of ex-port taxes and export prohibitions, justified as needed for strategic consideration and promotion of local processing. Moreover, the highest number of export restrictions were in products such as waste and scraps, reflecting the growing importance placed on environmental concerns. Export restrictions in upstream critical minerals such as ores and minerals increased at nearly twice the rate, which reflects protectionist measures used to support domestic downstream industries by restricting export of upstream products.

Secondly, our paper contributes to the literature that studies the interconnections between trade restrictions and clean energy transitions. The report by International Energy Agency (2021) explores the link between clean energy technologies and the increasingly important role of critical minerals in this space. In its special report The Role of Critical Minerals in Clean Energy Transitions, it examines the mineral requirements for a number of key emerging clean energy technologies, and sheds light on some of the lessons to be drawn from past disruptions in the free flow of such critical minerals. It estimates that the production of an electric car or an onshore wind plant requires almost six to nine times the critical mineral inputs compared to a conventional cars or gas-fired power plants. This demonstrates the increasingly important role critical minerals would play in driving the green transition, and ensuring their reliable supply has been an important policy tool adopted by many countries. For instance, in the last fifteen years, some of major industrial economies such as Australia, China, Canada, the EU, Japan, and the United States, have introduced some forms of strategies aimed at securing future supplies of critical minerals.

The ambition of achieving net-zero emissions by 2050 hinges upon uninterrupted supply of critical minerals, as they form key components in the development of green technologies. This is well established by a number of detailed reports by key international agencies. Kim et al. (2021) examines the mineral requirements of various clean energy technologies and notes that, under a scenario consistent with achieving the Paris Agreement goals, the share of critical minerals in total demand driven by clean energy technologies is projected to increase substantially over the next two decades. Specifically, this share is expected to exceed 40% for copper and rare earth elements, 60-70% for nickel and cobalt, and nearly 90% for lithium.

Similarly, the World Bank report titled *Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition* makes a case for how improvements in green technologies could drive up demand for critical minerals, projecting that by 2050, production of certain critical minerals, such as lithium, cobalt, and graphite, could increase by almost 500% Hund et al. (2023).

Despite this growing demand for critical minerals of importance for the green transition, their production remains highly concentrated among a few countries. The International Energy Agency's (IEA) 2021 report titled *The Role of Critical Minerals in Clean Energy Transitions* projected that in 2023, the top three producing countries would account for over 75% of total global output for lithium, cobalt, and rare earth elements. This concentration is even more skewed when it comes to certain specific elements due to their capital-intensive nature of production.

It must be noted that quantitative restrictions are generally prohibited by the rules governing international trade, as set by the WTO (GATT Article XI). How-ever, their use is allowed under certain specific circumstances, for instance, for the protection of human, animal or plant life or health (GATT Article XX:b), environ-mental reasons (GATT Article XX:g), national security (Article XXI:b), or balance-of-payments reasons (GATT Articles XI:2, XII).

The remainder of the paper is structured as follows: Section 2 presents data and descriptive statistics. Section 3 presents empirical strategy and results. Section 4 concludes and offers some policy implications.

2. Data and descriptive statistics

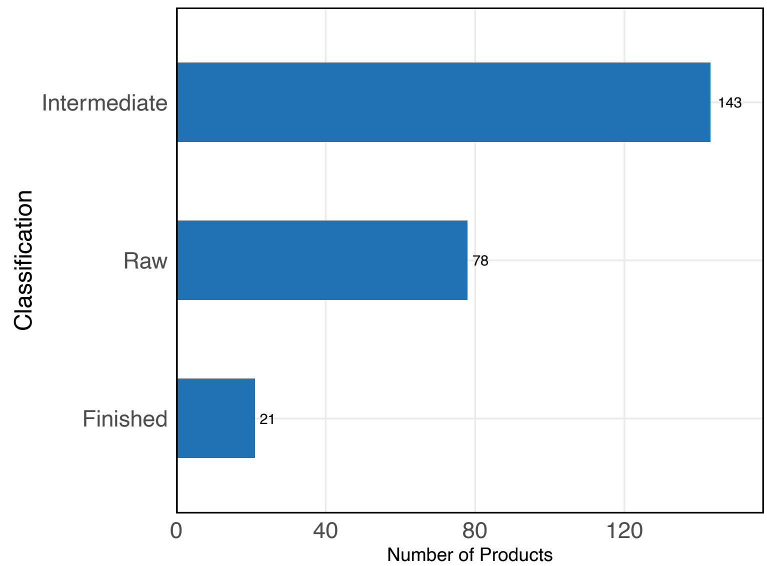
2.1 Critical mineral green products

We utilize the novel Trade in Critical Minerals (TiCM) database, developed through a collaboration between the Asian Development Bank (ADB) and the World Trade Organization (WTO). TiCM identifies 242 products as essential for green transition.[3] The products comes from all three stages of the supply chain, namely the raw and semi-processed materials (e.g. Gold unwrought, Copper ores), intermediate products (e.g. Copper waste, Aluminum alloy), and finished products (e.g. Solar diodes, Battery parts) reflecting critical minerals' role in clean technologies such as electric vehicles, solar panels, and batteries.[4]

The TiCM constructs critical mineral green products data for green trade by selecting product-level data from UN Comtrade. Product selection is informed by international classifications and criticality frameworks, including the methodology proposed by Graedel et al. (2012b), which evaluates metals based on supply risk, environmental implications, and vulnerability to supply disruptions.

