Digging Up the Value Chain: Mineral Export Restrictions and Industrial Upgrading

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Abstract

This paper studies mineral export restrictions as an instrument of industrial policy. I develop a general equilibrium model in which export restrictions lower domestic mineral prices and implicitly subsidize downstream manufacturing. Welfare gains, however, require the activation of scale externalities in downstream sectors, except when the restricting country has substantial market power in mineral markets. Using a novel global dataset of mineral export restrictions combined with product-level upstream-downstream linkages, I show that this condition is largely unmet. While downstream exports rise in both value and quantity following restrictions, these gains dissipate rapidly along the value chain and are confined to basic metal products, the immediate downstream sector. There is no significant export-stimulating effect for technologically complex goods or products that rely on extensive complementary inputs. Overall, mineral export restrictions can generate sector-specific downstream gains but are insufficient to induce the broad-based industrial upgrading that many developing country governments envision.

Keywords: Export restrictions, industrial upgrading, industrial policy.
JEL Codes: F13, F14, O14, O25.

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1 Introduction

Minerals are no longer simply for sale. In recent years, resource-rich developing countries have increasingly adopted export restrictions on raw minerals as part of their industrialization strategies (OECD, 2025). These measures, ranging from taxes and quotas to outright bans, are often framed as industrial policy tools to promote domestic processing, capture greater value added, and reduce dependence on volatile commodity revenues. Yet despite their growing prevalence, the economic rationale behind these policies remains poorly understood. Why do governments increasingly turn to mineral export restrictions over other instruments? Through what mechanisms can such restrictions promote downstream industrial development and improve domestic welfare? And do they actually work in practice? This paper addresses these interrelated questions using novel global data on the use of such restrictions. The answer is nuanced: economic theory offers ambiguous welfare predictions, as potential terms-of-trade gains and downstream scale externalities must be weighed against the allocative distortions they create. Empirically, while such restrictions do stimulate downstream exports, the gains are confined to basic processing stages and fall short of broad-based industrial upgrading.

I first document three stylized facts that shed light on the growing popularity of mineral export restrictions. First, developing countries tend to specialize in exporting upstream products while importing processed goods, creating incentives to promote higher value-added downstream activities through industrial policy. Second, while poorer countries adopt fewer industrial policy interventions overall, export restrictions account for a much larger share of their policy portfolio. I relate this observation to the fiscal pressure these governments face: export restrictions are administratively simpler than subsidies or directed credit and require minimal fiscal outlays. Third, raw minerals are natural targets for such measures: extracted directly from nature, they occupy the most upstream positions in global value chains, while resource-rich economies tend to exhibit strong revealed comparative advantage in these minerals but not in their downstream products. This asymmetry offers a classic rationale for industrial policies designed to unlock latent comparative advantages (Harrison and Rodríguez-Clare, 2010). Together, these facts explain why mineral export restrictions have become a popular instrument for promoting downstream industrialization. Whether this popularity is warranted depends on the mechanisms through which such restrictions operate.

To clarify the mechanisms and welfare implications of mineral export restrictions, I develop a parsimonious two-country, two-sector general equilibrium model. The framework features an upstream mining sector that relies on exogenous mineral reserves and a downstream manufacturing sector characterized by external economies of scale. Modeled as an export tax, mineral

export restrictions create a wedge between domestic and world mineral prices, acting as an implicit subsidy to downstream manufacturing. This triggers labor reallocation toward manufacturing, with output expanding more than proportionally through scale externalities. The welfare effect of such export taxes is theoretically ambiguous, reflecting the interplay between potential terms-of-trade gains, efficiency gains from scale externalities, and the allocative distortions they introduce. Nevertheless, the model delivers a testable implication: absent substantial market power in mineral markets, downstream manufacturing expansion is a necessary condition for domestic welfare improvement, as scale externalities are then the only channel through which the policy can offset its distortion costs.

The rest of the paper addresses the empirical questions motivated by the model: do mineral export restrictions actually induce downstream manufacturing expansion, and if so, do such gains extend beyond immediate downstream sectors to generate broader industrial upgrading? I focus on exports as the empirical counterpart to domestic production. In small open economies, export performance closely tracks sector size, and the model's prediction of downstream expansion should manifest as increased downstream exports if the scale channel is operative. Answering this question requires overcoming two empirical challenges. First, existing data on mineral export restrictions are fragmented and lack systematic global coverage. I construct a novel dataset spanning 2008–2023 using the Global Trade Alert (GTA) database, documenting 125 restriction episodes targeting raw minerals in HS Chapters 25 and 26, implemented by 29 developing countries. Second, mapping upstream-downstream linkages at sufficient granularity is difficult: conventional input-output tables are too coarse to trace specific downstream uses of raw minerals, given their low substitutability across types. I employ the AI-generated production network (AIPNET) developed by Fetzer et al. (2024), which identifies upstream-downstream relationships at the HS6 level using large language models. Linking these datasets with HS6-level global trade data from CEPII-BACI, I examine how export restrictions affect exports of both targeted minerals and downstream products at different stages of processing.

Exploiting variation in the timing, implementing country, and product coverage of mineral export restrictions, I estimate their effects on export value and quantity along the value chain using a triple-differences framework that controls for country–product, country–year, and product–year fixed effects. I first estimate the direct effects on exports of the restricted minerals themselves, and then examine downstream effects by leveraging upstream–downstream linkages from AIPNET to identify products that rely on restricted minerals as inputs. Throughout, export restrictions are treated as absorbing at the country–product level: once a restriction is introduced, the treatment indicator remains active thereafter. This reflects both the structure of the policy

data, in which removals are often unobserved or replaced by other restrictive measures, and the staggered-adoption design underlying the empirical strategy. All regressions are estimated using Poisson pseudo-maximum likelihood (PPML), which accommodates heteroskedasticity and the prevalence of zero trade flows.

The first set of results establishes that mineral export restrictions bind in practice, generating large and persistent declines in exports of the targeted minerals. Export values fall by 37 percent and export quantities by 57 percent on average following the imposition of a restriction, while unit values rise modestly. Event-study estimates confirm the absence of pre-trends and show that export declines persist and intensify over time. The contraction operates primarily along the intensive margin: export volume falls sharply, but export participation and destination concentration remain largely stable, indicating that restrictions curtail mineral exports mainly by reducing shipments to existing trading partners rather than inducing exit from export markets.

Turning to downstream outcomes, the results show that mineral export restrictions generate positive but uneven export responses. On average, upstream restrictions increase downstream export values by 11 percent and export quantities by 19 percent, with no systematic change in unit values. These gains accumulate gradually over time and are accompanied by some diversification along the destination margin, as downstream exporters reach a larger number of foreign markets and become less reliant on a small set of dominant buyers. However, they fall short of broad-based industrial upgrading: export expansion occurs predominantly in products where countries already possess a revealed comparative advantage, rather than through entry into new product lines. Positive downstream effects also require substantial market power in the targeted minerals to materialize.

Most importantly, downstream responses are highly uneven along the value chain. I develop a graph-theoretic approach to identify the relative downstreamness of products with respect to restricted minerals, and group downstream products by their position along mineral-related production networks. Export gains are confined to the earliest processing stages: for products located closest to raw minerals, export values and quantities increase by 17 and 31 percent, respectively, while those at more advanced stages show no statistically significant response. Moreover, export growth at early stages is driven primarily by quantity expansion rather than value upgrading, suggesting that restrictions stimulate volume rather than foster movement into higher-value activities. Sectoral evidence mirrors these patterns. Export gains are concentrated in basic metal products, the most immediate downstream sector of raw minerals, whereas technologically sophisticated industries such as machinery and electronics, transport equipment, and precision instruments exhibit negligible or even negative effects.

Evidence on the underlying mechanisms reveals why gains do not extend further down the value chain. Partitioning downstream products by technological complexity and complementary input requirements reveals that export gains arise exclusively among technologically simple products with low reliance on intermediate inputs, for which export values and quantities increase by up to 40 percent following upstream restrictions. In contrast, products with higher complexity or greater input reliance show little to no response. Taken together, these findings indicate that mineral export restrictions reallocate activity toward mineral-intensive and technologically simple processing stages but do not generate broad-based industrial upgrading or facilitate entry into more advanced value chain segments.

The baseline results are robust to a range of alternative specifications. Re-estimating using log-linear OLS yields coefficients very similar to the PPML results. To address concerns about staggered adoption and heterogeneous treatment effects, I apply recent difference-in-differences estimators robust to treatment timing, which confirm the absence of pre-trends and produce post-treatment dynamics closely aligned with the baseline. The results are also robust to restricting the sample to developing countries, excluding China, focusing on ever-treated countries and products, and removing broad non-targeted policy episodes. Alternative definitions of raw minerals, including metallic versus non-metallic minerals, ore-only classifications, and the ADB-WTO critical minerals list, leave the qualitative conclusions unchanged.

While the main analysis uses exports as a proxy for domestic production, I also present indirect evidence on production-side adjustments using global mine production data from the U.S. Geological Survey and downstream import data. Mineral export restrictions do not reduce upstream mining output, while imports of mineral-related downstream products decline following policy implementation. Together with the export results, these patterns are consistent with raw minerals being diverted from export markets toward domestic processing rather than a contraction in extraction activity. Importantly, these domestic adjustments also mirror the uneven downstream export responses documented earlier: reductions in import dependence are concentrated in basic processing stages and do not extend to more technologically complex or input-intensive industries.

Taken together, this paper speaks to both the potential and the limitations of mineral export restrictions as an industrial policy tool. The theoretical analysis shows that welfare gains require activating scale externalities in downstream manufacturing, a condition that the empirical evidence only partially supports. While such restrictions do stimulate exports of basic processed goods, the absence of responses in technologically complex sectors suggests that scale externalities are limited in scope. Complementary measures, such as building productive capabilities,

adopting frontier technologies, and easing input bottlenecks, are therefore needed for countries to climb further up the value chain. These results underscore the need for realistic expectations about what trade-based interventions can achieve, and point to important complementarities between restrictive measures and capacity-building policies. As resource nationalism and industrial policy return to the forefront of economic policy worldwide, understanding these trade-offs becomes increasingly critical for policymakers navigating the tensions between short-term revenue needs and long-term development objectives.

Related Literature. This paper contributes to four strands of literature. First, it directly speaks to the literature on trade and industrial policy (Harrison and Rodríguez-Clare, 2010; Juhász et al., 2023; Reed, 2024). Recent empirical studies have documented substantial gains from targeted industrial policy instruments in the East Asian growth miracles (Liu, 2019; Barwick et al., 2025; Lane, 2025). These findings, however, stand in contrast to contemporaneous theoretical work suggesting that welfare gains from exploiting economies of scale through industrial policy are at most modest (Lashkaripour and Lugovskyy, 2023; Bartelme et al., 2025). Whether industrial policy can induce the same growth paths in developing countries today remains an open question. This paper examines mineral export restrictions, an industrial policy tool particularly relevant for resource-rich developing countries, and provides the first empirical assessment of their effectiveness in promoting downstream industrial upgrading.

This paper also contributes to the extensive literature on natural resources and development, particularly research on the Dutch disease (van der Ploeg, 2011; Venables, 2016; Mien and Goujon, 2021). It is well known that resource rents can generate de-industrialization pressures through real exchange rate appreciation and factor reallocation (Corden and Neary, 1982), while weak governance and uneven rent distribution amplify these effects (Mehlum et al., 2006; Ross, 2015). However, most existing studies adopt a macroeconomic perspective, focusing on aggregate outcomes such as GDP growth. While macro-stabilization tools like sovereign wealth funds have been widely discussed, the role of industrial policy in resource-rich economies received far less attention. Such countries may in fact require *more*, rather than less, industrial policy, as the "adverse specialization" of their economies creates pervasive market failures (Asche, 2018). Furthermore, the existing literature focuses predominantly on oil exporters, whereas countries with mineral resources may face different constraints (Davis, 1995). With global demand for critical minerals surging, these mineral-rich economies may have greater opportunities to achieve economic diversification through targeted industrial policies.

On mineral export restrictions, this paper is most closely related to the recent work of Bosker et al. (2025) and Kee and Xie (2025), which examine the downstream effects of Indonesia's nickel export ban, and to Alfaro et al. (2025), which documents spillover effects of China's rare-earth export ban on downstream technological innovation through global supply chains. While these studies analyze specific national policies, this paper provides the first systematic empirical assessment of mineral export restrictions across countries and mineral products worldwide. In doing so, it complements existing descriptive accounts of export restrictions on critical minerals in the context of rising demand from high-tech industries and increasing geopolitical tensions (Kim, 2010; Korinek and Kim, 2011; Wu, 2020).

Finally, this paper relates to the literature on countries' (revealed) comparative advantage and its evolution over time (Costinot et al., 2012, 2013; Levchenko and Zhang, 2016; Antràs and De Gortari, 2020). Atkin et al. (2021) formalize the famous "development ladder" metaphor, showing that trade can trap countries on the lower rungs of specialization and lead to dynamic welfare losses. Rather than assuming that productive capacity automatically improves through learning-by-doing in lower stages of production, this paper examines mineral export restrictions as a policy instrument through which governments explicitly attempt to climb the ladder and identifies key barriers that prevent these countries from success. As such policies aim to develop industries in which countries currently lack comparative advantage, this paper also speaks to the classic literature on infant industry protection, albeit operating through export restrictions rather than import tariffs (Krueger and Tuncer, 1982; Head, 1994; Melitz, 2005).

The remainder of the paper is organized as follows. Section 2 documents stylized facts on export restrictions and their targeting of raw minerals. Section 3 develops the theoretical framework. Sections 4 and 5 describe the data sources and empirical strategy. Sections 6 and 7 report the main findings and a range of robustness exercises. Section 8 provides complementary evidence on domestic manufacturing production. Section 9 concludes.

2 Stylized Facts

This section presents three stylized facts that underpin the use of mineral export restrictions. First, a country's position in the global trading system is closely correlated with its level of development, with poorer countries specializing in more upstream products. In response, many developing countries have turned to industrial policies aimed at moving up the value chain. Second, among all industrial policy instruments, export restrictions have become a particularly common choice and are used predominantly by developing countries. Third, the distinctive

characteristics of raw minerals, most notably their position at the early stages of production, make them especially attractive targets for such measures.

2.1 Trade Specialization and Development

I start by examining the relationship between a country's development level and its position in the global trading system, measured by the average upstreamness of its export basket. As shown in Figure 1, countries with higher income levels tend to have lower average export upstreamness. In other words, richer countries export goods closer to final demand, whereas poorer countries mainly export upstream goods such as raw materials and basic intermediates. In the sample excluding oil exporters, a doubling of GDP per capita is associated with a 0.164-stage shift in the average export composition toward final demand.

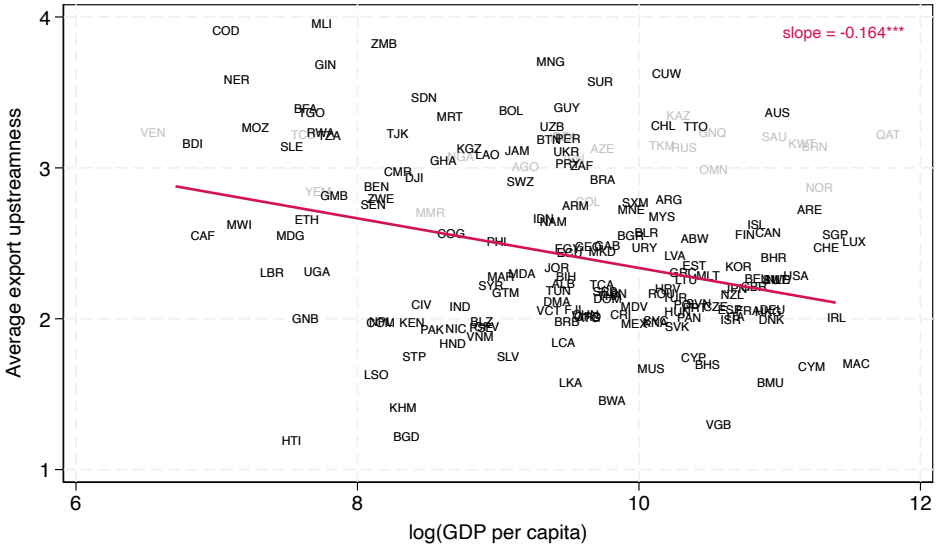


Figure 1. Income levels and trade specialization

Notes: This figure shows the relationship between a country's real GDP per capita (from Penn World Table v10.01) and its average export upstreamness in 2015, constructed using CEPII-BACI export data and product-level upstreamness measures from Liao et al. (2020). Countries where mineral fuels (primarily oil) account for more than 50% of total exports are shown in gray and excluded from the linear regression.

The observed negative correlation suggests that developing countries are relatively specialized in upstream sectors. This raises a classic question in development policy: shall countries accommodate their current position, or shall they attempt to move downstream, even at the expense of short-term efficiency? In his well-known debate with Justin Lin on industrial policy, Ha-Joon Chang argues that developing country governments should actively promote higher

value-added activities to accelerate structural economic transformation (Lin and Chang, 2009). The rationale behind this developmentalist approach rests on the premise that downstream sectors are subject to unrealized Marshallian externalities or coordination failures that leave them inefficiently small. By targeting these sectors with appropriate industrial policies, a country may gradually realize its "latent comparative advantage" and embark on a path of sustained development (Harrison and Rodríguez-Clare, 2010). With the resurgence of global interest in industrial policy, this approach has attracted increasing attention from developing-country governments, reflected in a growing use of policy instruments aimed at promoting domestic manufacturing and moving up the value chain and toward higher value-added activities.

2.2 Industrial Policies in Developing Countries

Although the strategic objective of industrial upgrading is widely shared, the specific policy instruments adopted differ markedly between advanced and developing economies. Recent research documents that most recorded industrial policy interventions originate from high-income countries, where measures typically involve fiscally intensive tools such as direct subsidies, state loans, and trade finance. By contrast, budget constraints and limited state capacity in developing countries restrict the use of such instruments. Instead, these countries tend to rely on interventions that are deemed low-cost and administratively simple by policymakers, with export restrictions becoming increasingly prominent.[1]

Figure 2 illustrates this contrast by comparing the distribution of all industrial policy interventions with that of export restrictions across countries at different income levels. A clear divergence emerges: high-income countries account for the largest share of industrial policy interventions; however, export restrictions constitute only 1.1 percent of their policy portfolio. On the other hand, although low-income countries adopt far fewer interventions overall, export restrictions account for more than 11 percent of their industrial policies. This pattern also holds in absolute terms: most export restrictions recorded in the GTA database are implemented by lower-middle and upper-middle income countries.

Figure A2 in the appendix plots the time trends in export restrictions imposed by developing countries. The left panel shows their annual count, which rose modestly around 2010–2011, declined gradually thereafter, and then surged sharply after 2019. This pattern holds even after excluding measures related to the COVID-19 pandemic and economic sanctions. The right panel depicts export restrictions as a share of all industrial policy interventions in the GTA

[1] Industrial policy interventions are drawn from the Global Trade Alert (GTA) database. Section 4 provides details on the database and the definition of export restrictions.

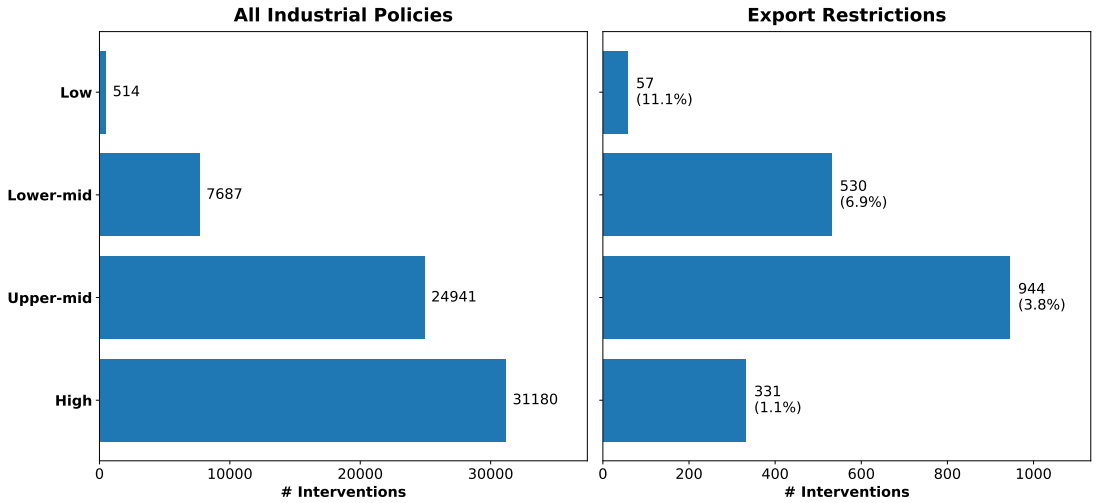


Figure 2. Industrial policies and export restrictions by income group

Notes: This figure presents the number of industrial policy interventions and export restrictions by the income level of the imposing countries, as recorded in the GTA database from 2008 to 2023. Country income groups are based on the World Bank's 2015 classification.

database, indicating that the recent increase is not driven by changes in data coverage. The resurgence of export restrictions among developing countries is striking because such measures often violate GATT/WTO rules. It reflects a weakening commitment to multilateral trade norms, driven partly by escalating geopolitical tensions and the paralysis of the WTO dispute settlement system since 2019.

When used as an industrial policy instrument, export restrictions deliberately run against a country's comparative advantage by curbing exports of goods in which the country currently specializes. Tables A4 and A5 in the appendix show that such measures indeed disproportionately target upstream goods with stronger revealed comparative advantage. The rationale behind export restrictions is that rediverting raw materials toward domestic markets can encourage investment in processing and stimulate downstream production. However, such interventions also risk depressing upstream exporting revenues and distorting resource allocation. Ultimately, whether these policies actually succeed in boosting downstream exports remains unknown.

2.3 Raw Minerals as Targets

In this paper, I focus on export restrictions targeting raw minerals, defined as products classified under two HS chapters: Chapter 25 (non-metallic minerals) and Chapter 26 (metallic minerals). These minerals are either exported in raw form or undergo only rudimentary processing, such

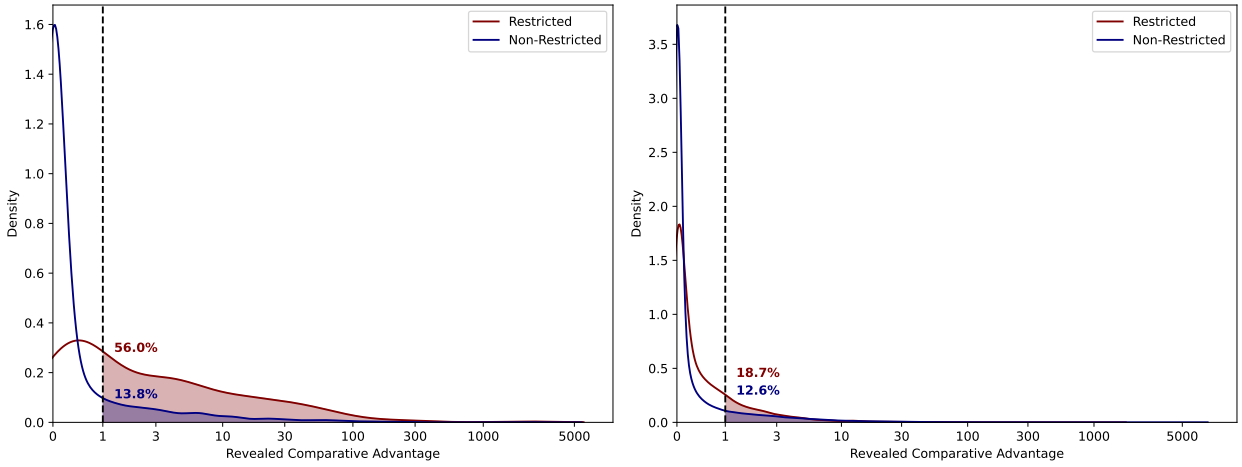
as washing, crushing, or roasting.[2] Raw minerals constitute a relatively small yet economically significant product category. At the six-digit HS level, they encompass 109 products, accounting for 2.1 percent of all tradable goods. In 2015, they accounted for 20.1 percent of global trade in quantity but only 1.4 percent in value, reflecting their extremely low unit prices. This stark gap also highlights the motivation for resource-rich developing countries to move up the value chain through the promotion of processing and downstream industries related to these minerals.

In theory, distinctive characteristics of raw minerals make them ideal targets for export-led industrial policies under various "winner-picking" criteria (Reed, 2024). Raw minerals occupy the most upstream positions in value chains, with very few other products situated at comparable distances from final demand. This reflects two factors: minerals are primary products extracted directly from nature, similar to agricultural commodities, and they serve as inputs for exceptionally long downstream production chains. Such upstream positioning gives these sectors disproportionate influence over the broader economy: in the presence of market distortions, governments have strategic incentives to prioritize upstream sectors due to strong backward linkages (Liu, 2019). For resource-rich developing countries, this logic makes raw minerals natural candidates for strategic trade interventions.

A second consideration relates to the patterns of revealed comparative advantage (RCA). For the implementing country, the targeted minerals are often the products in which it exhibits the strongest RCA. However, this upstream advantage rarely translates into competitiveness in downstream processing industries. Figure 3 illustrates this pattern using data from the year prior to export restrictions. The left panel shows that targeted raw minerals display remarkably higher RCA than non-targeted minerals in the same country, with more than half exceeding one and some surpassing one hundred. In contrast, the right panel reveals that downstream products of targeted minerals exhibit RCA comparable to all other products. Table A3 in the appendix reports a detailed comparison; a t-test confirms no statistically significant difference in mean RCA between the two groups. With rising global demand for mineral-related downstream products, this asymmetry in RCA echoes the argument on latent comparative advantage and creates a compelling rationale for policies aimed at developing domestic downstream capabilities.[3]

[2]This definition excludes elements that do not occur naturally as standalone minerals (e.g., rare-earth metals) or that occur in free elemental form (e.g., gold and platinum). Mineral fuels are excluded from the baseline analysis because their predominant use as energy sources complicates the identification of downstream linkages. Some of these products are included under alternative definitions in robustness checks.

[3]Beyond these economic rationales, mineral export restrictions may also be driven by "resource nationalism": the political desire to assert sovereign control over natural resources (Wilson, 2015). Although such political motives may coexist with industrial policy objectives, this paper focuses on the economic consequences of these restrictions for downstream industrial development.



(a) Raw minerals

(b) Downstream products

Figure 3. Revealed comparative advantage: restricted vs. non-restricted

Notes: This figure compares the distribution of revealed comparative advantage (RCA) between products (or their upstream minerals) subject to export restrictions (red) and those without restrictions (blue), measured one year before the restrictions. Percentage labels indicate the share of products within each group with RCA greater than one.

Mineral export restrictions are also widely used in practice. Among all export restrictions recorded, raw minerals constitute the third most frequently targeted product category, following agricultural products (Chapters 1–24) and mineral fuels (Chapter 27). Notably, mineral export restrictions are often adopted with explicit industrial objectives, making their policy intent unusually transparent compared to restrictions on other product categories.[4] These features make mineral export restrictions a particularly suitable setting for examining the effectiveness of industrial policy in promoting downstream upgrading in developing countries.

3 Theory

In this section, I develop a parsimonious two-country, two-sector general equilibrium model of mineral export restrictions. The model features external economies of scale in the downstream processing sector, following Bartelme et al. (2025), and clarifies the trade-offs that arise when upstream export restrictions create price wedges and shape downstream production responses.

[4]For comparison, export restrictions on agricultural goods often aim at short-term market stabilization or food security, while those on mineral fuels are typically motivated by oligopolistic rent extraction or geopolitical considerations. Figure A1 in the appendix shows the distribution of export restrictions across product categories. Section D in the appendix discusses agricultural export restrictions and their downstream effects.

As detailed in Appendix **??**, the model can be extended to a continuum of sectors, allowing the effects of mineral export restrictions to propagate along the value chain.

3.1 Setup

Environment. There are two countries, Home and Foreign, with Foreign variables denoted by asterisks. Each country is endowed with labor (L, L^*) and mineral reserves (R, R^*). Labor is freely mobile across sectors within each country but immobile internationally, while mineral reserves are sector-specific fixed factors that earn rents. Where Home and Foreign equations are symmetric, I present only the Home equations.

Production. The *mining sector* produces minerals M using mineral reserves R and labor L_M under a Cobb-Douglas technology:

$$M = R^{\beta} L_M^{1-\beta}, \quad \beta \in (0,1). \tag{1}$$

Since R is a fixed factor, the mining sector exhibits decreasing returns to labor, and mineral reserves earn economic rents.

The *manufacturing sector* produces a final good Y under perfect competition with external economies of scale. Individual firm j's production function is:

$$y_j = A \cdot m_j^{\alpha} \cdot l_j^{1-\alpha} \cdot L_Y^{\gamma}, \quad \alpha \in (0,1),\ \gamma > 0, \tag{2}$$

where m_j is firm j's demand for mineral inputs, l_j is its labor demand, L_Y is aggregate manufacturing employment (treated as exogenous by each firm), and A is country-specific total factor productivity. The term L_Y^{γ} captures Marshallian external economies of scale: as the sector expands, aggregate productivity rises. Since each firm treats L_Y as exogenous, it faces constant returns to scale and the market structure is consistent with perfect competition; free entry drives profits to zero.

Preferences. Representative consumers in both countries have logarithmic utility defined over the manufacturing good:

$$U = \ln C, \tag{3}$$

so they spend all income on manufactures: $p_Y C = I$, where I is nominal income and p_Y is the consumer price of manufactures.

Trade. Both goods are tradable subject to iceberg trade costs $\tau > 1$. In the baseline equilibrium, Home exports minerals and imports manufactures. Let p_M and p_Y denote Home's domestic prices of minerals and manufactures, and let p_M^* and p_Y^* be their Foreign counterparts.

Home may impose an *ad valorem* export tax $t \in [0, 1)$ on mineral exports. The tax creates a wedge between the domestic mineral price in Home and the world (Foreign) mineral price:

$$p_M = \frac{1-t}{\tau} p_M^*. \tag{4}$$

For $t > 0$, the export tax drives the domestic mineral price below its free-trade level, implicitly subsidizing Home's downstream manufacturing sector through cheaper mineral inputs. Export tax revenues are collected by the Home government and rebated lump-sum to Home residents.

In contrast, manufactures are traded without additional policy distortions. Their domestic price in Home is therefore determined by the import-parity condition:

$$p_Y = \tau p_Y^*. \tag{5}$$

Income. Home's nominal income comprises labor income, mining rents, and tax revenues, while Foreign's nominal income comprises labor income and mining rents only:

$$I = wL + \beta p_M M + t \frac{p_M^*}{\tau} X_M, \tag{6}$$

$$I^* = w^* L^* + \beta p_M^* M^*, \tag{7}$$

where $X_M > 0$ denotes Home's mineral exports.

3.2 Equilibrium

Mining firms. Mining firms choose L_M to maximize profits, taking R as fixed. The first-order condition yields an upward-sloping mineral supply curve:

$$p_M = \frac{w}{(1-\beta)R^\beta} L_M^\beta, \tag{8}$$

with mineral output $M = R^\beta L_M^{1-\beta}$ and mining profits (rents to R) equal to $\pi_M = \beta p_M M$.

Manufacturing firms. Each manufacturing firm maximizes profits taking L_Y as given. Free entry and perfect competition drive price equal to unit cost:

$$p_Y = \frac{1}{\alpha^\alpha (1-\alpha)^{1-\alpha}} \cdot \frac{p_M^\alpha \, w^{1-\alpha}}{A L_Y^\gamma}. \tag{9}$$

Aggregating across firms, total manufacturing output is:

$$Y = \left(\frac{\alpha}{1-\alpha} \cdot \frac{w}{p_M} \right)^\alpha \cdot A L_Y^{1+\gamma}, \tag{10}$$

so that Y has elasticity $1+\gamma > 1$ with respect to L_Y: a larger manufacturing sector raises output both directly through greater labor input and indirectly through external economies of scale.

Market clearing. Labor in each country is allocated between the two sectors:

$$L_M + L_Y = L. \tag{11}$$

Home's mineral output serves both domestic manufacturing demand and exports:

$$M = \frac{\alpha \tau Y}{p_M} + X_M. \tag{12}$$

Foreign's mineral output, supplemented by Home's exports net of iceberg costs, meets Foreign manufacturing demand:

$$M^* + \frac{X_M}{\tau} = \frac{\alpha Y^*}{p_M^*}. \tag{13}$$

Trade balance requires that Home's mineral export revenues equal its manufacturing import expenditure:

$$\frac{p_M^*}{\tau} X_M = \tau X_Y, \tag{14}$$

where $X_Y > 0$ denotes Home's manufacturing imports.

Competitive equilibrium. A competitive equilibrium consists of prices and allocations $(p_M, p_Y, w, w^*, L_M, L_Y, L_M^*, L_Y^*, X_M)$ such that: mining firms maximize profits as in (8); manufacturing firms earn zero profits as in (9); labor markets clear as in (11) (with the corresponding conditions holding symmetrically in Foreign); and mineral markets clear as in (12)–(13).

Given zero profits, balanced household budgets, and lump-sum redistribution of tax revenues, Walras' Law ensures the trade balance (14) holds automatically. The Foreign manufacturing price is taken as the numéraire, $p_Y^* = 1$, implying $p_Y = \tau$.

3.3 Comparative Statics

I analyze the effects of a marginal increase in the mineral export tax by totally differentiating the equilibrium conditions, expressing all responses as $d\ln x/dt$. Let $\Gamma \equiv \gamma L_M/(\beta L_Y)$ capture the strength of external economies relative to the mining sector. The stability condition requires $\Gamma < 1-\alpha$ for both countries.

The most immediate implication of the export tax concerns the adjustment of domestic and world mineral prices. By introducing a wedge between them, the tax lowers the domestic mineral price and raises the world mineral price, with the incidence split determined by relative supply conditions in the two countries.

Lemma 1 (Price pass-through) *A mineral export tax drives the domestic and world mineral prices in opposite directions:*

$$\frac{d\ln p_M}{dt} = \frac{\Phi - 1}{1-t} < 0, \qquad \frac{d\ln p_M^*}{dt} = \frac{\Phi}{1-t} > 0, \tag{15}$$

where $\Phi \equiv B/(B+B^*) \in (0,1)$ is the pass-through coefficient, with B and B^* positive composites of structural parameters summarizing supply conditions in Home and Foreign, respectively.

Proof. See Appendix B.1.1. ■

The price effects of the export tax propagate to factor markets through the zero-profit condition in manufacturing: cheaper mineral inputs expand the sector, strengthen external economies, and bid up wages. The opposite holds in Foreign, where the higher world mineral price raises manufacturing costs and depresses wages.

Proposition 1 (Wages) *A mineral export tax raises Home wages and lowers Foreign wages:*

$$\frac{d\ln w}{dt} = \frac{\alpha+\Gamma}{1-\alpha-\Gamma}\cdot\frac{1-\Phi}{1-t} > 0, \qquad \frac{d\ln w^*}{dt} = -\frac{\alpha+\Gamma^*}{1-\alpha-\Gamma^*}\cdot\frac{\Phi}{1-t} < 0. \tag{16}$$

Proof. See Appendix B.1.2. ■

The wage response reflects an underlying reallocation of labor across sectors: as the domestic mineral price falls, mining becomes less profitable, releasing labor to manufacturing.

Proposition 2 (Sectoral reallocation) *A mineral export tax shifts labor from mining to manufacturing in Home, and in the opposite direction in Foreign:*

$$\frac{d\ln L_Y}{dt} = \frac{\Gamma/\gamma}{1-\alpha-\Gamma}\cdot\frac{1-\Phi}{1-t} > 0, \qquad \frac{d\ln L_Y^*}{dt} = -\frac{\Gamma^*/\gamma}{1-\alpha-\Gamma^*}\cdot\frac{\Phi}{1-t} < 0. \tag{17}$$

Proof. See Appendix B.1.3. ■

Labor reallocation toward manufacturing amplifies manufacturing output through external economies of scale: a larger workforce raises not only direct labor input but also sector-wide productivity, so the output response exceeds what labor reallocation alone would predict.