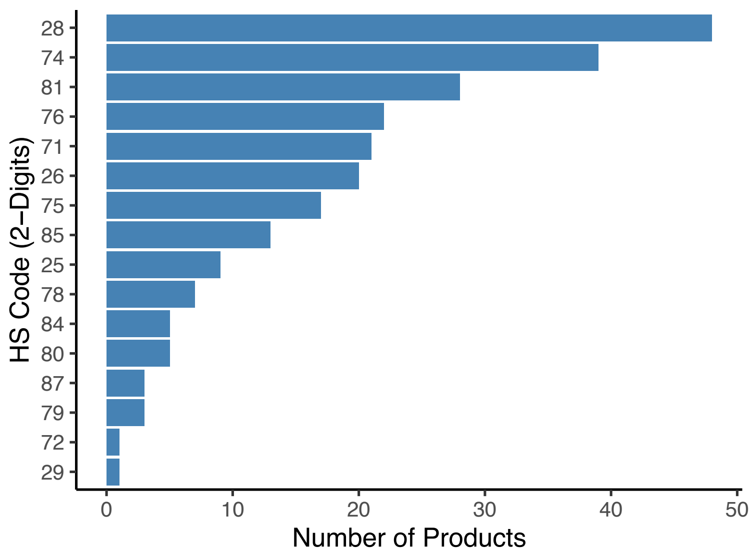
Figure 3 displays the number of products identified by ADB-WTO as mineral products for green transition, grouped by 2-digit HS codes. The classification shows a strong concentration of products in HS 28 (inorganic chemicals) and HS 74 (copper and articles thereof), followed by HS 81 (other base metals, including cobalt and tungsten) and HS 26 (ores, slag, and ash). These categories reflect upstream and intermediate processing stages of critical mineral supply chains, particularly relevant to battery components, solar technologies, and electric vehicles. The figure highlights that a small number of HS chapters dominate the classification of critical mineral green products, underscoring the strategic importance of chemical compounds and refined base metals in the clean energy transition.

Figure 2: Number of critical mineral green products identified by ADB–WTO



Source: Authors' own calculations based on ADB–WTO classification.

Figure 3: Number of critical mineral green products at 2-digit HS code level



Note: Authors' own calculations based on ADB–WTO classifications

3. This identification employs the methodology discussed in Graedel et al. (2012b).

4. Electric vehicles, solar panels, and batteries are finished critical mineral green products.

2.2 Export restrictions

Our study relies on a dataset of industrial policies (IPs) during 2009–2022, which is compiled by Juhász et al. (2025) from the Global Trade Alert (GTA) database Evenett et al. (2022). We select the GTA for its systematic and comprehensive coverage of trade policy interventions, where export related interventions are a subset which is the focus of our research.

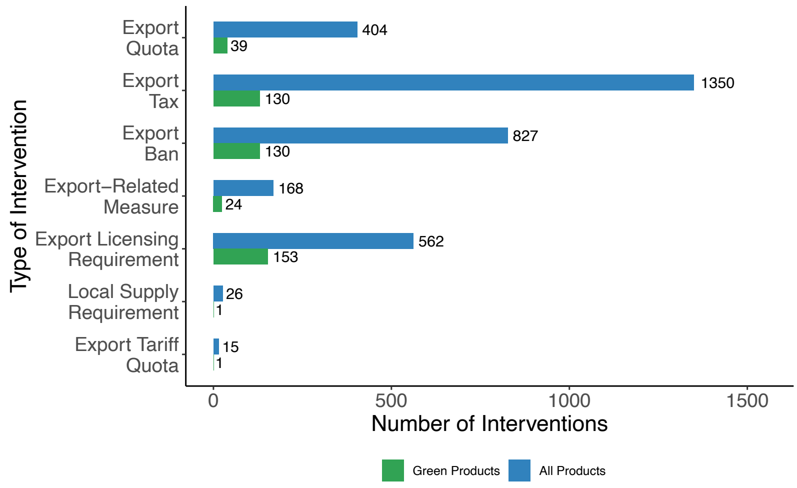
In this paper, we define export restrictions as comprising of seven GTA policy intervention types, such as: "Export ban", "Export licensing requirement", "Export quota", "Export-related non-tariff measure, n.e.s.", "Export tariff quota", "Export tax", and "Local supply requirement for exports". We also include "Export tax" to this definition as this curtails export activity, regardless of whether or not it generates government revenue. Clarisse (2022) defines export restrictions as tools that actively restrict export activity to achieve industrial policy goals—such as promoting domestic processing or lowering local prices—rather than those primarily aimed at generating government revenue.

The Global Trade Alert (GTA) dataset reports an export restriction by recording the data on the country that implements a restriction both bilaterally and unilaterally, along with a list of affected products identified by their HS codes at the 6-digit level. To assess the relevance of these interventions to critical mineral green products, we merge the dataset based on the information of implementing country, year, affected country and associated product codes with a predefined list of critical mineral green products at the HS6 level, as defined in Section 2.1. This matching process enables us to identify whether a given intervention targets at least one critical mineral green product. As a result, we construct a product-level dataset of critical mineral green products that flags any export related intervention on it.

Figure 4 summarizes the distribution of export restrictions across all products in the GTA database, and compares them to those that specifically target critical mineral green products. For instance, out of 827 recorded export bans, only 130 are found to involve at least one critical mineral green product. A similar pattern holds across other intervention types, such as export licensing requirements and export-related non-tariff measures. This indicates that while export restrictions are widely used, only a fraction of them are targeted at critical mineral green products.

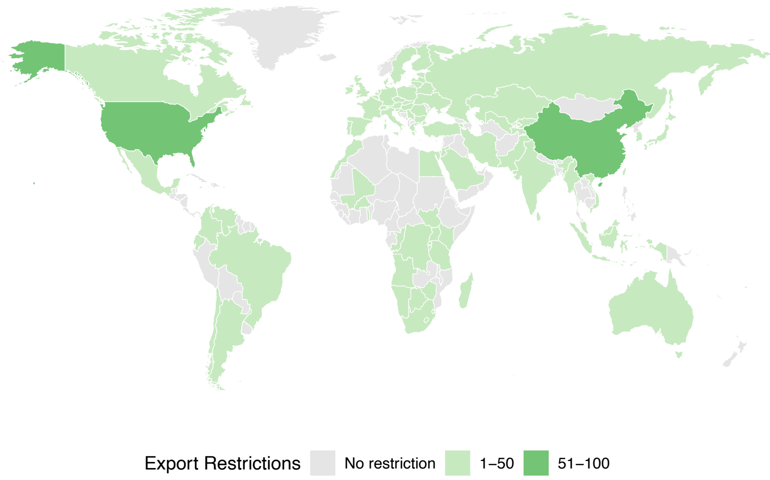
Figure 5 presents the global distribution of export restrictions by showing the number of export interventions implemented by each country. Countries are shaded according to the total number of interventions recorded in the GTA database. Darker shades indicate a higher number of export restrictions. Notably, China stands out with more than 100 interventions, followed by countries such as the United States, India, and Russia, each with a moderate to high number of restrictions (51–100). In contrast, many countries, particularly in Sub-Saharan Africa and parts of Southeast Asia, implement fewer than 50 interventions or none at all. This geographic dispersion underscores the concentration of export-related policy activity in large economies characterized by substantial trade volumes and strategic industrial interests.