Corollary 1 (Manufacturing output) *A mineral export tax expands Home manufacturing output and contracts Foreign manufacturing output:*

$$\frac{d\ln Y}{dt} = \frac{\alpha+\Gamma(1+1/\gamma)}{1-\alpha-\Gamma}\cdot\frac{1-\Phi}{1-t} > 0, \qquad \frac{d\ln Y^*}{dt} = -\frac{\alpha+\Gamma^*(1+1/\gamma)}{1-\alpha-\Gamma^*}\cdot\frac{\Phi}{1-t} < 0. \tag{18}$$

Proof. See Appendix B.1.4. ■

Together, these results trace the full transmission mechanism of the mineral export tax. The price wedge depresses domestic mineral costs, triggering labor reallocation toward manufacturing and an amplified output expansion through external economies of scale, while simultaneously raising world mineral prices and contracting Foreign manufacturing. The asymmetric effects on Home and Foreign set the stage for the welfare analysis that follows.

3.4 Welfare

We measure welfare by $W \equiv \ln C = \ln(I/p_Y)$. Since $p_Y = \tau$ is fixed by the normalization, welfare changes reduce to proportional income changes: $dW = d\ln I$. The welfare effect of the export tax decomposes into two terms: a fiscal dividend from the terms-of-trade improvement, and a net domestic effect capturing the redistribution between labor income and mining rents.

Proposition 3 (Welfare decomposition) *A marginal increase in export tax changes welare by:*

$$\frac{dW}{dt} = \frac{\Lambda(1-\Phi)}{1-t} + \frac{s_T}{t}, \qquad \frac{dW^*}{dt} = -\frac{\Lambda^*\Phi}{1-t}, \tag{19}$$

where Λ *is given by:*

$$\Lambda \equiv \frac{s_w(\alpha+\Gamma) - s_R[\beta(1-\alpha-\Gamma)+(1-\beta)]}{\beta(1-\alpha-\Gamma)}, \tag{20}$$

with Home income shares:

$$s_w \equiv \frac{wL}{I}, \qquad s_R \equiv \frac{\beta p_M M}{I}, \qquad s_T \equiv \frac{t}{1-t} \cdot \frac{p_M X_M}{I}, \tag{21}$$

satisfying $s_w + s_R + s_T = 1$. *Foreign income shares* s_w^*, s_R^*, *and* Λ^* *are defined analogously.*

Proof. See Appendix B.1.5. ■

Λ measures the net welfare effect on Home of a marginal *decrease* in the domestic mineral price. It reflects two opposing forces: a positive *wage effect*, whereby lower mineral prices reduce manufacturing costs, expand the sector, strengthen external economies, and raise labor income; and a negative *rent effect*, whereby lower mineral prices decrease mining revenues accruing to reserve owners. When manufacturing externalities are strong and the economy is labor-intensive ($\Lambda > 0$), the wage effect dominates. When mining rents are large and externalities are weak ($\Lambda < 0$), the rent effect dominates. The same logic applies to Λ^*: Foreign welfare improves if and only if the rent gains from the higher world mineral price outweigh the wage losses from contracted manufacturing.

Corollary 2 (Welfare improvement condition) *A mineral export tax improves Home welfare if and only if:*

$$s_T > \frac{t}{1-t} \cdot \Lambda(\Phi - 1). \tag{22}$$

Proof. Setting $dW/dt > 0$ in Proposition 2 yields condition (22) directly. ■

The left-hand side of equation (22) is the fiscal dividend — the export tax revenue as a share of Home income — and is always positive. The right-hand side is the net domestic cost, whose sign depends on Λ: if $\Lambda > 0$ (manufacturing-intensive economy), the export tax unambiguously improves welfare; if $\Lambda < 0$ (resource-intensive economy), welfare improves only if the fiscal dividend is sufficiently large, which requires a large export volume share $p_M X_M / I$, strong Home market power (large Φ), or weak dominance of mining rents (small Λ).

Global welfare. Summing dW/dt and dW^*/dt from Proposition 2:

$$\frac{d(W + W^*)}{dt} = \frac{\Lambda - (\Lambda^* - \Lambda)\Phi}{1-t} + \frac{s_T}{t}. \tag{23}$$

The second term, s_T/t, reflects the contribution of mineral export revenues to Home income; abstracting from this distributional term, global welfare hinges on the first term alone. When Home is resource-intensive ($\Lambda < 0$) and Foreign is manufacturing-intensive ($\Lambda^* > 0$), both

components of the first term are negative. Global welfare therefore falls unless fiscal dividends are large enough to offset the deadweight losses from distorted mineral allocation. In other words, mineral export restrictions may benefit the restricting country, yet are most likely to be globally inefficient precisely in the configurations where they are commonly observed.

Remark on technology gaps. The model does not require Home and Foreign to share identical manufacturing productivity. An exogenous comparative disadvantage in manufacturing ($A < A^*$) influences welfare through equilibrium objects including the income shares s_w, s_R, and the externality parameter Γ. Lower productivity reduces the scale of Home manufacturing, altering labor allocation and thereby affecting the strength of scale externalities embodied in Γ, which in turn shapes Λ. The welfare improvement condition (22) therefore accommodates technology gaps implicitly through these equilibrium adjustments.

Extension: Continuum of sectors. The baseline two-sector framework extends naturally to a continuum of sectors organized along a value chain, with each stage combining labor and the output of the preceding stage. In this environment, the price wedge introduced at the mineral stage propagates downstream through input–output linkages, lowering input costs at successive processing stages. Under mild assumptions, the qualitative structure of the welfare improvement condition (22) remains similar. The full derivation is provided in Appendix B.2.

3.5 Summary

The model delivers a clear implication: mineral export restrictions can raise Home welfare only if the fiscal dividend and the gains from manufacturing expansion are large enough to offset domestic distortion costs. Downstream expansion is central to this logic: it is the mechanism through which the policy generates scale externalities. Without downstream expansion, the export tax merely distorts mineral allocation and compresses mining rents, with no offsetting efficiency gains. This motivates the empirical strategy that follows. Rather than taking a stand on welfare directly, I focus on a necessary implication of the model: do mineral export restrictions induce downstream export expansion? A positive response is consistent with the welfare-improving region of the model; a null or negative response would indicate that the policy fails to activate the mechanism required for welfare gains.

4 Data

Mineral Export Restrictions. I compile a novel dataset of global mineral export restrictions using trade and industrial policy records from the Global Trade Alert (GTA) database, which has systematically tracked government interventions affecting international trade since 2008 (Evenett, 2009). For each intervention, the GTA database records detailed information such as the implementing country, announcement and implementation dates, removal date, eligibility criteria, and the affected sectors and products. I restrict the sample to entries recorded through 2023, yielding 66,486 distinct government interventions.

Export restrictions are government interventions that limit or condition the export of certain goods. In the GTA database, export restrictions are classified as distortionary measures that include export bans, export quotas, export taxes, export licensing requirements, or other export-related interventions (n.e.c.). “Distortionary" refers to policies that raise trade barriers, such as newly introduced bans, tighter quotas, or increased export taxes. I exclude measures related to the COVID-19 pandemic and country-specific economic sanctions, as these policies follow distinct logics and operate through mechanisms different from those studied in this paper. I also restrict the sample to mineral export restrictions that apply to all trade partners, thereby excluding geopolitically motivated policies.

The final dataset comprises 125 mineral export restrictions imposed by 29 countries, affecting 418 distinct country–product pairs. Figure 4 illustrates their global distribution. China, India, and Indonesia are the most frequent implementers, yet the use of such measures is geographically widespread. Notably, no high-income countries have implemented mineral export restrictions during this period. Tables A1 and A2 in the appendix provide details on implementing countries and the most frequently targeted mineral products. Mineral export restrictions are highly targeted within countries but diverse across countries. On average, each restriction targets fewer than two six-digit HS codes within a country. Across countries, however, the specific minerals targeted vary considerably, both among different minerals and between metals and non-metals. This reflects differences in natural resource endowments and policy focus.

International Trade. I use product-level bilateral trade data for 2002–2023 from the CEPII-BACI database, which reconciles discrepancies in reported exports and imports in the original UN Comtrade data (Gaulier and Zignago, 2010). The BACI dataset covers trade flows between 230 countries, classified into 5,219 six-digit products based on the Harmonized System (HS) nomenclature. I aggregate bilateral trade flows to the exporter–product–year level, measuring each country’s total exports of a given product worldwide.

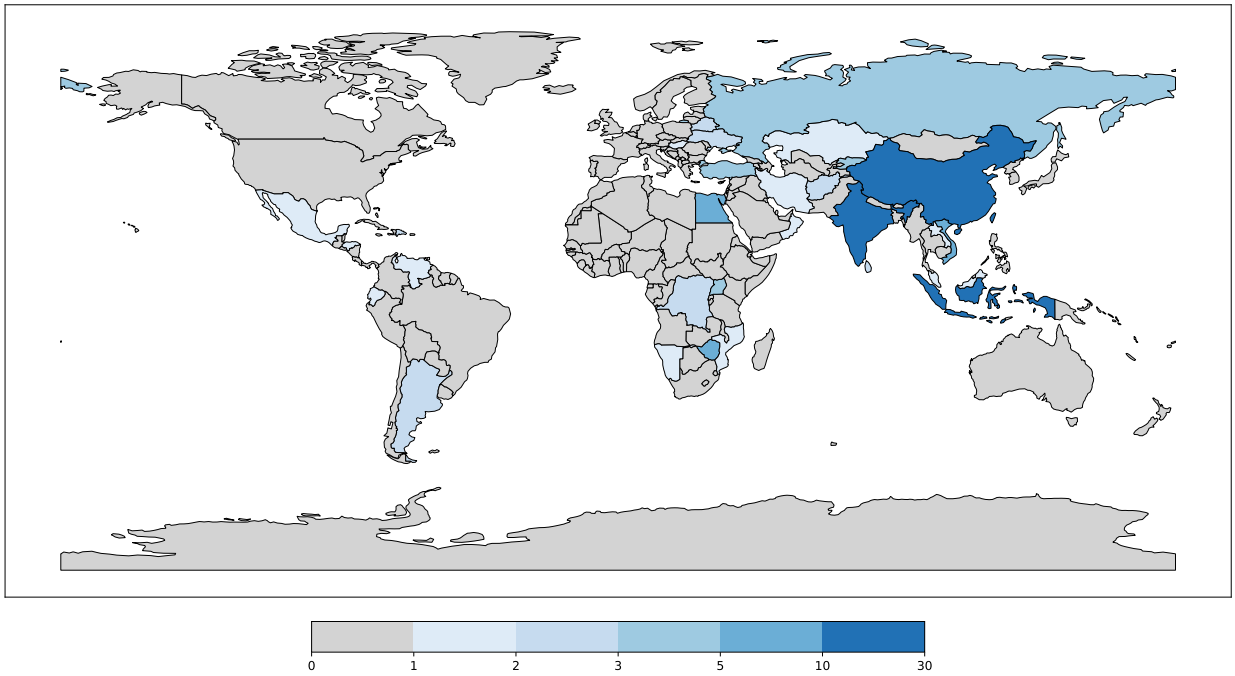


Figure 4. Global distribution of mineral export restrictions

Notes: The map displays the cumulative number of mineral export restriction measures imposed during the sample period (2009–2023), as recorded in the GTA database. Darker shades indicate a higher number of measures, while countries shown in grey have no recorded restrictions.

Upstream-Downstream Linkages. To construct granular upstream–downstream linkages at the product level, I use the AI-generated Production Network (AIPNET) dataset developed by Fetzer et al. (2024). This dataset employs large language models to map upstream and downstream connections for each six-digit HS product based on information about their production processes. Such detail is essential for my analysis, as conventional input–output tables at the sector or industry level cannot distinguish among specific raw minerals or their downstream uses.[5] To illustrate the type of product-level linkages captured by AIPNET, Figure A3 in the appendix traces all downstream products originating from iron ores (HS 2601.11 and 2601.12), including intermediate inputs like pig iron and ferro-alloys, processed steel products, and final goods such as machinery and transport equipment. This example highlights AIPNET's unique ability to trace the iron–steel value chain across all production stages, providing the granularity needed for downstream analysis.

[5]For example, the BEA input–output table groups copper, nickel, lead, and zinc into a single industry (212230), and gold, silver, and "other metal ores" into another (2122A0). Section C in the appendix provides a detailed comparison between AIPNET and the BEA input–output table.

5 Empirical Strategy

My empirical strategy consists of two parts. First, I examine the direct impact of mineral export restrictions — that is, their effects on the exports of the targeted minerals. Second, I analyze their effects along the value chain, assessing whether upstream restrictions indeed stimulate the exports of mineral-related downstream products.

5.1 Direct Effects of Mineral Export Restrictions

Although it may seem obvious that export restrictions reduce exports of the targeted goods, testing this relationship is necessary for two reasons. First, the GTA database is not comprehensive: the concentration of recorded mineral export restrictions in middle-income countries may partly reflect under-reporting in low-income countries, where policy changes are not always publicly disclosed or documented. Second, the enforcement of export restrictions varies widely across countries and products. For instance, politically connected exporters may automatically receive licenses required to continue exporting. Evaluating such poorly enforced or purely nominal measures without accounting for these issues could yield misleading conclusions.

To examine the direct effects of mineral export restrictions, I use all country–product–year observations for raw minerals and estimate the following triple-differences equation:

$$Y_{ikt} = \exp\left[\alpha + \beta \cdot ER_{ikt} + \gamma_{ik} + \delta_{it} + \eta_{kt}\right] + \varepsilon_{ikt}, \tag{24}$$

where Y_{ikt} denotes the export value or quantity of raw mineral product k by country i in year t; ER_{ikt} is an indicator equal to one if product k is subject to an export restriction imposed by country i in year t; γ_{ik}, δ_{it}, and η_{kt} denote country–product, country–year, and product–year fixed effects, respectively; and ε_{ikt} is the error term.

I assume that export restrictions are *absorptive* at the country-product level: once a restriction is recorded, the indicator ER_{ikt} switches to one for relevant country-product pairs and remains one thereafter, regardless of whether the restriction is later removed. This strong assumption is motivated by three considerations. First, it is consistent with the core assumption underlying staggered adoption framework widely used in difference-in-differences (DiD) designs. Allowing treatment to turn on and off over time under heterogeneous treatment timing introduces biases that are difficult to address and invalidates most, if not all, recent DiD estimators designed for heterogeneous treatment effects (de Chaisemartin and D'Haultfoeuille, 2023). Second, the GTA database provides limited information on policy removal. Many governments do not report

when a policy becomes inactive.[6] In some cases, the original measure is replaced by another type of restriction, creating multiple entries for the same country–product pair.[7] Third, the GTA database does not track export restrictions enacted before 2008. Treating the first recorded measure as the start of treatment is thus a practical choice, capturing the first observable tightening of export controls within the sample period. In this case, the estimated effects should be interpreted as a *lower bound* of the true impact of prior export restrictions.

I estimate the equation using the Poisson pseudo-maximum likelihood (PPML) estimator proposed by Silva and Tenreyro (2006), now standard in the trade literature. Unlike traditional OLS estimators applied to log-linearized models, PPML works in levels and naturally accommodates zero trade flows. This feature is particularly relevant in my setting, as zero exports account for 48 percent of all country–product–year observations for raw minerals. PPML also addresses heteroskedasticity, which can bias estimates in log-linear regressions, and ensures that large trade flows do not disproportionately drive the results.

5.2 Mineral Export Restrictions Along the Value Chain

The downstream effects of mineral export restrictions are examined in a similar way. Specifically, I estimate the following equation:

$$Y_{ikt} = \exp\left[\alpha + \beta_1 \cdot ER^{\text{up}}_{ikt} + \beta_2 \cdot ER_{ikt} + \gamma_{ik} + \delta_{it} + \eta_{kt}\right] + \varepsilon_{ikt}, \tag{25}$$

where ER^{up}_{ikt} equals one if any upstream raw mineral input to product k, as identified by AIPNET, is subject to an export restriction imposed by country i in year t. ER_{ikt} controls for direct restrictions on product k itself. All other terms match those in Equation 24. Both export restriction indicators are constructed under the absorptive assumption discussed above, and the equation is again estimated via PPML.

Equation 25 is estimated on all country–product–year observations for manufactures, excluding raw minerals since the focus is on downstream products. Agricultural products (Chapters 1–24) and mineral fuels (Chapter 27) are excluded as well, since they do not use raw minerals as inputs and are therefore irrelevant for tracing downstream effects.[8] I also exclude arms and ammunition (Chapter 93) and works of art and antiques (Chapter 97) due to their unique char-

[6] Among the 125 mineral export restrictions in my sample, 70 have no recorded removal dates.

[7] For example, Indonesia lifted its 2014 export ban on raw nickel ores in 2017 by replacing it with a licensing requirement, and then reimposed another ban in 2020.

[8] According to AIPNET, no raw minerals are linked to agricultural or fuel products, except for salt (HS 2501.00), which is associated with certain processed food items.

acteristics. Table A7 in the appendix reports the total number of products and mineral-linked downstream products by sector. Raw minerals are most frequently linked to sectors including basic metals, machinery and electronics, chemicals, and stone and glass.

Figure A4 in the appendix illustrates how treatment status evolves across all country–product pairs over time. By the end of the sample period, only 1.35 percent of raw mineral pairs and 0.97 percent of downstream product pairs are subject to export restrictions. This limited coverage reflects that such measures are concentrated in a handful of resource-rich developing countries and target a narrow subset of raw minerals. Consequently, most country–product pairs remain untreated and serve as the never-treated control group in the estimation.

6 Results

This section presents the main empirical results. I first examine the effectiveness of mineral export restrictions by testing whether imposing such policies indeed reduces exports of targeted minerals. Next, I estimate whether these restrictions stimulate exports of downstream products. I discuss how two factors shape these effects: a country's market power in upstream mineral markets and its pre-existing comparative advantage in downstream industries. I also assess if such restrictions lead to expansion into new downstream products and export markets. Finally, I investigate whether mineral export restrictions drive industrial upgrading by promoting the production of more downstream and technologically complex goods.

6.1 Policy Effectiveness

Table 1 presents the estimation results of Equation 24, which tests the policy effectiveness of export restrictions in reducing raw mineral exports. The results confirm that export restrictions significantly curtail mineral exports. Column (1) shows that the imposition of a restriction reduces export value by 37.0 percent, while Column (2) indicates an even larger decline in export quantity of 57.1 percent.[9] All specifications control for country-product, country-year, and product-year fixed effects to account for time-invariant country-product characteristics, country-specific time trends, and global commodity price fluctuations.

The larger decline in quantity relative to value suggests that prices rise following the implementation of restrictions, which would be consistent with restricted supply driving up prices in international markets. However, the estimate for unit values in Column (3), while

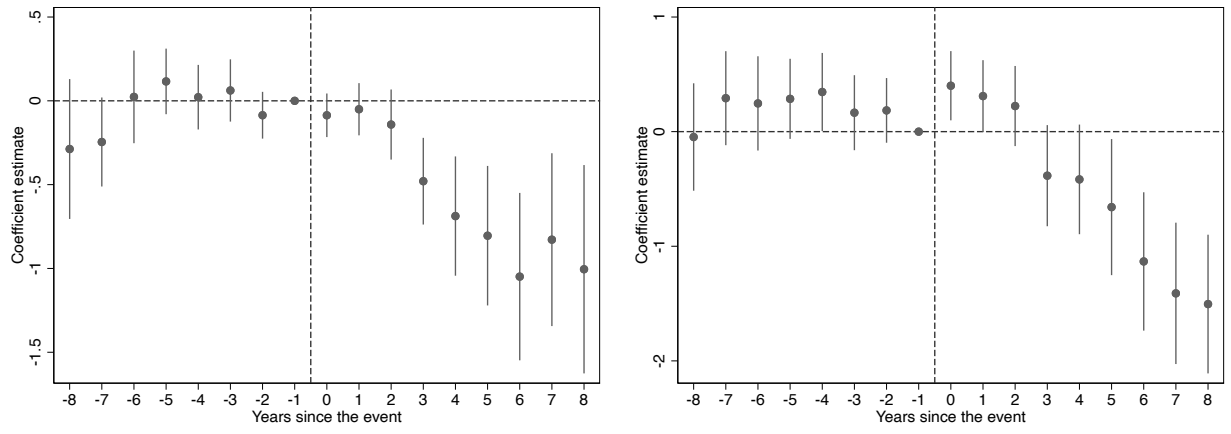
[9] PPML coefficients are converted to percentage effects using $\left(\exp(\hat{\beta})-1\right)\times 100$, where $\hat{\beta}$ is the estimated coefficient for the export restriction term.

Table 1. Direct effects of mineral export restrictions

	Export Value	Export Quantity	Unit Value
Export Restriction	-0.462***	-0.713***	0.0441
	(0.142)	(0.156)	(0.0586)
Country-Product FE	✓	✓	✓
Country-Year FE	✓	✓	✓
Product-Year FE	✓	✓	✓
Estimator	PPML	PPML	OLS
# of Clusters	16,512	16,377	14,152
# of Obs.	357,198	354,239	188,803

Notes: This table reports the estimated effects of export restrictions on exports of targeted raw minerals. Dependent variables include export value and quantity (in levels) and unit values (in logs). Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

positive, is not statistically significant. This null result could reflect two factors. First, unit values may be an imperfect proxy for prices due to compositional changes in the quality or grade of minerals exported. Second, many mineral-exporting countries may lack sufficient market power to influence global prices through unilateral supply restrictions, which I will return to later. In this case, importing countries may simply substitute toward alternative suppliers, dampening price effects. Nevertheless, these results provide strong evidence that export restrictions effectively reduce mineral exports, achieving their intended policy objective.



(a) Export Value (b) Export Quantity

Figure 5. Direct effects: event study

Notes: This figure plots the estimated dynamic effects of export restrictions on exports of targeted raw minerals, based on coefficient estimates from event-study regressions. Bars represent 95% confidence intervals, with standard errors clustered at the country–product level.

To assess whether the observed effects are driven by pre-existing trends, I estimate event-study specifications for both export value and quantity. These regressions interact the treatment indicator with event-time dummies defined by years relative to the restriction's imposition. Figure 5 plots the estimated coefficients for each event year. The results show no significant pre-trends: coefficients prior to treatment are small and statistically indistinguishable from zero, while the decline in exports emerges clearly after the policy takes effect.

The direct effects of mineral export restrictions are delayed but persistent: the negative effects become statistically significant only after a lag. However, once they emerge, exports of targeted minerals continue to decline throughout the sample period. While this pattern may seem puzzling, it can be partly explained by two common policy features. First, countries often begin with lenient measures and include buffer periods between announcement and enforcement to allow firms to adjust their contracts. Second, export restrictions also typically tighten as domestic processing capacity expands, amplifying their long-run effects. As discussed earlier, I treat mineral export restrictions as absorbing states. Under this specification, the initial imposition of a restriction signals the government's attention to a mineral's strategic value, with policy measures potentially intensifying thereafter.

Table 2. Direct effects: export status and destination

	Export Status	# of Destinations	Top Destination Share	Destination HHI
Export Restriction	-0.0227*	-0.0715***	0.0126	0.0117
	(0.0122)	(0.0238)	(0.00965)	(0.0114)
Country-Product FE	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓
Estimator	OLS	PPML	OLS	OLS
Pre-treatment Mean	0.978	21.2	0.655	0.551
# of Clusters	16,512	16,512	14,251	14,251
# of Obs.	363,264	357,198	190,645	190,645

Notes: This table presents the estimated effects of export restrictions on export status and destination concentration for targeted raw minerals. Dependent variables include export status, number of destinations, top destination share, and the Herfindahl index. Pre-treatment mean refers to the average value of each outcome for treated country–product pairs in the year before the restriction. Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 2 examines how export restrictions affect both the likelihood of exporting targeted minerals and the geographic composition of these exports. Mineral export restrictions were adopted by countries that were already major exporters: prior to policy implementation, 97.8 percent of treated countries exported the targeted mineral to an average of 21 destinations.

However, these exports were highly concentrated geographically, with the top destination accounting for over 65 percent of exports and the Herfindahl index exceeding 0.5. Following the imposition of restrictions, countries become modestly less likely to export the targeted mineral, with export probability declining by 2.3 percentage points. The number of export destinations also falls significantly by 6.9 percent, equivalent to approximately 1.5 fewer destinations on average. However, neither the top destination share nor the Herfindahl index shows significant change. Compared to the sharp declines in export value and quantity, the relatively modest changes along the extensive margin indicate that most of the export contraction occurs through reduced exports to existing destinations. In other words, mineral export restrictions appear to operate mainly through the intensive margin, proportionally lowering exports across trading partners rather than changing the concentration pattern of trading partners.

6.2 Export-Stimulating Downstream Effects

Table 3. Downstream effects of mineral export restrictions

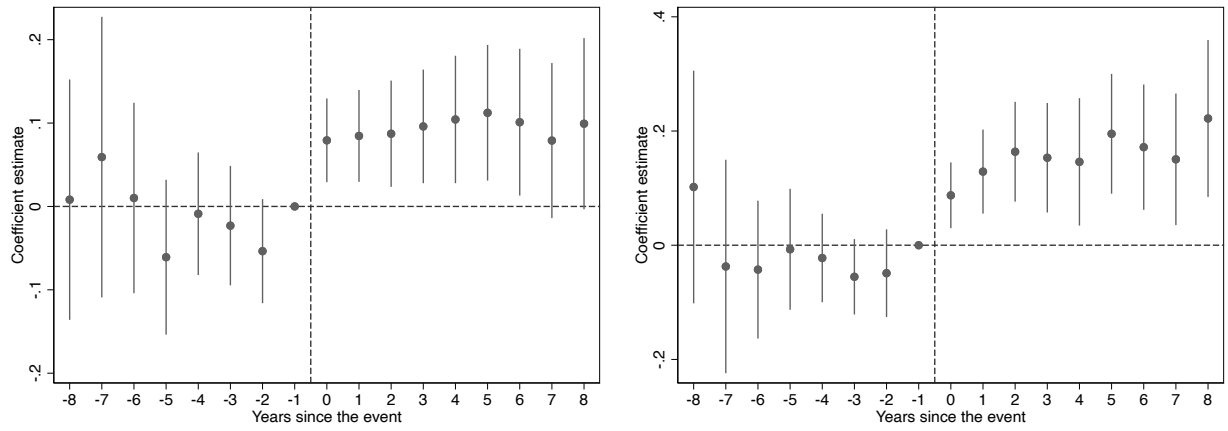
	Export Value		Export Quantity		Unit Value	
Export Restriction (Up)	0.104**	0.104**	0.173***	0.175***	0.00502	0.00515
	(0.0443)	(0.0443)	(0.0507)	(0.0509)	(0.00855)	(0.00855)
Export Restriction (Own)		-0.0213		-0.0903*		-0.00746
		(0.0226)		(0.0486)		(0.00864)
Country-Product FE	✓	✓	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓	✓	✓
Estimator	PPML	PPML	PPML	PPML	OLS	OLS
# of Clusters	724,746	724,746	718,349	718,349	650,453	650,453
# of Obs.	15,714,019	15,714,019	15,575,760	15,575,760	9,473,075	9,473,075

Notes: This table reports the estimated effects of upstream mineral export restrictions on exports of downstream products. Dependent variables include export value and quantity (in levels) and unit values (in logs). Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

I now turn to examining whether upstream restrictions stimulate exports of downstream mineral-related products along the value chain. Table 3 presents the estimation results of Equation 25. Columns (1) and (3) present the baseline estimates on export value and quantity. In contrast to the effects on targeted minerals, exports of downstream products increase significantly when their upstream minerals become subject to export restrictions. Specifically, export value rises by 11.0 percent and export quantity by 18.9 percent. As the increase in quantity exceeds that in value, export prices may decline following upstream restrictions. Column (5)

tests this by using unit values as a proxy for export prices. The estimated coefficients are slightly positive, statistically insignificant, and economically small, at roughly one-tenth of the price effects observed for targeted minerals. This weak result likely reflects the prevalence of zero trade flows in the data. Because unit values can only be computed for positive exports, this requirement reduces the sample size by about half.

Mineral-related downstream products can sometimes themselves be subject to export restrictions. To isolate the causal effects of upstream policies, Columns (2), (4), and (6) control for the export restriction status of downstream products. When restricted, their exports decline, although the effect is modest and only marginally significant for quantity. Importantly, accounting for such direct restrictions leaves the estimated upstream effects virtually unchanged. This confirms that the positive effects documented reflect upstream restrictions rather than concurrent downstream policies. Taken together, these results suggest that limiting raw mineral exports encourages greater processing activity and a reallocation toward downstream production.



(a) Export Value (b) Export Quantity

Figure 6. Downstream effects: event study

Notes: This figure plots the dynamic effects of upstream mineral export restrictions on exports of downstream products, based on coefficient estimates from event-study regressions. Bars represent 95% confidence intervals, with standard errors clustered at the country–product level.

Figure 6 replicates the event study analysis for downstream products. None of the pre-treatment coefficients are statistically significant, confirming that the observed increase in downstream exports is caused by upstream export restrictions rather than pre-existing trends. In contrast to targeted upstream minerals, downstream exports respond more quickly, with positive effects emerging almost immediately after the policy takes effect. This faster response likely reflects the ability of existing domestic processing firms to scale up production using

previously underutilized capacity. However, the magnitude of the effects is considerably smaller for downstream products, and the effects amplify more slowly over time.

Table 4. Downstream effects: export status and destination

	Export Status	# of Destinations	Top Destination Share	Destination HHI
Export Restriction (Up)	0.00461**	0.0392***	-0.00825***	-0.00936***
	(0.00212)	(0.00427)	(0.00181)	(0.00195)
Country-Product FE	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓
Estimator	OLS	PPML	OLS	OLS
Pre-treatment Mean	0.848	26.3	0.575	0.463
# of Clusters	724,746	724,746	653,631	653,631
# of Obs.	15,714,019	15,714,019	9,553,210	9,553,210

Notes: This table presents the estimated effects of upstream mineral export restrictions on export status and destination concentration for downstream products. Dependent variables include export status, number of destinations, top destination share, and the Herfindahl index. Pre-treatment mean refers to the average value of each outcome for treated country–product pairs in the year before the restriction. Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 4 examines how mineral export restrictions affect the destination structure of downstream exports. Compared to raw minerals, fewer countries were able to export downstream products prior to the restrictions. Moreover, global demand for these products was more dispersed, as reflected in a higher average number of destinations and lower export concentration. Following the imposition of upstream restrictions, the probability that a country exports a given downstream product increases by only 0.5 percentage points, suggesting limited entry into entirely new product markets. In contrast, the expansion occurs primarily along the intensive margin: the number of export destinations rises by 3.9 percent, while among active exporters, both the top destination share and the Herfindahl index decline by approximately 0.8 and 0.9 percentage points, respectively. These patterns indicate that upstream restrictions induce countries to scale up and diversify exports of downstream products in which they already have a presence, rather than spurring broad-based entry into new product categories. This concentration on existing capabilities, which I return to later, suggests a strategic deepening of comparative advantage rather than experimental expansion into unfamiliar markets.

6.3 How Do Export Restrictions Work?

The preceding results indicate that mineral export restrictions can stimulate downstream exports. However, this aggregate pattern may mask substantial heterogeneity in policy effectiveness. As countries differ in their mineral endowments and industrial capacities, not all are equally positioned to benefit from upstream export restrictions, nor do all downstream products respond in the same way. I examine two factors that shape the magnitude of these effects: the restricting country's market share in upstream minerals and its revealed comparative advantage (RCA) in downstream products. The former captures the market power required to influence global prices and supply chains, while the latter reflects production capabilities and competitiveness prior to policy implementation. Together, these two variables help identify whether mineral export restrictions operate by reinforcing existing industrial strengths or by fostering new development in downstream production. To ensure consistency, this subsection focuses exclusively on mineral-related downstream products, for which the corresponding upstream market share is well defined and cross-product RCA comparisons are meaningful.

Table 5. Downstream effects: heterogeneity by upstream market share

	Below 1%		1% to 30%		Above 30%	
	Value	Quantity	Value	Quantity	Value	Quantity
Export Restriction (Up)	-0.0409	0.0127	0.0875	0.0852	0.284**	0.363**
	(0.0952)	(0.0664)	(0.0573)	(0.0797)	(0.137)	(0.149)
Country-Product FE	✓	✓	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓	✓	✓
Estimator	PPML	PPML	PPML	PPML	PPML	PPML
# of Clusters	158,611	157,469	27,009	26,955	22,716	22,129
# of Obs.	3,452,525	3,427,797	589,464	588,284	479,700	466,703

Notes: This table reports the estimated effects of upstream mineral export restrictions on exports of downstream products. Dependent variables include export value and quantity (in levels) and unit values (in logs). Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 5 reports the downstream effects, dividing the sample into three groups based on the restricting country's pre-treatment market share in the upstream mineral: negligible (below 1%), moderate (1% to 30%), and dominant (above 30%). Export restrictions have virtually no effect on downstream exports when the restricting country holds only a negligible market share. In this group, the estimated coefficients for both export value and quantity are statistically indistinguishable from zero, with the former even turning negative. As market power increases, the effects of export restrictions become more pronounced. For countries with moderate market

shares, the point estimates rise to 9.1 percent for value and 8.9 percent for quantity, although they remain statistically insignificant given the limited sample size. The effects are largest and statistically significant only for countries with substantial market dominance. For countries with market shares exceeding 30 percent, export value increases by 32.8 percent and quantity by 43.8 percent, both considerably larger than the baseline results.

These results highlight market power as a necessary condition for export restrictions to succeed. Without sufficient control over global supply, countries are unable to create a significant price wedge between domestic and international input markets, let alone stimulate downstream processing. The concentration of significant effects among market-dominant mineral exporters indicates that only a small subset of countries with near-monopolistic positions can realistically hope to use upstream export restrictions to promote downstream industrial development.

Table 6. Downstream effects: heterogeneity by downstream RCA

	Low RCA (< 1)		High RCA (≥ 1)	
	Value	Quantity	Value	Quantity
Export Restriction (Up)	-0.0842	0.0697	0.108*	0.189***
	(0.0598)	(0.0768)	(0.0600)	(0.0693)
Country-Product FE	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓
Estimator	PPML	PPML	PPML	PPML
# of Clusters	183,275	181,567	25,092	25,022
# of Obs.	4,004,346	3,967,105	528,932	527,850

Notes: This table reports the estimated effects of upstream mineral export restrictions on exports of downstream products. Dependent variables include export value and quantity (in levels) and unit values (in logs). Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Even if a country holds upstream market power, do mineral export restrictions truly work as portrayed by policymakers, expanding downstream exports into products that the country could not competitively produce before? Table 6 addresses this question by estimating the downstream effects of export restrictions using samples divided by whether the restricting country has high or low RCA in the affected downstream product prior to implementing the restriction, with the threshold set at one. As we have already seen in Figure 3, restricting countries are not competitive in producing most mineral-related downstream products: only 12.6% of country-product pairs hold a pre-treatment RCA greater than one.

The results are less encouraging: export restrictions generate significant downstream effects only when countries already possess revealed comparative advantage in the affected products.

Among high-RCA pairs, export value rises by 11.4 percent and quantity by 20.8 percent, both statistically significant. In contrast, where comparative advantage is absent, export restrictions fail to stimulate downstream activity. The estimated effects are statistically insignificant and economically small, with the coefficient on export value again turning negative.

Therefore, export restrictions do not create comparative advantage from scratch. By lowering domestic input costs relative to foreign competitors, such policies enable countries to scale up and diversify exports in downstream products where they already have a presence, consistent with the earlier finding of expansion along the intensive margin. However, they cannot compensate for structural weaknesses in downstream production capabilities, technology, or complementary inputs when these foundations are lacking. Because these factors are correlated with a product's position along the value chain, this raises a further set of questions: how far do the export-stimulating effects extend along the chain, which types of products benefit, and through what mechanisms? These issues are explored in the next subsection.

6.4 Industrial Upgrading: Reality or Myth?

Industrial upgrading is often cited as a key policy objective of mineral export restrictions, yet its precise meaning remains ambiguous. Broadly speaking, it refers to a process through which countries build productive capacity and move into more downstream segments of production with higher value-added. Raw minerals are positioned at the very upstream end of supply chains, followed by multiple processing stages before reaching final demand, each involving products that differ markedly in complexity and input requirements. In this context, industrial upgrading indicates progressively acquiring the capability to produce and export an increasingly diverse range of downstream goods. Therefore, understanding how deeply the effects of mineral export restrictions propagate along the value chain and which types of products benefit the most is essential for assessing their effectiveness in promoting industrial upgrading.