Figure 4: Export restrictions on all GTA listed products vs. critical mineral green products



Note: Authors' own calculation based on GTA data by Evenett et al. (2022).

Figure 5: Number of restrictions by implementing countries



Source: Authors' own calculations based on GTA data by Evenett et al. (2022)

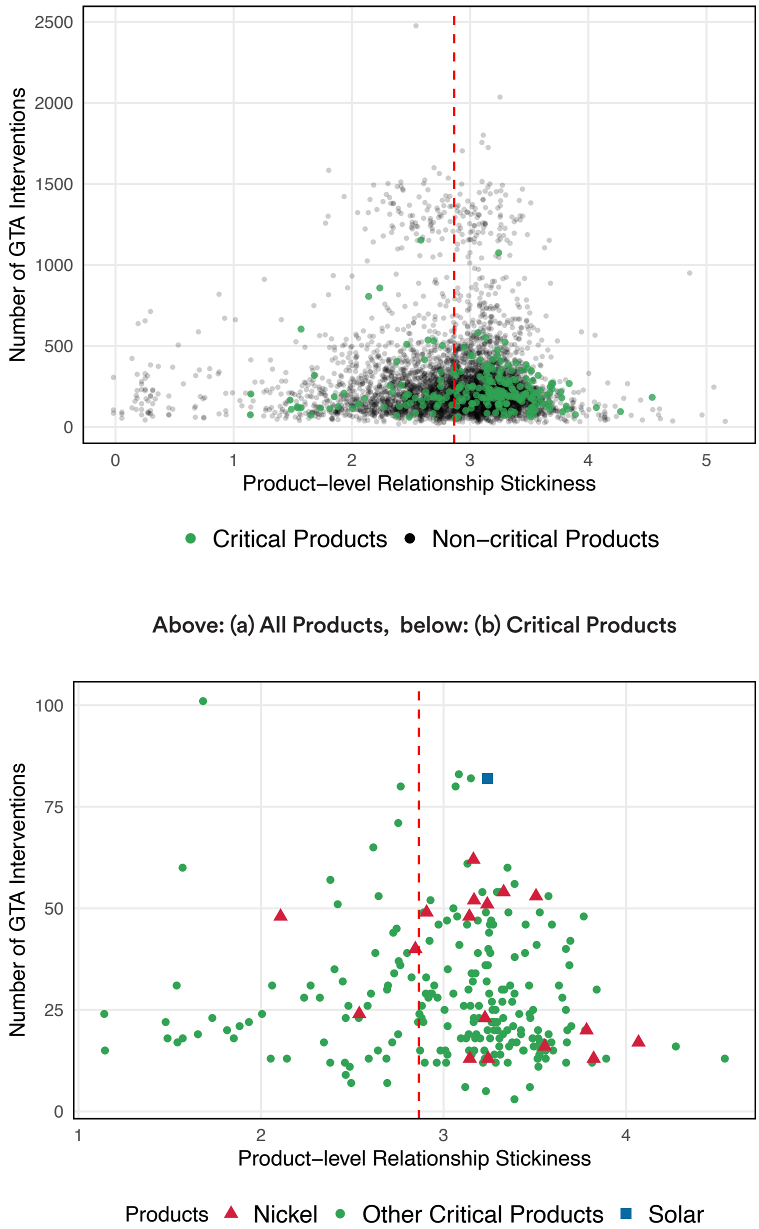
2.3 Product stickiness

To understand the heterogeneous effects of export restrictions across products, we draw on the concept of product relationship stickiness developed by Martin et al. (2023). Relationship stickiness captures how difficult it is for firms to replace trading partners due to high search and switching costs, customization needs, or relationship-specific investments. Products with high stickiness are typically intermediates or complex components that require repeated transactions between the same buyer and seller, while low-stickiness products, such as standardized commodities are more easily substitutable. Figure 6 illustrates the distribution of relationship stickiness across products. The red line marks the sample median, dividing products into low-and high-stickiness groups. Translating this measure into trade outcomes, Figure 6b shows that out of 242 critical mineral green products, 176 lie above the median level of stickiness. On average, highly sticky products face about 30 export restrictions, compared to 25 among low-stickiness products. This pattern suggests that governments tend to target products with limited substitutability—those embedded in durable buyer–seller relationships—since restrictions on such products can exert pressure in global markets. Hence, understanding relationship stickiness provides a microeconomic foundation for why some export bans disrupt trade more severely than others.

2.4 BACI trade data

We use the BACI dataset developed by CEPII to analyze trade flows in critical mineral green products Gaulier and Zignago (2010). BACI provides harmonized international trade data covering over 200 countries for more than 5,000 HS6-level products during the period of 2007–2023. By merging this dataset with the curated list of critical mineral green products, we generate data suitable for both econometric and descriptive analysis. Here we present summary statistics that identify the leading trade partners and most heavily traded items in critical mineral green products sector.

Figure 6: Export restrictions and product stickiness

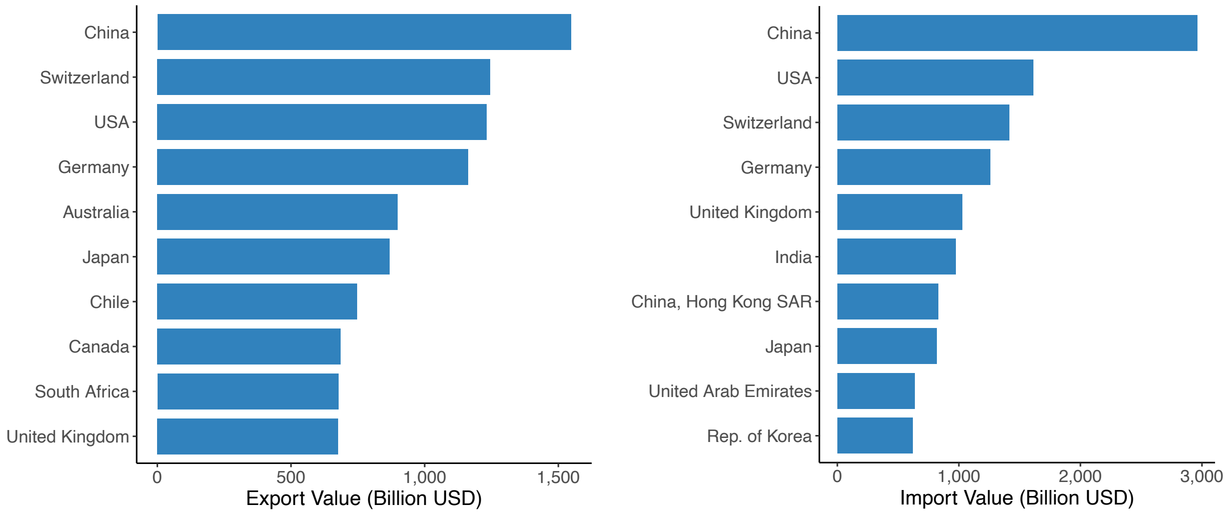


Note: Relationship stickiness is from Martin et al. (2023). The red dashed line indicates the median product-level stickiness (2.865). Nickel corresponds to HS codes are 750110, 750120, 750210, 750220, 750300, 750400, 750511, 750512, 750521, 750522, 750610, 750620, 750711, 750712, 750720, 750810, and 750890. Solar products correspond to HS code 854041. Other critical mineral green products are defined according to the TiCM classification of critical mineral green products. Authors' own calculations.

Figure 7 presents the top ten exporters and importers of critical mineral green products between 2007 and 2023. China ranks as the largest exporter and importer over the period, followed by Switzerland, the United States, and Germany. These patterns reflect the central role of advanced economies and industrial hubs in the global trade of environmentally significant materials.

Figure 8 highlights the top ten critical mineral green products traded globally. Gold (unwrought and semi-worked), copper cathodes, and solar diodes dominate the list in terms of trade value. This ranking underscores the

Figure 7: Top critical mineral green product exporters and importers (2009–2022)



(a) Top 10 exporters **(b) Top 10 importers**

Note: This figure presents the total export and import values of critical mineral green products traded between 2009 and 2022. China is the largest exporter and importer over this period.

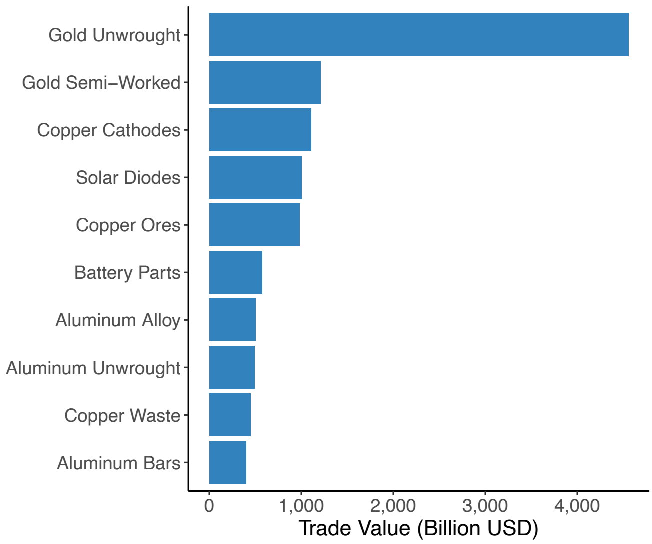
dual importance of raw materials and components essential for renewable energy technologies and low-carbon transitions.

Figure 9 presents a set of Sankey diagrams illustrating the global trade flows of four key critical mineral green products between 2007 and 2023. Each panel maps the major bilateral trade relationships, with exporters on the left and importers on the right; the width of each flow represents the cumulative trade value, enabling a visual comparison of trade volumes across countries and products.

Figure 9a focuses on copper ores (HS 260300), where Chile, Peru, and Australia emerge as the dominant exporters. China stands out as the principal importer, receiving substantial volumes from all major producers, followed by Japan, India, and the European Union. Figure 9b displays the trade of refined copper (HS 740311). Again, Chile leads the exporter list alongside the EU, Zambia, Russia, and Zambia. China and the EU are the largest importers, reflecting their central roles in copper-intensive manufacturing sectors.