The AIPNET dataset depicts the full value chain associated with upstream minerals but does not provide an explicit indicator of the position of downstream products along that chain. To construct such a measure, I develop a method based on the Tarjan algorithm in graph theory, which finds the strongly connected components (SCCs) of a directed graph (Tarjan, 1972).[10] The resulting measure captures each product's *downstreamness*, or network distance, relative to

[10] Strongly connected components (SCCs) are maximal sets of nodes in a directed graph such that any two nodes within the set are mutually reachable via directed paths. Collapsing each SCC into a single node removes circular dependencies and yields a directed acyclic graph (DAG), which allows upstream–downstream ordering and layer depth in the AIPNET network to be uniquely and consistently defined for each upstream mineral. Further details on the algorithm and the resulting network decomposition are provided in Appendix E.

its upstream mineral. To address the fact that differences in export restrictions across countries can generate different exposure distances for the same downstream product, I assign the modal distance across countries, taking the maximum in the event of ties.

By construction, the relative downstreamness measure is only defined for mineral-related downstream products. To obtain comprehensive coverage across all products, I additionally use the *upstreamness* measure developed by Antràs et al. (2012) Based on direct requirement coefficients from standard input–output tables, this approach computes a product's absolute weighted average production-stage distance from final demand.[11] This measure is anchored at final demand and constructed in the opposite direction to the propagation of export restriction effects. Therefore, I use it primarily as a robustness check.

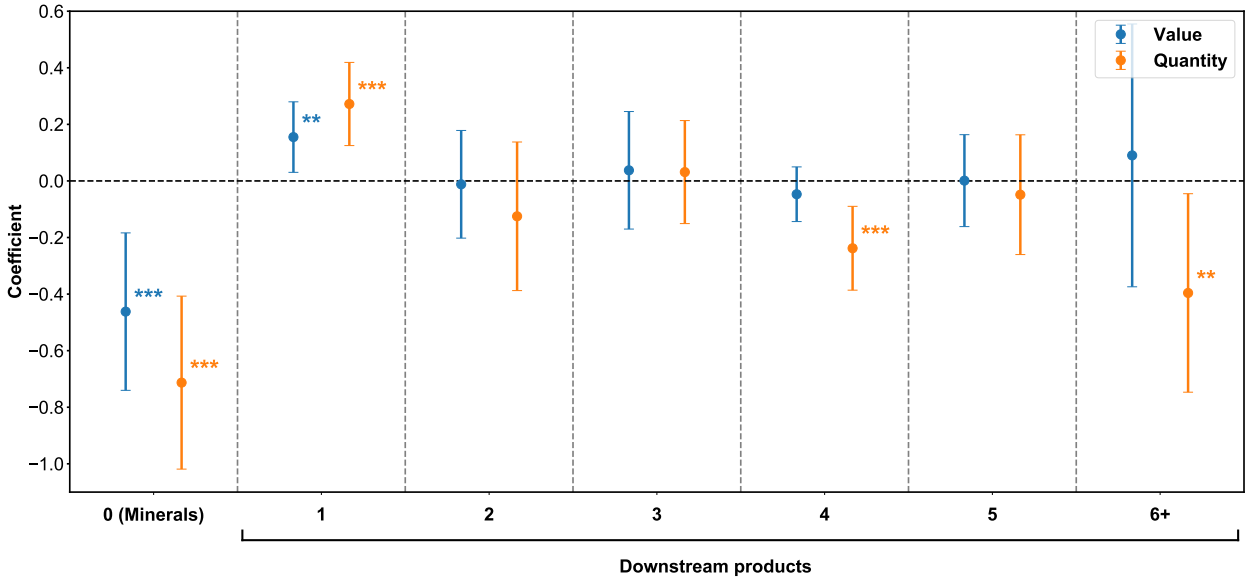


Figure 7. How far do export restrictions propagate along the value chain?

Notes: This figure shows heterogeneous treatment effects of upstream mineral export restrictions on exports across downstream production stages. Treatment effects are estimated separately for each production stage. Bars denote 95% confidence intervals, with standard errors clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

[11] The upstreamness of industry i is calculated by

$$U_i = 1 \times \frac{F_i}{Y_i} + 2 \times \frac{\sum_{j=1}^{N} d_{ij} F_j}{Y_i} + 3 \times \frac{\sum_{j=1}^{N} \sum_{k=1}^{N} d_{ik} d_{kj} F_j}{Y_i} + \ldots,$$

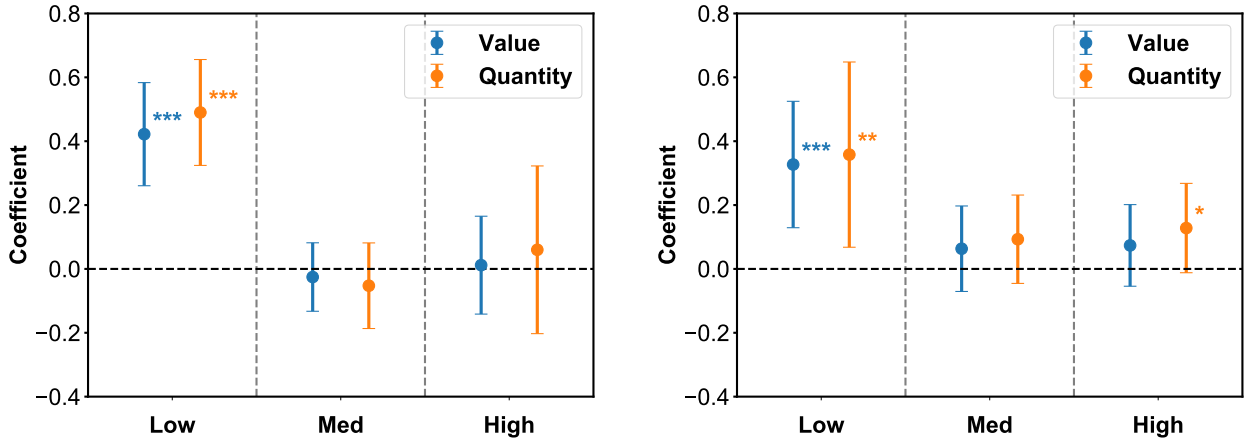
where Y_i denotes the gross output of industry i, F_i the value of its final use, and d_{ij} the dollar amount of sector i's output required to produce one dollar's worth of output in industry j. By construction, $U_i \geq 1$, with larger values indicating greater distance from final demand. In this paper, the index is computed using the R algorithm developed by Liao et al. (2020), based on the 2012 BEA input–output table covering 204 industries.

Figure 7 reveals that the effects of upstream mineral export restrictions on downstream exports vary systematically across production stages. For comparison, I also include the direct effects on targeted minerals reported in Table 1. Export-stimulating effects are observed only for downstream products at the first stage, where export values and quantities increase by 16.8 percent and 31.2 percent, respectively. The divergence between these two coefficients indicates that export growth at this stage is driven primarily by volume expansion rather than value upgrading, consistent with low or declining unit values or specialization in lower-value varieties at early processing stages. Beyond the first stage, estimated effects on both export values and quantities quickly attenuate and become statistically indistinguishable from zero. Nevertheless, the coefficient pattern is also suggestive: the value–quantity gap observed upstream disappears in midstream and reverses downstream, where some of the quantity coefficients turn negative and significant. This coefficient pattern suggests a reallocation of downstream activity at more advanced stages: only activities associated with higher unit values appear to persist, while lower–value, volume-intensive activities are likely displaced or reoriented toward earlier processing stages. Table A8 in the appendix reports results using the upstreamness measure, which yield the same qualitative pattern. Taken together, mineral export restrictions generate measurable export gains only at the earliest downstream stage, where production remains closely tied to raw material inputs.

What prohibits the effects of upstream mineral export restrictions from propagating further along the value chain? I propose two key barriers that correlate with value-chain position: technological complexity and complementary input requirements. As products move downstream, production processes become increasingly complex, requiring sophisticated capabilities and specialized knowledge that cannot be acquired through cheaper raw materials alone. Simultaneously, downstream production relies more heavily on diverse complementary inputs from other sectors. When final products require numerous intermediate inputs, the cost advantage from one subsidized mineral becomes diluted as other inputs must still be purchased at world prices. Consequently, while lower mineral costs may facilitate entry into basic processing activities, they offer diminishing advantages as production becomes more technologically elaborate and less dependent on any single raw material input.

I measure technological complexity using the Product Complexity Index (PCI) developed by the Observatory of Economic Complexity (OEC) (Simoes and Hidalgo, 2011). As a proxy for complementary input requirements, I calculate the average PCI of upstream products connected to each downstream product in AIPNET. As a proxy for complementary input requirements, I

calculate the average PCI of upstream products linked to each downstream product in AIPNET.[12] Figures A6 in the appendix show that, for mineral-related products, all of these measures tend to increase as production moves downstream along the value chain. However, this relationship between complexity, input requirements, and value-chain position does not extend to the full set of HS codes, as some light manufactures (e.g., textiles and apparel) tend to be both downstream and technologically simple, reflecting their short value chains. Therefore, partitioning the sample by complexity or input requirements, rather than by value-chain position, offers a more direct test: if these mechanisms are correct, export gains should be concentrated in products that are technologically simple and require relatively few complementary inputs.



(a) Complexity (b) Input requirements

Figure 8. Industrial upgrading constraints: complexity and input requirements

Notes: This figure shows heterogeneous treatment effects of upstream mineral export restrictions on exports across downstream product groups. Downstream products are divided into terciles by technological complexity or input requirements (average input complexity), and treatment effects are estimated separately for each group. Bars denote 95% confidence intervals, with standard errors clustered at the country–product level. Corresponding regression results are reported in Tables A9 and A10 in the appendix. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Figure 8 confirms this prediction. While downstream export-stimulating effects exist, they are concentrated exclusively in products with the lowest levels of technological complexity and input requirements. For these products, the estimated effects are substantial, with export growth reaching approximately 40 percent in both value and quantity. In contrast, products with greater complexity or reliance on complementary inputs show little to no measurable response. In other words, the impact of mineral export restrictions is confined to basic processing stages,

[12]This method accounts for the availability of complementary inputs in developing country settings, as more complex inputs tend to be harder to source domestically. The regression results remain robust when using a simple count of upstream inputs instead.

with technological complexity and diverse input requirements serving as binding constraints that prevent cheaper minerals from translating into export gains further downstream.

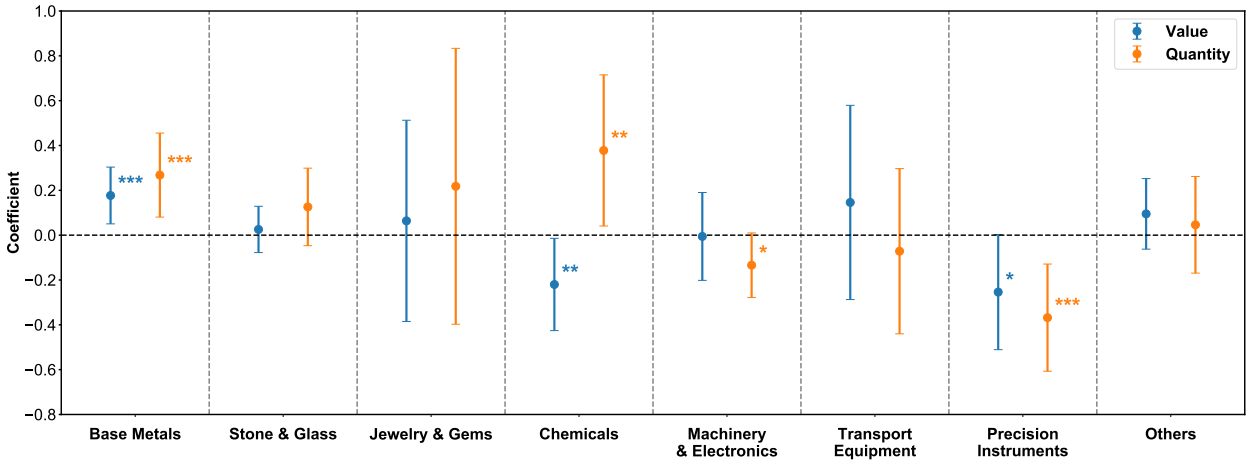


Figure 9. Sectoral patterns of downstream export response

Notes: This figure shows heterogeneous treatment effects of upstream mineral export restrictions on exports across downstream sectors. Treatment effects are estimated separately for each sector. Bars denote 95% confidence intervals, with standard errors clustered at the country–product level. Corresponding regression results and sector-level summary statistics are reported in Table A11 in the appendix. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Figure 9 further breaks down this pattern across downstream sectors, revealing marked differences in the magnitude and direction of the effects. The export-stimulating effects are concentrated almost entirely in base metals, where upstream policies lead to substantial increases in both export value and quantity. By contrast, no comparable gains are observed in more technologically sophisticated sectors such as machinery and electronics, transport equipment, and precision instruments, where the estimated effects are small or even negative. The chemicals sector exhibits a mixed pattern: restrictions raise export quantities but lower export values, indicating an expansion in lower-value processing rather than in more advanced segments.

Taken together, these findings reinforce the central conclusion of the analysis. Mineral export restrictions appear to generate measurable export gains only in the most mineral-intensive and technologically simple stages of production. They do not seem to facilitate entry into more sophisticated downstream activities. Instead, the evidence suggests a tendency for countries to remain concentrated in basic processing where comparative advantage is directly tied to subsidized mineral inputs. Within the period covered by this study, there is little evidence of broad-based industrial upgrading beyond these initial stages.

7 Robustness Checks

This section assesses the robustness of the baseline findings to alternative empirical specifications. Across different estimation methods, sample constructions, and definitions of raw minerals, the core results remain stable: export restrictions significantly reduce exports of targeted minerals and increase downstream product exports.

7.1 Alternative Estimation Methods

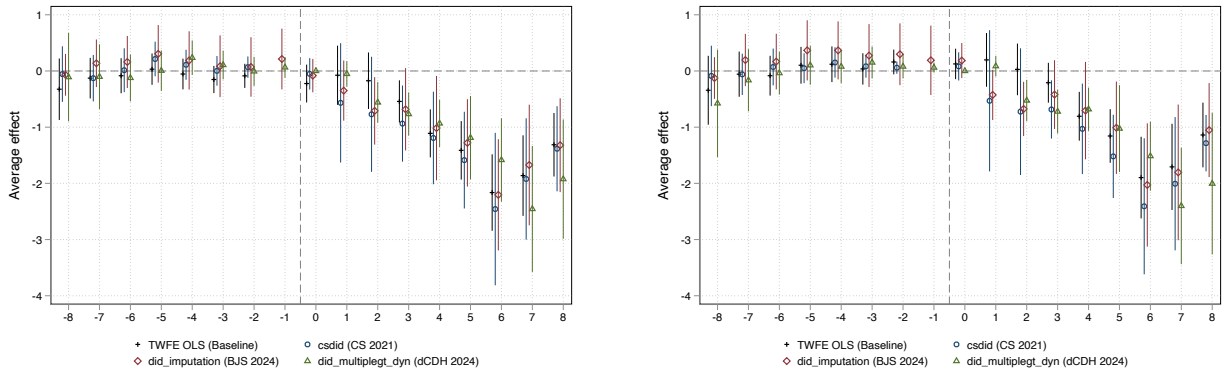
Due to the prevalence of zero trade flows in the data, all baseline regressions are estimated using PPML in levels. While PPML is widely used in the trade literature, its finite-sample performance can be sensitive to extreme observations and to incidental-parameter distortions when high-dimensional fixed effects are included (Weidner and Zylkin, 2021). As a first robustness check, I re-estimate equations 24 and 25 using log-linear OLS specifications. Since log-transformations eliminate zero flows and may induce heteroskedasticity, I weight country-product pairs by their 2008 export values, which partly mitigates size-based heteroskedasticity.

Tables A12 and A13 in the appendix report the results. Since taking logs mechanically drops all zero-trade observations, this comparison is limited to the intensive margin. Despite this limitation, the coefficient estimates for the full sample remain very similar to baseline and statistically significant. Given that most observations in the sample are never-treated, I further test the validity of the control group by restricting the sample to only affected countries and affected products. As shown in both tables, this restriction does not alter the effects of export restrictions on targeted minerals and actually more than doubles the effects for downstream products. The coefficients remain highly significant across all specifications. These robustness checks confirm that the main findings are not artifacts of using the PPML estimator.

It is now well-established that two-way fixed effects (TWFE) estimators for difference-in-differences models produce biased estimates when treatment effects are heterogeneous and treatment timing varies (de Chaisemartin and D'Haultfoeuille, 2023; Roth et al., 2023). Mineral export restrictions in my sample were introduced over a 15-year period and likely induced heterogeneous treatment effects, particularly for downstream products. As a result, staggered adoption may bias baseline estimates. To address this, I use three estimators that account for both staggered timing and treatment effect heterogeneity: `csdid` (Callaway and Sant'Anna, 2021), `did_imputation` (Borusyak et al., 2024), and `did_multiplegt_dyn` (de Chaisemartin and D'Haultfoeuille, 2024). Since these estimators do not accommodate non-linear models, I use the OLS specifications reported in Tables A12 and A13 as the baseline. I estimate coefficients

for targeted minerals using the full sample. However, due to computational constraints, the analysis of downstream products is limited to affected countries and affected products.

Figures 10 and 11 report all estimated coefficients, including those using the TWFE estimator. The different estimators produce very similar results. For downstream products, the heterogeneity-robust estimators correct the pre-treatment bias present in the TWFE estimates and reveal no evidence of pre-trends. Estimates beyond five years before or after the policy implementation become less precise due to insufficient observations. Nevertheless, the baseline results appear unaffected by treatment time heterogeneity, likely because the majority of the sample consists of never-treated country-product pairs. Table A14 in the appendix presents the Bacon decomposition for the OLS regressions (Goodman-Bacon, 2021). Across all four baseline specifications, over 90 percent of the estimated coefficient is driven by comparisons using never-treated units as controls, with minimal weight placed on comparisons across different treatment timing groups. This pattern further mitigates concerns about bias from treatment effect heterogeneity in the baseline estimates.