Figure 9c turns to copper waste and scrap (HS 740400), where the EU and the United States are the primary exporters. China is by far the largest importer, indicating its reliance on secondary copper sources to support domestic

Figure 8: Top 10 critical mineral green products traded (2007–2023)

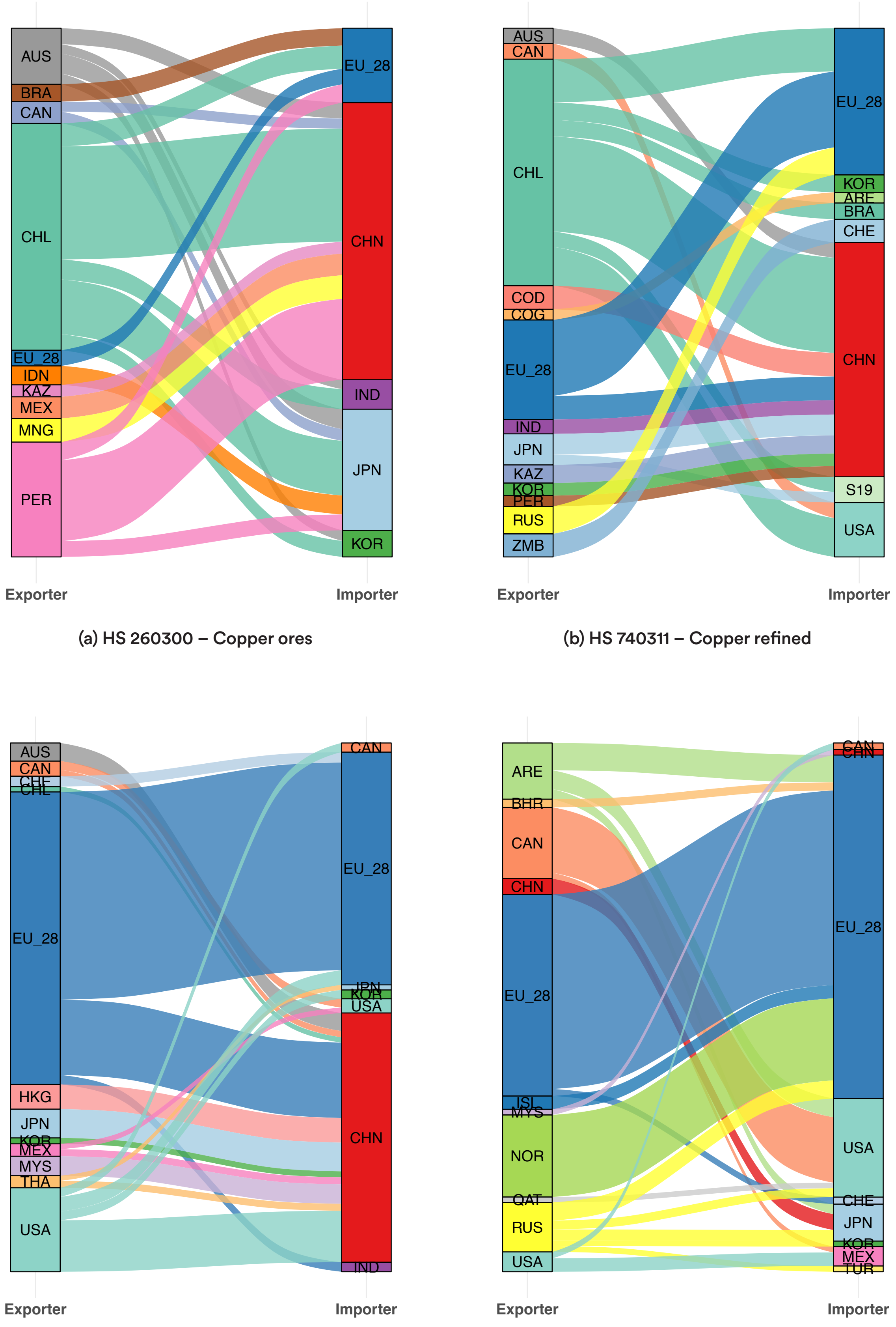


Note: The figure illustrates the total trade value of the top 10 critical mineral green products from 2007 to 2023, aggregated across all trading partners.

processing and circular economy goals. Finally, Figure 9d examines unwrought aluminium (HS 760120), with major export flows originating from the EU, Russia, the United Arab Emirates, and Canada. Key importers include the EU, United States, China, and Japan, high-lighting the global dispersion, but highly interdependent nature of aluminium supply chains.

Together, these diagrams underscore the strategic importance of a few key players, particularly China and the EU, in both the upstream and downstream segments of critical mineral trade. The data also reveal a degree of concentration and dependency that may carry implications for trade resilience and policy coordination in the context of global energy transitions.

Figure 9: critical mineral green products trade flows



(a) HS 260300 – Copper ores

(b) HS 740311 – Copper refined

(c) HS 740400 – Copper waste and scrap

(d) HS 760120 – Unwrought aluminum

3. Empirical strategy and results

This section presents our empirical strategy and results. Subsection 3.1 describes the econometric specification that quantify the impact of export restrictions on trade flows at the product level using an event-study approach. Subsection 3.2 discusses the results.

3.1 Effects of export restrictions on trade flows at the product level

We exploit the variations in export restriction measures at different product levels to estimate their impact on trade flows. Following Rotunno and Ruta (2024) and Chen (2025), we adopt an event-study specification that examines how export restrictions influence trade across different stages of production, namely, the raw materials, intermediate, and finished products.

Formally, we estimate the following regression model:

$$In\,(y_{i,k,t}) = \sum_{\ell=-10}^{10} \beta\, ExportRestriction_{i,k,t+\ell} + \delta_{i,t} + \gamma_{k,t} + \phi_{i,k} + \epsilon_{i,k,t}$$

The dependent variable $y_{i,k,t}$ denotes the value of exports of product k from country i in year t, measured at the HS 6-digit product level. The variable $ExportRestriction_{i,k,t+\ell}$ is an indicator equal to 1 if product k from exporter i is subject to an export restriction, ℓ years relative to its implementation. In Equation (1), the count ℓ denotes the period before and after the announcement of the restriction, ranging from -10 (10 years before treatment – i.e., the year 2014 for products that are treated in 2023) to 10 (10 year after treatment – i.e., 2016 for products that entered into treatment in 2007). The coefficients β captures the effects of export restrictions on trade flows before and after their introduction, ℓ years relative to its implementation.

The export restriction variable is constructed as a matrix of policy interventions recorded in the GTA database, covering various forms of export restrictions, including export bans, export taxes, export quotas, export licensing requirements, export-related measures, local supply requirements, and export tariff quotas. Each policy type represents a distinct mechanism through which governments restrict outbound trade.

The term $\delta_{i,t}$ captures exporter-year fixed effects, absorbing time-varying factors specific to the exporting country such as macroeconomic conditions, policy changes, or exchange rate fluctuations. The term $\gamma_{k,t}$ represents product-year fixed effects, controlling for global demand or supply shocks that vary by product over time. The exporter–product fixed effects $\phi_{i,k}$ account for all time-invariant characteristics specific to a country–product pair, including technological capability, resource endowment, or historical specialization. Finally, $\epsilon_{i,k,t}$ is the idiosyncratic error term. This specification isolates the causal effect of export restrictions by comparing changes in trade flows of affected products relative to unaffected ones within the same exporter–product pair and time period, thereby accounting for both observable and unobservable confounding factors across multiple dimensions.

As the empirical strategy involves multiple treatment timings, we adopt the approach of Sun and Abraham (2021) to correct for the negative bias associated with the conventional two-way fixed effects estimator.

3.2 Results

Figure 10 presents the event–study estimates of export restrictions on critical mineral green product trade flows. The pre-treatment coefficients are close to zero and statistically insignificant, indicating the absence of differential pre-trends between treated and untreated products prior to the introduction of export restrictions. This sup-ports the validity of the identifying assumption that, in the absence of restrictions, trade flows would have evolved similarly across groups. After the implementation of export restrictions, the coefficients turn negative and remain below zero for several years, suggesting a persistent decline in exports following policy intervention.

Referring to Table 1, the average treatment effect on the treated (ATT) for log quantity is estimated at −0.126 and is statistically significant at the 10 percent level.

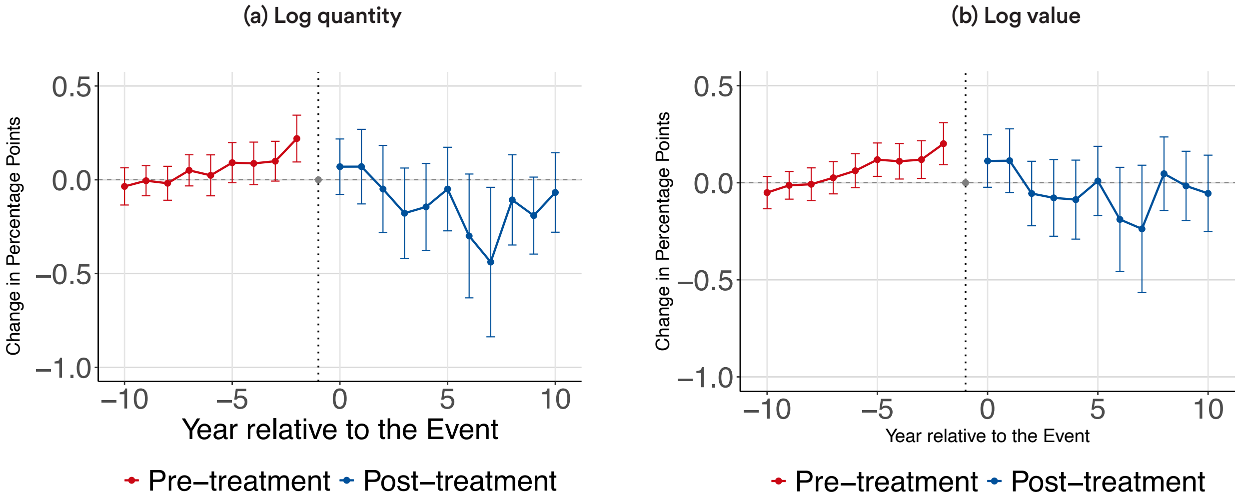
This implies that export restrictions reduce export quantities by approximately 11.8 percent relative to the counterfactual level in unrestricted products.[5] In contrast, the effect on log value is also negative (−0.039) but not statistically significant, indicating that while export restrictions significantly constrain the physical volume of trade, the corresponding decline in export values is less pronounced, possibly due to price adjustments or compositional effects in the restricted products.

Robustness check: As a robustness exercise, we re-estimate Equation (1) focusing exclusively on raw critical minerals, defined as products under HS Chapters 25 and 26 following Chen (2025). These commodities represent the upstream segment of global production chains and are particularly exposed to export restrictions that target raw material supplies.

Figure 11 presents the event-study estimates, while Table 2 reports the corresponding regression results. The coefficients trace a sharp decline in export quantities immediately after the introduction of export restrictions, followed by a persistent contraction in subsequent years. The effect on export value is similarly negative, al-though slightly less pronounced. The post-treatment coefficients are statistically significant, while pre-trend estimates remain close to zero, indicating no anticipatory effects prior to the implementation of restrictions.

5. Using semi-elasticities of 'Export Restriction', the trade effects are calculated in percentage terms as $(e^{\beta\, dummy} - 1) \times 100$.