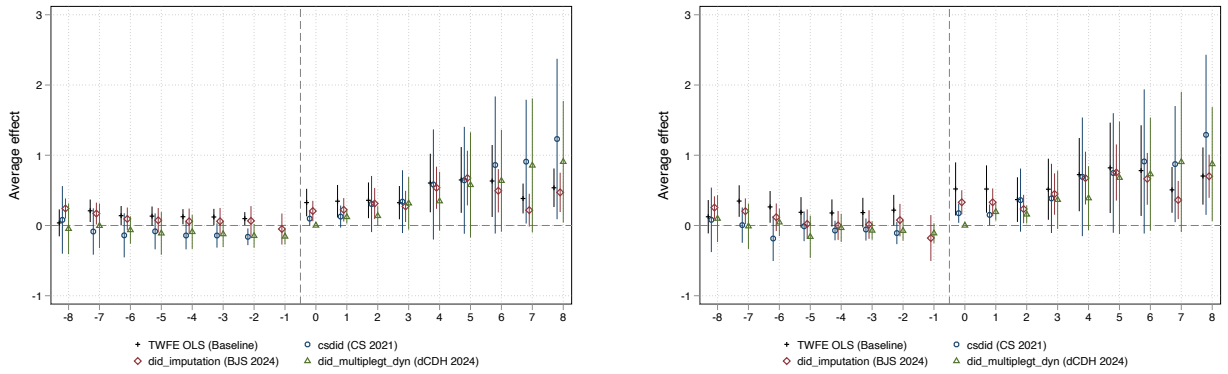


(a) Export Value (b) Export Quantity

Figure 10. Heterogeneous diff-in-diff estimates: targeted minerals

Notes: This figure shows the estimated treatment effects of mineral export restrictions on exports of targeted minerals using alternative difference-in-differences estimators that account for treatment timing heterogeneity. Standard errors are clustered at the country-product level.

Finally, the ETWFE estimator proposed by Wooldridge (2023) is, to my knowledge, the only heterogeneity-robust estimator currently available that accommodates non-linear models, enabling a direct robustness check of the PPML baseline. Figures A7 and A8 in the appendix present the estimated coefficients using the `jwdid` command implemented by Nagengast and Yotov (2025) and Nagengast et al. (2025). The estimated post-treatment dynamics closely track those from the baseline specification, lending further support to the main results.



(a) Export Value

(b) Export Quantity

Figure 11. Heterogeneous diff-in-diff estimates: downstream products

Notes: This figure shows the estimated treatment effects of mineral export restrictions on exports of downstream products using alternative difference-in-differences estimators that account for treatment timing heterogeneity. Regressions are estimated on samples including only ever-treated countries and products. Standard errors are clustered at the country-product level.

7.2 Alternative Samples

In addition to estimation choices, alternative sample constructions and definitions of "raw minerals" may affect the results. I now evaluate the sensitivity of the findings to these variations. The first set of robustness tests addresses several concerns regarding sample comparability and policy motives. The fact that mineral export restrictions are almost exclusively implemented by developing countries raises the concern that treated and control observations may not be comparable. I therefore re-estimate Equations 24 and 25 on a sample restricted to developing (non–high-income) countries. A further concern is that countries or products never exposed to export restrictions may differ systematically from those affected at least once. To avoid comparing such structurally distinct observations, I narrow the sample to countries that have ever imposed mineral export restrictions and to products that have ever been targeted. I also exclude China, which is the largest user of mineral export restrictions in the sample and whose measures often reflect broader geopolitical considerations, making its policy episodes less comparable to those of other countries. Finally, I drop broad-based export restrictions that cover more than 100 products or more than 10 raw minerals, as such sweeping measures likely reflect policy motives different from those underlying more targeted interventions. As presented in Figure 12, the results remain closely aligned with the baseline estimates across all these alternative sample constructions.

Another set of robustness checks examines the definition of raw minerals, which in the baseline analysis comprises HS Chapters 25 and 26. Given that this classification aggregates

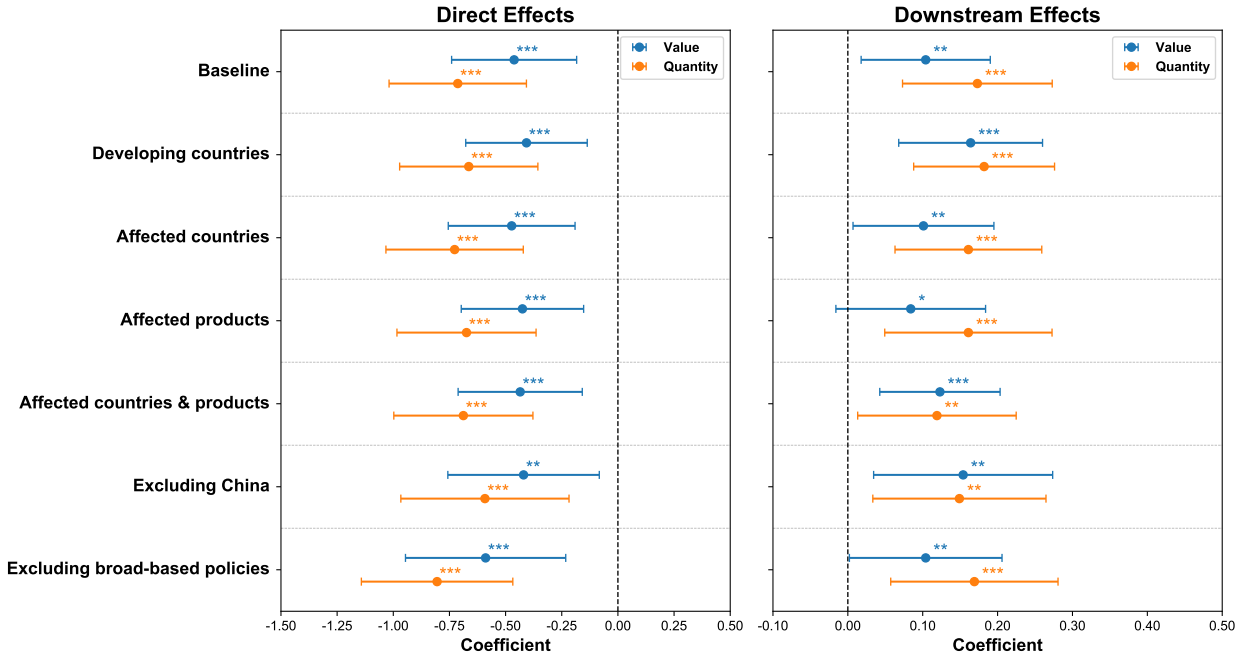


Figure 12. Robustness checks: alternative samples

Notes: This figure shows the estimated effects of upstream mineral export restrictions on downstream product exports across alternative sample selections. Treatment effects are estimated separately for each specification. Bars represent 95% confidence intervals with standard errors clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

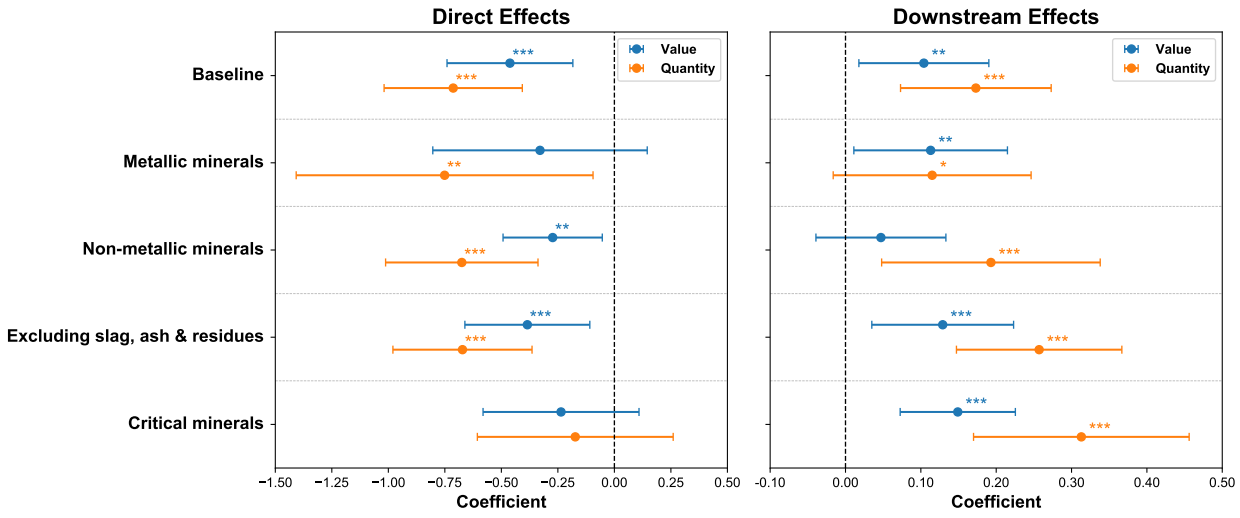


Figure 13. Robustness checks: alternative mineral definitions

Notes: This figure shows the estimated effects of upstream mineral export restrictions on downstream product exports under alternative definitions of raw minerals. Treatment effects are estimated separately for each specification. Bars represent 95% confidence intervals with standard errors clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

products with heterogeneous industrial applications, I explore several alternative specifications. First, I split the baseline definition into metallic and non-metallic minerals and estimate the regressions separately for each category. I then refine both groups by excluding slag, ash, and residues, restricting attention to raw mineral ores. Finally, I adopt the definition of critical minerals from the ADB–WTO Trade in Critical Minerals (TiCM) database, which incorporates certain chemical products, most notably rare-earth compounds (Asian Development Bank and World Trade Organization, 2024).[13] Figure 13 presents the results, which again align closely with the baseline estimates. It is interesting to note that export restrictions on minerals classified as "critical" stimulate substantially larger downstream responses, while their direct export-curbing effects become noticeably smaller. This pattern is consistent with the idea that downstream industries continue to rely on external demand and, in some cases, inward foreign direct investment to build domestic production capacity.

8 Domestic Production

This section analyzes the domestic production effects of mineral export restrictions. In the absence of direct product-level data on downstream output, I adopt a two-fold approach. First, building on the finding that export restrictions reduce raw mineral exports while increasing exports of more processed products, I examine whether domestic mineral production remains stable, which would be consistent with minerals being diverted from export markets to domestic processing. Second, I examine whether import dependence for downstream products declines, providing complementary evidence of domestic manufacturing expansion.

8.1 Domestic Mineral Production

Virtually all countries implementing mineral export restrictions are producers of the targeted minerals. Moreover, most minerals lack direct-use applications and require processing before consumption. These characteristics enable indirect inference of domestic processing activity under export restriction policies: the gap between mine production and recorded exports primarily reflects domestic retention for downstream use, provided that inventory accumulation

[13] There is no universally accepted definition of critical minerals: the United States, China, and the European Union each maintain separate lists that do not align with one another. More importantly, these classifications primarily reflect the strategic and technological priorities of industrialized economies, particularly concerns about supply-chain security. This perspective tends to overlook the mineral inputs that are central to the industrialization paths of developing countries, which is the main focus of this paper (Franks et al., 2025).

remains stable during the restriction period. This assumption is reasonable given the high storage costs of raw minerals and the uncertainty surrounding restriction duration.

Mine production data are sourced from the U.S. Geological Survey's Mineral Commodity Summaries (MCS), which provide comprehensive global coverage of mineral output. I use data from 2002 to 2023 to align with the main analysis period. The original dataset covers 84 minerals, of which 41 can be matched to products classified under HS Chapters 25 and 26[14]. Despite this breadth, coverage in the MCS data remains incomplete at the country–mineral level. To mitigate potential biases arising from missing observations, I conduct several analyses using alternative sample constrution methods. First, I re-estimate the regressions using a balanced panel consisting of country–mineral pairs with complete coverage over all 22 years (2002–2023). Second, I interpolate missing observations for country–mineral pairs with intermittent coverage. For both samples, I further conduct a robustness check excluding the residual category of "other countries," whose definition is not consistent across minerals.

Table 7. Effects of mineral export restrictions on domestic mine production

	Baseline	Balanced Panel		Interpolated Panel	
		All Countries	Excl. Residual	All Countries	Excl. Residual
Export Restriction	0.0373	0.00253	0.127	0.0356	0.147
	(0.364)	(0.377)	(0.427)	(0.360)	(0.391)
Country-Mineral FE	✓	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓	✓
Mineral-Year FE	✓	✓	✓	✓	✓
Estimator	PPML	PPML	PPML	PPML	PPML
# of Clusters	809	291	258	809	766
# of Obs.	11,721	6,402	5,676	12,241	11,349

Notes: This table reports estimates of the effects of mineral export restrictions on domestic mine production of targeted minerals. The dependent variable is mine production quantity in levels. Standard errors are clustered at the country–mineral level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 7 reports the estimated effects of mineral export restrictions on domestic mine production quantities of targeted minerals. Across all specifications, the estimated coefficients are statistically insignificant and uniformly positive. This indicates that export restrictions do not reduce upstream mining output. Taken together with earlier results showing a contraction in raw mineral exports and an expansion in downstream processed exports, the evidence is

[14]Unmatched minerals include those without standalone HS codes at the raw mineral level, those that primarily appear in refined or processed forms rather than as raw ores, and minerals whose trade is predominantly recorded outside HS Chapters 25 and 26 (most notably under Chapter 28 as chemical products). Minerals lacking reliable production statistics in the MCS data are also excluded from the sample.

consistent with minerals being retained domestically and absorbed by local manufacturing activities, rather than a decline in extraction.

8.2 Import Dependency

Table 8. Effects of mineral export restrictions on downstream imports

	Import Value		Import Quantity		Unit Value	
Export Restriction (Up)	-0.0497	-0.0497	-0.211**	-0.210**	0.00606	0.00642
	(0.0380)	(0.0380)	(0.0863)	(0.0853)	(0.00728)	(0.00728)
Export Restriction (Own)		0.00543		-0.0166		-0.0236**
		(0.0306)		(0.0652)		(0.00950)
Country-Product FE	✓	✓	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓	✓	✓
Estimator	PPML	PPML	PPML	PPML	OLS	OLS
# of Clusters	850,674	850,674	847,648	847,648	819,956	819,956
# of Obs.	18,370,078	18,370,078	18,305,375	14,498,094	14,498,094	9,473,075

Notes: This table reports the estimated effects of upstream mineral export restrictions on imports of downstream products. Dependent variables include export value and quantity (in levels) and unit values (in logs). Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

I now examine how export restrictions affect downstream import patterns as an indirect measure of domestic production capacity. The analysis mirrors the baseline approach but substitutes import data for export data, using otherwise identical datasets and regression specifications. As reported in Table 8, both import value and quantity show negative coefficients, with the quantity coefficient achieving statistical significance. These findings suggest that countries implementing mineral export restrictions subsequently reduce their reliance on imported downstream products. Under the assumption of stable domestic absorption over time, this import reduction implies a compensating increase in domestic production. Figure A10 in the appendix disaggregates these effects by product complexity and input requirement terciles. The import decline concentrates in the lowest tercile for both dimensions, consistent with the export patterns documented in Figure 8. This concentration suggests that any increases in domestic production remain limited to early-stage processing rather than propagating to more downstream industries.

9 Conclusion

This paper examines whether mineral export restrictions can serve as an industrial policy tool for promoting downstream industrial upgrading. I develop a general equilibrium model in which upstream export restrictions act as an implicit subsidy to downstream manufacturing, triggering labor reallocation and output expansion. The welfare effect is theoretically ambiguous, but the model delivers a clear implication: downstream manufacturing expansion is a necessary condition for welfare improvement in the absence of substantial market power. Empirically, I test this prediction using a novel dataset of global mineral export restrictions combined with product-level upstream-downstream linkages. While mineral export restrictions do generate positive responses in downstream exports, gains are confined to the earliest processing stages and dissipate quickly further down the value chain. Technological complexity and complementary input requirements act as binding constraints that prevent broad-based industrial development, pointing to a form of partial and shallow upgrading rather than sustained movement toward higher value-added segments of the value chain.

The findings speaks to both the potential and the limitations of mineral export restrictions. The theoretical analysis shows that welfare gains require activating scale externalities in downstream manufacturing, a condition that the empirical evidence only partially supports. While such restrictions do stimulate exports of basic processed goods, the absence of responses in technologically complex sectors suggests that scale externalities are limited in scope. Complementary measures, such as building productive capabilities, adopting frontier technologies, and easing input bottlenecks, are therefore needed for countries to climb further up the value chain. These results underscore the need for realistic expectations about what trade-based interventions can achieve, and point to important complementarities between restrictive measures and capacity-building policies. As resource nationalism and industrial policy return to the forefront of economic policy worldwide, understanding these trade-offs becomes increasingly critical for policymakers navigating the tensions between short-term revenue needs and long-term development objectives.

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Digging Up the Value Chain: Mineral Export Restrictions and Industrial Upgrading

Qingyu Chen*

March 4, 2026

ONLINE APPENDIX

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A Additional Figures and Tables

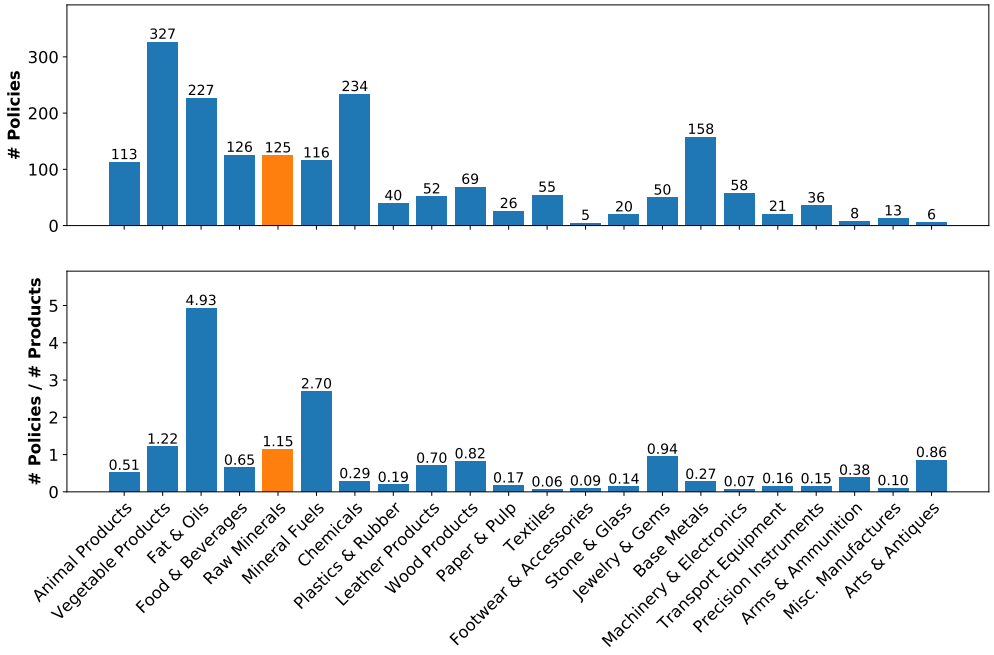


Figure A1. Export restrictions by product category

Notes: This figure displays the number of export restriction policies implemented between 2009 and 2023 across 22 broad product categories defined at the HS section level (upper panel) and the average number of policies per product within each category (lower panel). Data are drawn from the Global Trade Alert (GTA) database.