Figure 10: Event-study: baseline



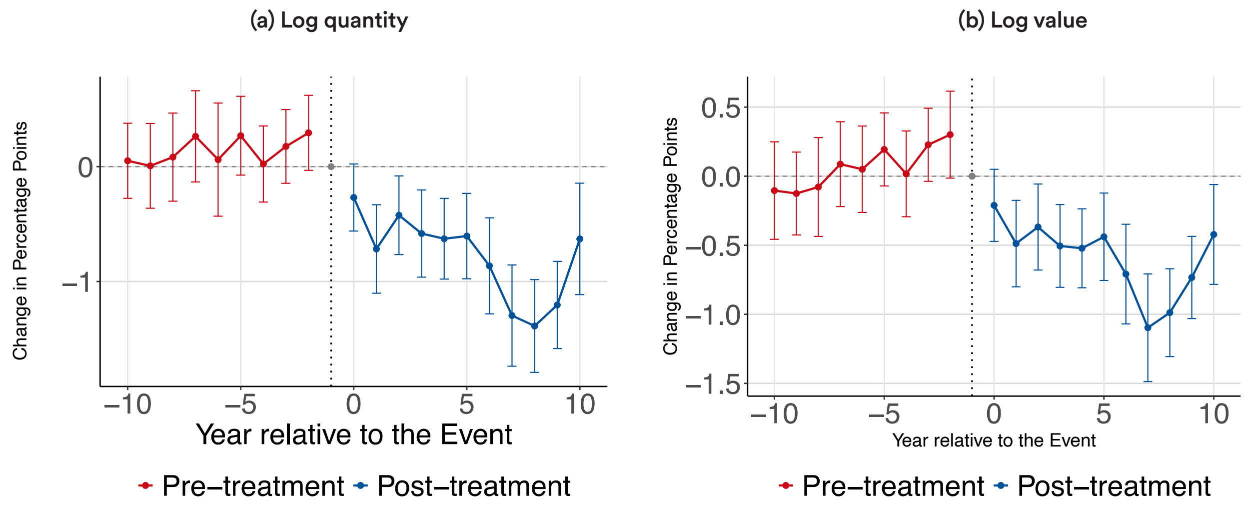
Note: Event–study estimates are based on Equation (1), following the methodology of Sun and Abraham (2021). Confidence intervals are shown at the 95% level, with standard errors clustered at the exporter–product level.

Table 1: Regression results: Export restrictions and trade outcomes

	Dependent variable	
	Log quantity	Log value
Export Restriction	-0.126*	-0.039
	(0.074)	(0.059)
Exporter–Product FE	✓	✓
Country×Year FE	✓	✓
Product×Year FE	✓	✓
Observations	177,743	177,743
R^2	0.882	0.882

Note: Regressions estimates are based on Equation (1), following the methodology of Sun and Abraham (2021). Standard errors are clustered at the exporter–product level. *p < 0.1, **p < 0.05, ***p < 0.01.

Figure 11: Event-study: Robustness check



Note: Event–study estimates are based on Equation (1), following the methodology of Sun and Abraham (2021). Confidence intervals are shown at the 95% level, with standard errors clustered at the exporter–product level.

Table 2: Robustness check with HS Code 25 and 26: Export restrictions and trade outcomes

	Dependent variable	
	Log quantity	Log value
Export Restriction	-0.782***	0.589***
	0.116)	(0.102)
Exporter–Product FE	✓	✓
Country×Year FE	✓	✓
Product×Year FE	✓	✓
Observations	74,619	74,688
R^2	0.840	0.845

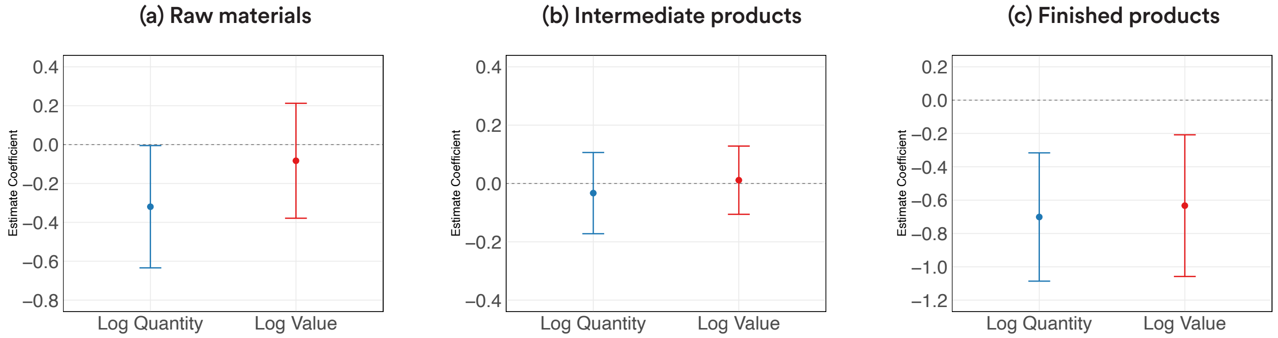
Note: Regressions estimates are based on Equation (1), following the methodology of Sun and Abraham (2021). Standard errors are at the exporter–product level. *p < 0.1, **p < 0.05, ***p < 0.01.

Different product classification. In this part we analyse the impact of export restriction with disaggregated product classifications. The TiMC classifies (Figure 2) the critical mineral green products into three categories, namely, raw material, inter-mediate input and finished products. Products at different stages of the supply chain differ in their importance to the green transition. Thus, we now run regressions by subgroups. This section examines which product classifications are more affected by export restrictions imposed by the exporter.

Product relationship stickiness: Building on the product classification, we next examine which types of products are most sensitive to export restrictions. We capture this heterogeneity using product relationship stickiness, a measure developed by Martin et al. (2023), which reflects how costly it is for firms to switch suppliers. Based on Figure 6, raw materials fall under high relationship stickiness category whereas finished products fall under low relationship stickiness category. As discussed in Section 2.3, export restrictions are positively correlated with product stickiness, implying that products with higher switching costs and fewer substitutes tend to be more relationship-specific. In such cases, restrictions are expected to generate stronger negative trade effects, due to the fact that firms cannot easily replace constrained suppliers.

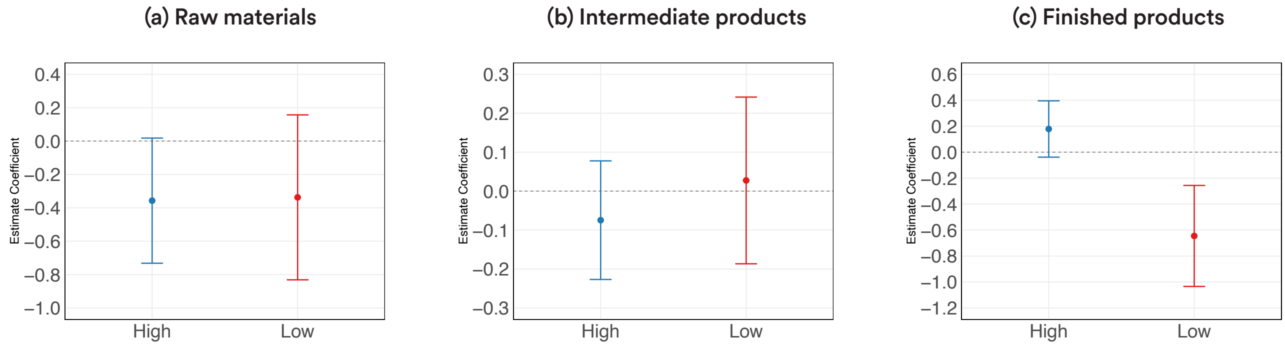
Figure 13 illustrates these heterogeneous effects by product type. For raw mate-rials (Figure 13a), the coefficient for high-stickiness products is −0.357 and statistically significant at the 10% level. This implies that export restrictions reduce trade in high-stickiness raw materials by approximately

Figure 12: Export restrictions by product classification



Note: Coefficient plot estimates are based on Equation (1), following the methodology of Sun and Abraham (2021). Confidence intervals are shown at the 95% level, with standard errors clustered at the exporter–product level.

Figure 13: Export restrictions and product stickiness by product type



Note: Coefficient Plot estimates are based on Equation (1), following the methodology of Sun and Abraham (2021). Confidence intervals are shown at the 95% level, with standard errors clustered at the exporter–product level.

30%.[6] The negative and significant result for raw materials is consistent with the findings in Figure 12a, where trade in raw materials declines when export restrictions are imposed.

This pattern is in alignment with the evidence in Liu et al. (2025), who show that targeted products experience a reduction in imports by sanctioned countries, and with Chen (2025), who finds that exports of such targeted critical raw materials decrease. A higher degree of product relationship stickiness indicates that these raw materials have fewer substitutes, leading to a more pronounced contraction in trade volumes when restrictions are applied. In contrast, the effect is weaker and statistically insignificant for low-stickiness raw materials, where firms can more easily substitute across suppliers or adjust sourcing patterns in response to trade restrictions.

For intermediate products, according to Figure 13b, the coefficients are not statistically significant, indicating that supply-chain adjustments may be more complex and possibly offset by substitution across products within production networks.

Finally, for finished products, referring to Figure 13c; the higher product stickiness shows no significant effect, while the low-stickiness group exhibits a negative and statistically significant coefficient. This pattern suggests that finished products with lower product stickiness experience a greater reduction in trade when an export restriction is imposed on the product. This is because products traded in more competitive markets are more immediately affected by export restrictions, possibly reflecting demand contraction rather than long-term relational rigidity.

Overall, these results align with Martin et al. (2023)'s interpretation that stickier products are less responsive to short-run shocks such as uncertainty or policy interventions. In this context, this implies that export restrictions primarily disrupt trade in products with lower relational rigidity, while high-stickiness sectors experience smaller but more persistent effects due to entrenched supplier–buyer ties.

6. Using semi-elasticities of 'Export Restriction', the trade effects are calculated in percentage terms as $(e^{\beta\, dummy} - 1) \times 100$.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4. Conclusion and policy implications

Based on the empirical analysis, it is clear that export restrictions have a significant and negative impact on the trade flows of critical mineral green products, which are essential for clean energy transition. Our findings indicate that, on average, export restrictions lead to an approximate 11.8% reduction in the export of critical mineral green products. However, the effects of these trade barriers are not uniform, and varies significantly depending on the type of product. Our analysis reveals that the negative trade impact is particularly strong for raw materials with high “relationship stickiness”, implying that they are difficult to substitute and have high supplier-switching costs. For these high-stickiness raw materials, which are also characterised by high geographical concentration, export restrictions lead to a trade reduction of about 30%. This indicates that policies restricting the export of these specialized raw materials can be particularly disruptive to global supply chains. Conversely, for finished products, it is the products with low stickiness that are most affected, suggesting that markets with more competition and easier substitution are more immediately impacted by such restrictions potentially due to immediate surge in prices, supply shocks, and scramble for alternatives. For intermediate products, the impact of export restrictions was found to be statistically insignificant.

The findings of this paper have several important policy implications. One, as critical raw materials are characterised by relationship stickiness due to their concentrated supply and limited substitutability, export restrictions at this stage have dramatic impact on trade volumes. Therefore, policymakers should weigh the benefits they may accrue from short-term protectionist policies against its long-term risk of increased supply chain disruptions, impact on competitiveness, increased costs and delayed transition to a low-carbon economy.

Two, the concentration of export-related policy restrictions in large economies with strategic industrial interests means that such economies have significant power and responsibility to influence the global market for critical mineral green products. As key exporters and processors of critical raw materials, the ability to shape market dynamics, influence investor decisions, and assist downstream industrial development worldwide, places them at the centre of global supply chains. Therefore, there is an urgent need to ensure greater transparency, monitoring, and discipline in the trade of critical mineral green products such that any form of export distortions is minimal. This can be achieved through greater dialogue in existing multilateral forums.

Three, for importing countries, the findings highlight the vulnerability of relying on a limited number of suppliers for critical material products, especially those with high relationship stickiness such as raw materials. In such cases, domestic policies should encourage the diversification of sourcing and investment in domestic production or recycling to reduce dependency and enhance their supply chain resilience.

Lastly, the varied impact of restrictions across different product types suggests that broad, untargeted policies may have unintended consequences. Policymakers should consider the specific characteristics of the products they are targeting, such as their substitutability and position in the value chain, to avoid unnecessary disruptions.

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Kaurna acknowledgement
We acknowledge and pay our respects to the Kaurna people, the original custodians of the Adelaide Plains and the land on which the University of Adelaide's campuses at North Terrace, Waite, and Roseworthy are built. We acknowledge the deep feelings of attachment and relationship of the Kaurna people to country and we respect and value their past, present and ongoing connection to the land and cultural beliefs. The University continues to develop respectful and reciprocal relationships with all Indigenous peoples in Australia, and with other Indigenous peoples throughout the world.