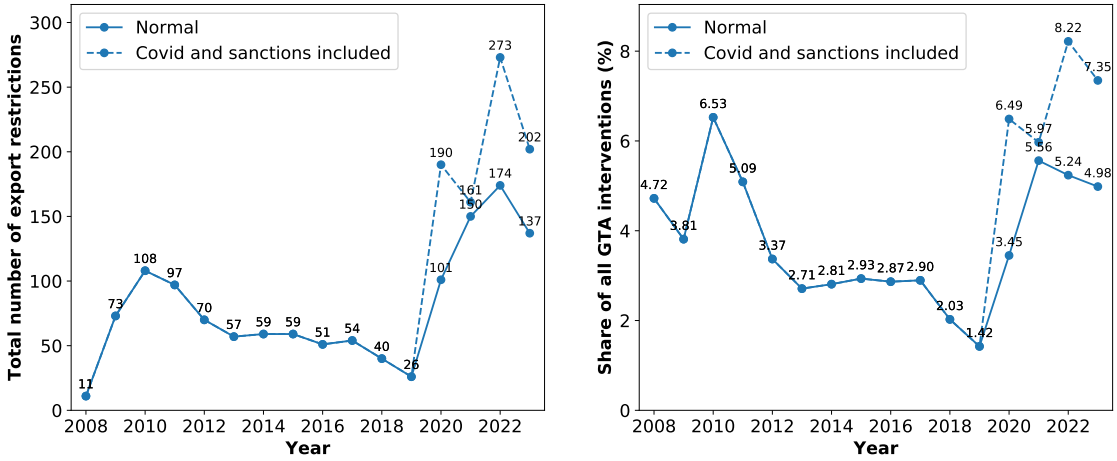


Figure A2. Export restrictions usage by year

Notes: This figure presents time trends of the total number of export restrictions imposed by non-high-income countries (left panel) and their share among all industrial policy interventions (right panel), as recorded in the GTA database from 2008 to 2023.

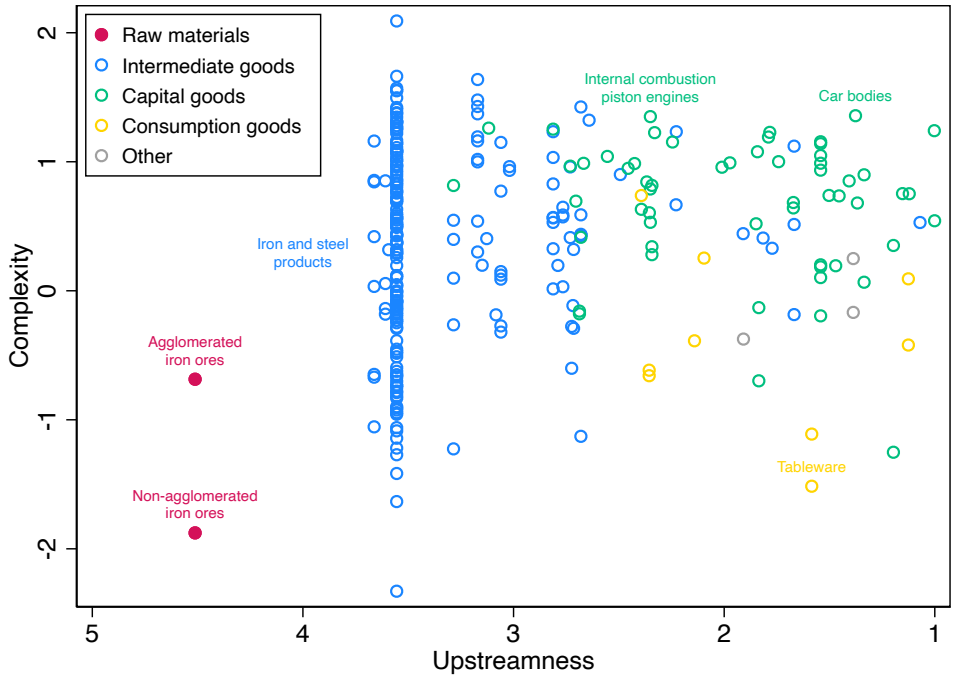
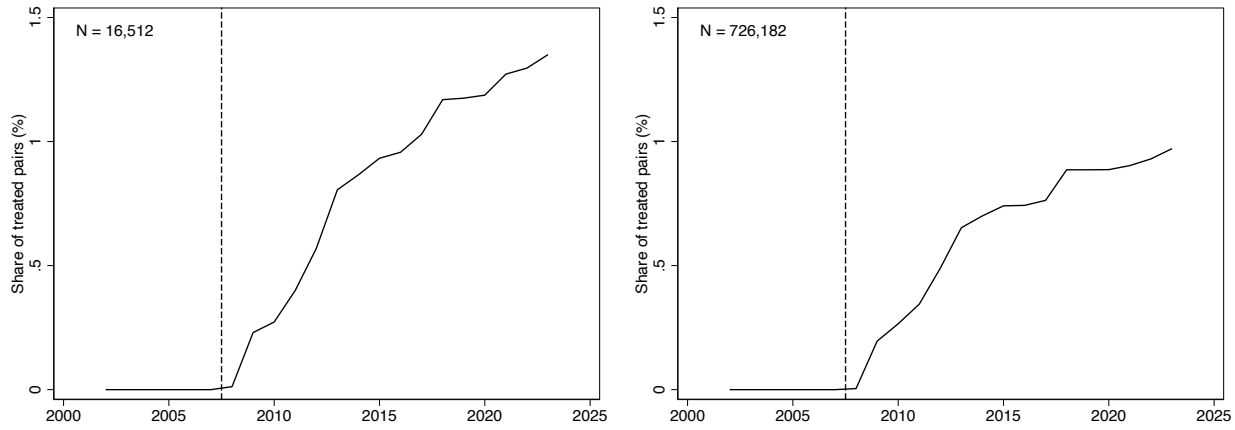


Figure A3. Products on the iron-steel value chain

*Notes:*This figure maps the positions of products along the iron–steel value chain as identified by AIPNET. The horizontal axis measures upstreamness (position along the value chain), while the vertical axis captures technological complexity. Colors distinguish products by end-use category: raw materials, intermediate goods, capital goods, and consumption goods.

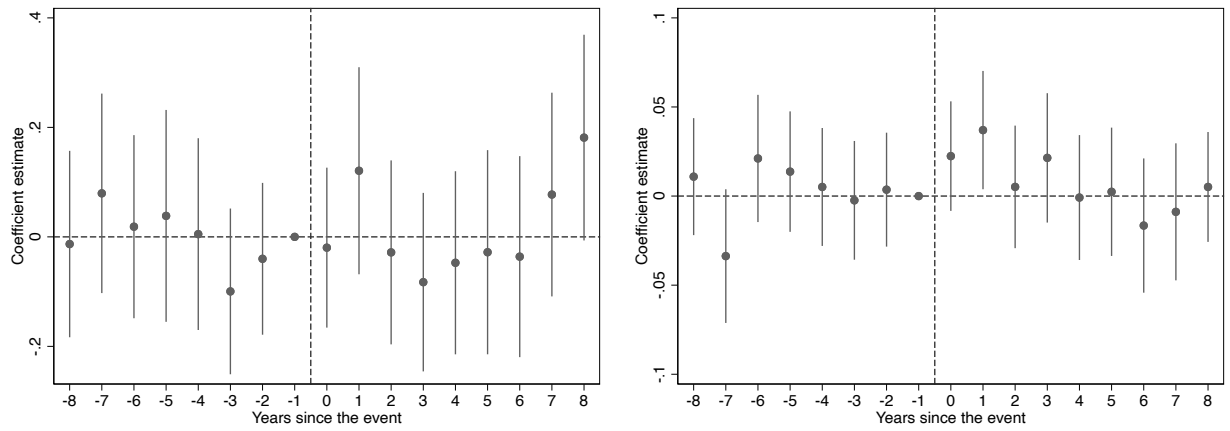


(a) Raw minerals

(b) Downstream products

Figure A4. Time trends of treatment status

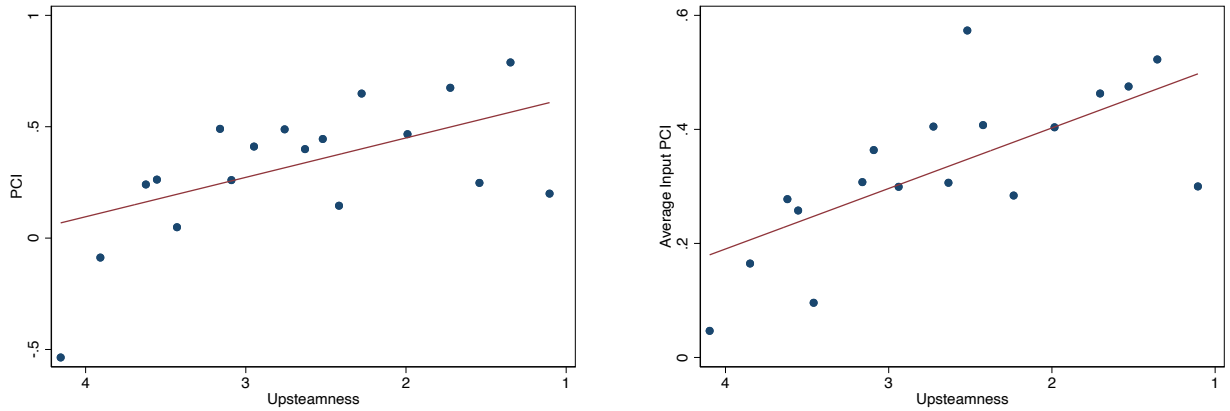
Notes: This figure plots the share of country–product pairs subject to mineral export restrictions over time for raw minerals and their downstream products. Shares are computed within each year using the estimation sample for the baseline regressions.



(a) Raw minerals (b) Downstream products

Figure A5. Price effects of mineral export restrictions: event study

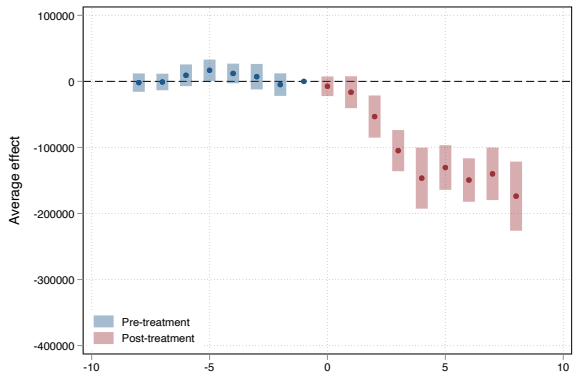
Notes: This figure plots the estimated dynamic effects of export restrictions on unit values of targeted raw minerals and downstream products, based on coefficient estimates from event-study regressions. Bars represent 95% confidence intervals, with standard errors clustered at the country–product level.



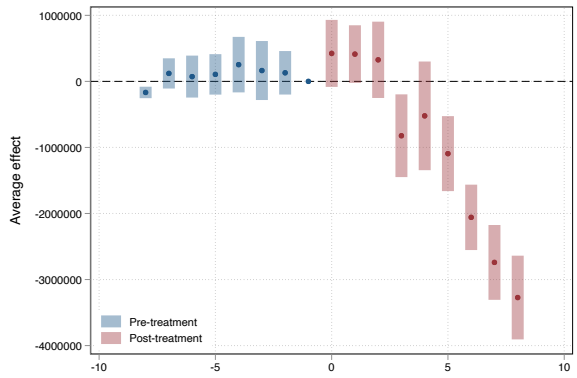
(a) Complexity (b) Input requirements

Figure A6. Value chain position and product-level characteristics

Notes: This figure summarizes key product characteristics across value-chain positions defined by AIPNET. Panel (a) plots average product complexity (PCI), and Panel (b) plots the average input PCI (a proxy for input sophistication) by upstreamness quartile. Products located further downstream tend to exhibit higher complexity and rely on more complex inputs, consistent with cumulative capability upgrading along the value chain.



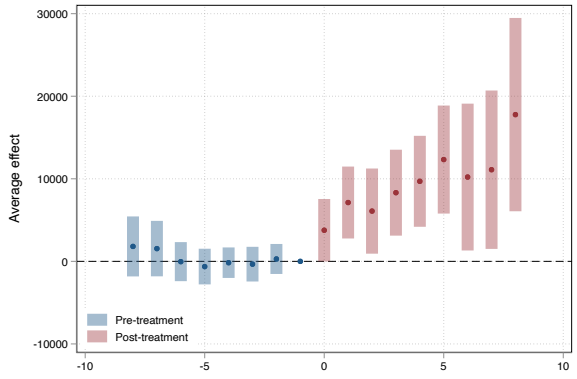
(a) Export Value



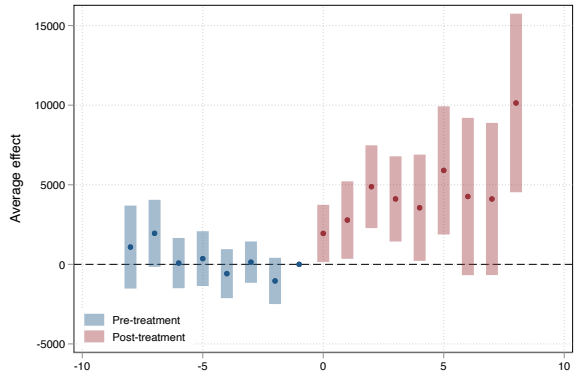
(b) Export Quantity

Figure A7. ETWFE estimates: targeted minerals

Notes: This figure shows the estimated treatment effects of mineral export restrictions on exports of both targeted minerals and downstream products, using a level specification. Estimates are obtained with the ETWFE estimator, which accommodates treatment effect heterogeneity in non-linear settings. Standard errors are clustered at the country–product level.



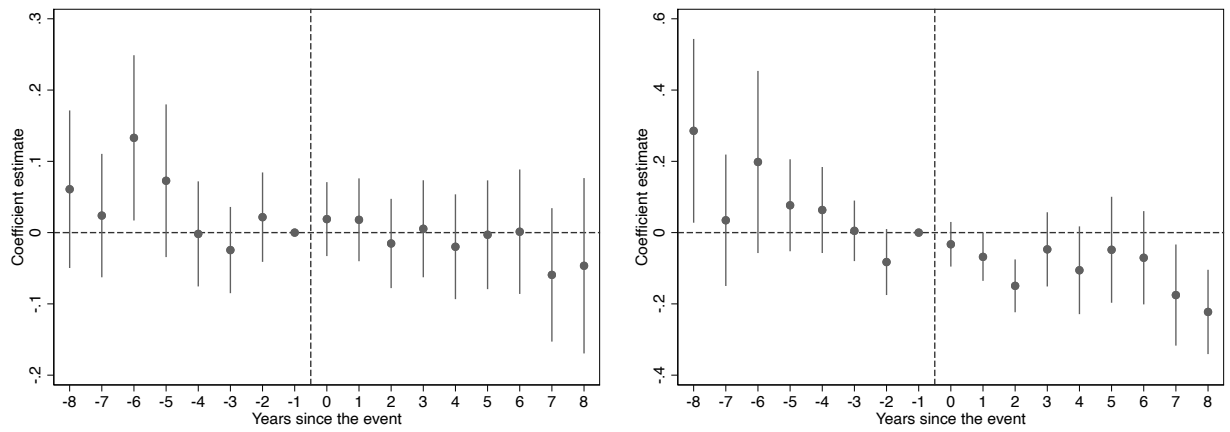
(a) Export Value



(b) Export Quantity

Figure A8. ETWFE estimates: downstream products

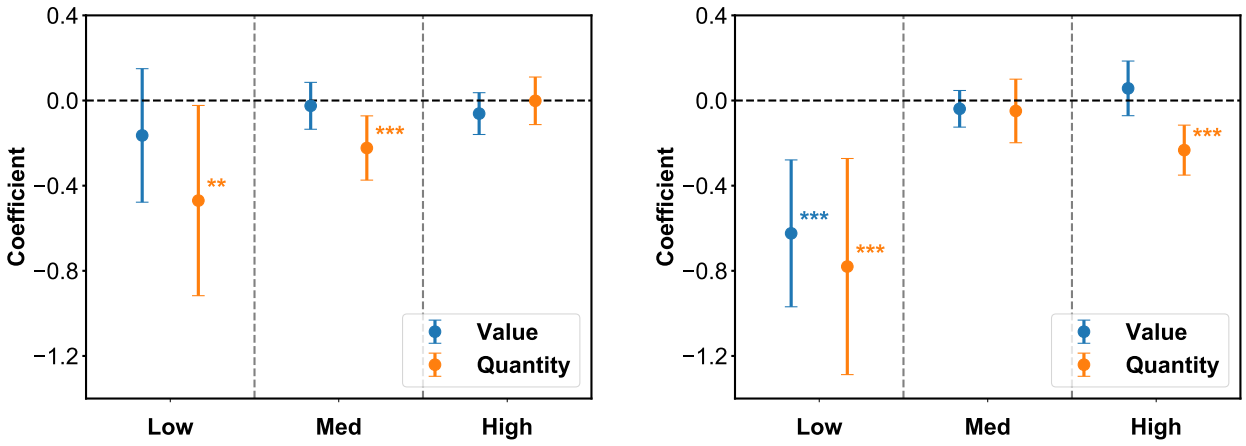
Notes: This figure shows the estimated treatment effects of mineral export restrictions on exports of both targeted minerals and downstream products, using a level specification. Estimates are obtained with the ETWFE estimator, which accommodates treatment effect heterogeneity in non-linear settings. Regressions are estimated on samples including only ever-treated countries and products. Standard errors are clustered at the country–product level.



(a) Import Value (b) Import Quantity

Figure A9. Downstream imports: event study

Notes: This figure plots the dynamic effects of upstream mineral export restrictions on exports of downstream products, based on coefficient estimates from event-study regressions. Bars represent 95% confidence intervals, with standard errors clustered at the country–product level.



(a) Complexity (b) Input requirements

Figure A10. Downstream imports: complexity and input requirements

Notes: This figure shows heterogeneous treatment effects of upstream mineral export restrictions on imports across downstream product groups. Downstream products are divided into terciles by technological complexity or input requirements (average input complexity), and treatment effects are estimated separately for each group. Bars denote 95% confidence intervals, with standard errors clustered at the country–product level. Corresponding regression results are reported in Tables A9 and A10 in the appendix. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A1. Number of export restriction policies and affected minerals by country

Country	**# Policies**	**# Minerals**
China	29	27
India	20	17
Indonesia	19	25
Egypt	9	15
Vietnam	6	15
Zimbabwe	5	10
Kyrgyzstan	4	2
Türkiye	3	8
Uganda	3	8
Russia	3	3
Afghanistan, Argentina, Belarus, DR Congo, Dominican Republic, Sri Lanka, Ukraine	2	—
Ecuador, Honduras, Hungary, Iran, Kazakhstan, Laos, Malaysia, Mexico, Mozambique, Namibia, Oman, Venezuela	1	—
Total	**125**	**75**

Notes: This table presents the number of export restriction policies and the corresponding mineral products affected at the HS6 level for each implementing country. Countries with few policies are grouped together to save space. HS Chapters 25 and 26 consist of 109 mineral products in total.

Table A2. Number of export restriction policies by mineral product

HS Code	Description	Category	# Policies	Lead Country
260111	Iron ores and concentrates, non-agglomerated	Metallic	30	India
260112	Iron ores and concentrates, agglomerated	Metallic	29	India
253090	Mineral substances n.e.s.	Non-Metallic	19	China
260300	Copper ores and concentrates	Metallic	17	Indonesia
260700	Lead ores and concentrates	Metallic	13	Indonesia
260400	Nickel ores and concentrates	Metallic	12	Indonesia
260800	Zinc ores and concentrates	Metallic	12	Indonesia
252329	Portland cement, non-white	Non-Metallic	11	Afghanistan
251511	Marble and travertine, crude or roughly trimmed	Non-Metallic	10	Kyrgyzstan
251512	Marble and travertine, merely cut	Non-Metallic	10	Kyrgyzstan
260200	Manganese ores and concentrates	Metallic	10	Indonesia
261310	Molybdenum ores and concentrates, roasted	Metallic	10	China
251020	Natural calcium phosphates and phosphatic chalk, ground	Non-Metallic	9	China
252620	Natural steatite and talc, crushed or powdered	Non-Metallic	9	China
260600	Aluminium ores and concentrates	Metallic	9	Indonesia
261400	Titanium ores and concentrates	Metallic	9	Indonesia

Notes: This table lists the top mineral products subject to export restriction policies, excluding those affected by fewer than eight policies. The last column presents the country that has implemented the largest number of export restrictions for each mineral product.

Table A3. Revealed comparative advantage: restricted vs. non-restricted

		RCA (Balassa Index)			% RCA >0	% RCA >1	p-value
		# of Obs.	Mean	Median			
Raw Minerals	Restricted	216	19.66	1.37	98.15	56.02	0.000
	Non-Restricted	2,702	2.60	0.0062	63.21	13.84	
Downstream Products	Restricted	13,049	1.13	0.16	89.42	18.65	0.260
	Non-Restricted	107,144	1.04	0.016	72.00	12.63	

Notes: This table reports summary statistics of the Revealed Comparative Advantage (RCA, Balassa Index) for restricted and non-restricted products. Columns show the number of observations, mean, median, and the percentage of RCA values greater than zero or one. The p-values are from one-sided t-tests with the null hypothesis H_0: the mean RCA of restricted products is less than or equal to that of non-restricted products.

Table A4. Motives behind export restrictions: product-level

	ER_i	ER_i	ER_i	ER_i	ER_i	ER_i
Upstreamness	0.328***		0.548***	0.0806***		0.117***
	(0.0311)		(0.0442)	(0.00744)		(0.00869)
Complexity		-0.0182	-0.0691*		-0.00415	-0.0133
		(0.0382)	(0.0391)		(0.00869)	(0.00840)
Estimator	Logit	Logit	Logit	OLS	OLS	OLS
(Pseudo-)R^2	0.0163	0.0001	0.0423	0.0224	0.0001	0.0530
# of Obs.	4,940	2,904	2,830	4,940	2,904	2,830

Notes: This table reports estimates from linear probability models predicting the imposition of export restrictions based on product-level upstreamness and complexity. Robust standard errors are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A5. Export restrictions and RCA: all products

	ER_{ik}	ER_{ik}	ER_{ik}	ER_{ik}	ER_{ik}
$\ln(\text{RCA})_{2008}$	0.277***	0.00245***	0.00245***	0.00260***	0.00256***
	(0.00501)	(5.00e-5)	(5.77e-5)	(5.33e-5)	(6.15e-5)
Country FE			✓		✓
Product FE				✓	✓
Estimator	Logit	OLS	OLS	OLS	OLS
(Pseudo-)R^2	0.0476	0.00497	0.0886	0.0359	0.120
# of Obs.	537,002	537,002	537,002	537,002	537,002

Notes: This table reports estimates from linear probability models predicting the imposition of export restrictions based on revealed comparative advantage (RCA). Robust standard errors are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A6. Export restrictions and RCA: raw minerals

	ER_{ik}	ER_{ik}	ER_{ik}	ER_{ik}	ER_{ik}
$\ln(\text{RCA})_{2008}$	0.274***	0.00563***	0.00588***	0.00651***	0.00679***
	(0.0211)	(5.28e-4)	(5.25e-4)	(5.85e-4)	(5.72e-4)
Country FE			✓		✓
Product FE				✓	✓
Estimator	Logit	OLS	OLS	OLS	OLS
(Pseudo-)R^2	0.0711	0.0148	0.190	0.0356	0.212
# of Obs.	8,805	8,805	8,796	8,805	8,796

Notes: This table reports estimates from linear probability models predicting the imposition of export restrictions based on revealed comparative advantage (RCA). Robust standard errors are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A7. Distribution of mineral-linked downstream products by sector

Sector	HS Chapter	# of Products	Mineral Downstream Products			Share (%)
			Metallic	Non-Mettalic	Total	
Chemicals	28-38	813	48	122	150	18.45
Plastics & Rubber	39-40	212	0	16	16	7.55
Leather Products	41-43	74	0	0	0	0.00
Wood Products	44-46	84	0	1	1	1.19
Paper & Pulp	47-49	150	0	64	64	42.67
Textiles	50-63	848	0	4	4	0.47
Footwear & Accessories	64-67	55	0	0	0	0.00
Stone & Glass	68-70	140	47	128	128	91.43
Jewelry & Gems	71	53	23	0	23	43.40
Base Metals	72-83	584	487	117	515	88.18
Machinery & Electronics	84-85	799	128	86	192	24.03
Transport Equipment	86-89	134	67	6	68	50.75
Precision Instruments	90-92	239	32	18	46	19.25
Misc. Manufactures	94-96	130	0	0	0	0.00
All Products		4315	832	562	1207	27.97

Notes: This table reports the number and share of downstream products linked to raw minerals by sector. "Metallic" refers to linkages with upstream minerals in Chapter 26, while "Non-Metallic" refers to those in Chapter 25. Linkages are identified using the AIPNET dataset.

Table A8. How far do export restrictions propagate along the value chain?

	Upstream		Midstream		Downstream	
	Value	Quantity	Value	Quantity	Value	Quantity
Export Restriction (Up)	0.0965*	0.254***	0.0564	0.0569	0.164	0.104
	(0.0528)	(0.0722)	(0.0568)	(0.0691)	(0.150)	(0.146)
Country-Product FE	✓	✓	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓	✓	✓
Estimator	PPML	PPML	PPML	PPML	PPML	PPML
# of Clusters	209,282	207,009	236,284	234539	227,736	225894
# of Obs.	4,547,465	4,498,057	5,128,569	5,091,093	4,936,749	4,897,071

Notes: This table reports the estimated effects of upstream mineral export restrictions on exports of downstream products. Dependent variables include export value and quantity (in levels). Downstream products are divided into terciles based on their upstreamness level. Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A9. Industrial upgrading constraints: complexity

	Low		Medium		High	
	Value	Quantity	Value	Quantity	Value	Quantity
Export Restriction (Up)	0.422***	0.490***	-0.0254	-0.0526	0.0118	0.0599
	(0.0824)	(0.0846)	(0.0547)	(0.0684)	(0.0782)	(0.134)
Country-Product FE	✓	✓	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓	✓	✓
Estimator	PPML	PPML	PPML	PPML	PPML	PPML
# of Clusters	168,334	167,265	221,328	219,547	246,502	243,961
# of Obs.	3,646,859	3,623,927	4,807,239	4,768,912	5,355,049	5,299,738

Notes: This table reports the estimated effects of upstream mineral export restrictions on exports of downstream products. Dependent variables include export value and quantity (in levels). Downstream products are divided into terciles based on their technological complexity. Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A10. Industrial upgrading constraints: input requirements

	Low		Medium		High	
	Value	Quantity	Value	Quantity	Value	Quantity
Export Restriction (Up)	0.327***	0.358**	0.0633	0.0930	0.0736	0.128*
	(0.101)	(0.148)	(0.0683)	(0.0706)	(0.0652)	(0.0714)
Country-Product FE	✓	✓	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓	✓	✓
Estimator	PPML	PPML	PPML	PPML	PPML	PPML
# of Clusters	160,314	159,134	254,610	252,631	261,539	258,809
# of Obs.	3,464,532	3,439,334	5,527,626	5,485,273	5,679,791	5,620,183

Notes: This table reports the estimated effects of upstream mineral export restrictions on exports of downstream products. Dependent variables include export value and quantity (in levels). Downstream products are divided into terciles based on their average input complexity. Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A11. Sectoral patterns of downstream export response

Sector	HS Chapters	Value	Quantity	Average Upstreamness	Average Complexity	Average Input Complexity
Base Metals	72-83	0.177***	0.268***	3.11	0.249	0.315
		(0.0646)	(0.0956)			
Stone & Glass	68-70	0.0255	0.126	2.48	0.207	0.523
		(0.0527)	(0.0882)			
Jewelry & Gems	71	0.0638	0.218	2.41	-0.408	0.414
		(0.229)	(0.314)			
Chemicals	28-38	-0.220**	0.378**	3.22	0.446	0.336
		(0.105)	(0.172)			
Machinery & Electronics	84-85	-0.00568	-0.134*	1.87	0.609	0.522
		(0.100)	(0.0734)			
Transport Equipment	86-89	0.146	-0.0716	1.51	0.287	0.402
		(0.221)	(0.188)			
Precision Instruments	90-92	-0.254*	-0.368***	1.50	0.723	0.531
		(0.131)	(0.122)			
Others	—	0.095	0.0462	2.31	-0.602	0.146
		(0.0803)	(0.110)			

Notes: This table reports the estimated effects of upstream mineral export restrictions on exports of downstream products by sector. Dependent variables include export value and quantity (in levels). For each sector, the average upstreamness, technological complexity, and input technological complexity are also reported. Standard errors are clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A12. Direct effects of export restrictions: OLS estimation

	Full Sample		Affected Countries & Products	
	Value	Quantity	Value	Quantity
Export Restriction (Up)	-0.762***	-0.605***	-0.703***	-0.508***
	(0.207)	(0.182)	(0.215)	(0.176)
Country-Product FE	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓
Estimator	OLS	OLS	OLS	OLS
# of Clusters	8,634	8,621	5,662	5,659
# of Obs.	154,729	153,754	107,109	106,660

Notes: This table presents the effects of export restrictions on the exports of targeted minerals. All coefficients are estimated using OLS with country-year, product-year, and country-product fixed effects. Country-product pairs are weighted by their export values in 2008. Standard errors are clustered at the country-year level. * p < 0.1, ** p < 0.05, *** p < 0.01.

Table A13. Downstream effects of export restrictions: OLS estimation

	Full Sample				Affected Countries & Products			
	Value	Value	Quantity	Quantity	Value	Value	Quantity	Quantity
Export Restriction (Up)	0.156**	0.156**	0.157**	0.157**	0.361***	0.361***	0.431***	0.430***
	(0.0690)	(0.0690)	(0.0740)	(0.0740)	(0.0735)	(0.0736)	(0.155)	(0.154)
Export Restriction (Own)		-0.0175		0.00122		-0.0966		-0.0660
		(0.0434)		(0.0420)		(0.0780)		(0.0856)
Country-Product FE	✓	✓	✓	✓	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓	✓	✓	✓	✓
Estimator	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS
# of Clusters	439,255	439,255	438,447	438,447	23,759	23,759	23,739	23,739
# of Obs.	8,130,390	8,130,390	8,063,575	8,063,575	457,850	457,850	454,777	454,777

Notes: This table presents the effects of export restrictions on the exports of downstream products. All coefficients are estimated using OLS with country-year, product-year, and country-product fixed effects. Country-product pairs are weighted by their export values in 2008. Standard errors are clustered at the country-year level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A14. Bacon decomposition: OLS estimation

	Targeted Minerals		Downstream Products	
Weight Component	Value	Quantity	Value	Quantity
Timing Groups vs. Never-treated	0.969	0.969	0.923	0.923
Between Timing Groups	0.031	0.031	0.077	0.077

Notes: This table reports the Bacon decomposition of the OLS estimator for the effects of export restrictions. Each row corresponds to the weight placed on comparisons between different treatment timing groups. Regressions include country–product and year fixed effects. Country–product pairs are weighted by their export values in 2008.

B Theory Appendix

B.1 Proofs

Throughout, I use the shorthand $d\ln x$ to denote dx/x, and express all comparative statics with respect to dt. The following intermediate results are used repeatedly.

Preliminary results. Differentiating the price wedge (4) logarithmically:

$$d\ln p_M = d\ln p_M^* - \frac{dt}{1-t}. \tag{A.1}$$

Differentiating the zero-profit condition (9) for Home (with $p_Y = \tau$ fixed) and substituting labor market clearing (11):

$$d\ln w = -\frac{\alpha+\Gamma}{1-\alpha-\Gamma}\, d\ln p_M. \tag{A.2}$$

Differentiating the mining supply curve (8) and mineral output $M = R^{\beta} L_M^{1-\beta}$:

$$d\ln M = \frac{1-\beta}{\beta(1-\alpha-\Gamma)}\, d\ln p_M. \tag{A.3}$$

From labor market clearing (11):

$$d\ln L_Y = -\frac{\Gamma/\gamma}{1-\alpha-\Gamma}\, d\ln p_M. \tag{A.4}$$

Mineral demand $D_M = \alpha\tau Y/p_M$ satisfies:

$$d\ln D_M = d\ln Y - d\ln p_M = \frac{\nu}{1-\alpha-\Gamma}\, d\ln p_M, \quad \nu \equiv 1+\Gamma/\gamma. \tag{A.5}$$

Analogous expressions hold for Foreign with Γ^* replacing Γ and $d\ln p_M^*$ replacing $d\ln p_M$.

B.1.1 Proof of Lemma 1

Step 1: Home mineral market. Let $s_{MH} \equiv D_M/M$ be the share of Home mineral output consumed domestically. Differentiating (12) and substituting (A.3) and (A.5):

$$\frac{1-\beta}{\beta(1-\alpha-\Gamma)}\, d\ln p_M = s_{MH} \cdot \frac{\nu}{1-\alpha-\Gamma}\, d\ln p_M + (1-s_{MH})\, d\ln X_M.$$

Solving for $d\ln X_M$:

$$d\ln X_M = B\, d\ln p_M, \quad B \equiv \frac{\kappa}{(1-s_{MH})(1-\alpha-\Gamma)} > 0, \tag{A.6}$$

where $\kappa \equiv (1-\beta)/\beta - s_{MH}\nu$.

Step 2: Foreign mineral market. Let $s^*_{MF} \equiv M^*/(M^* + X_M/\tau)$ be Foreign's mineral self-sufficiency share. Differentiating (13) and applying the Foreign analogues of (A.3) and (A.5), then substituting (A.6):

$$(1-s^*_{MF})\cdot B\, d\ln p_M = -B^*\, d\ln p^*_M, \quad B^* \equiv \frac{\nu^* - s^*_{MF}(1-\beta)/\beta}{1-\alpha-\Gamma^*} > 0.$$

Step 3: World price. Substituting (A.1) and letting $\tilde{B} \equiv (1-s^*_{MF})B$:

$$\tilde{B}\left(d\ln p^*_M - \frac{dt}{1-t}\right) = -B^*\, d\ln p^*_M.$$

Collecting terms in $d\ln p^*_M$ and solving:

$$\frac{d\ln p^*_M}{dt} = \frac{\tilde{B}/(\tilde{B}+B^*)}{1-t} \equiv \frac{\Phi}{1-t} > 0, \quad \Phi \equiv \frac{\tilde{B}}{\tilde{B}+B^*} \in (0,1).$$

Substituting back into (A.1):

$$\frac{d\ln p_M}{dt} = \frac{\Phi-1}{1-t} < 0.$$

□

B.1.2 Proof of Proposition 1

Home. Substituting $d\ln p_M/dt = (\Phi-1)/(1-t)$ into (A.2):

$$\frac{d\ln w}{dt} = -\frac{\alpha+\Gamma}{1-\alpha-\Gamma}\cdot\frac{\Phi-1}{1-t} = \frac{\alpha+\Gamma}{1-\alpha-\Gamma}\cdot\frac{1-\Phi}{1-t} > 0.$$

Foreign. Applying the Foreign analogue of (A.2) and substituting $d\ln p^*_M/dt = \Phi/(1-t)$:

$$\frac{d\ln w^*}{dt} = -\frac{\alpha+\Gamma^*}{1-\alpha-\Gamma^*}\cdot\frac{\Phi}{1-t} < 0.$$

□

B.1.3 Proof of Proposition 2

Home. Substituting $d\ln p_M/dt = (\Phi-1)/(1-t)$ into (A.4):

$$\frac{d\ln L_Y}{dt} = -\frac{\Gamma/\gamma}{1-\alpha-\Gamma}\cdot\frac{\Phi-1}{1-t} = \frac{\Gamma/\gamma}{1-\alpha-\Gamma}\cdot\frac{1-\Phi}{1-t} > 0.$$

Foreign. Applying the Foreign analogue of (A.4) and substituting $d\ln p_M^*/dt = \Phi/(1-t)$:

$$\frac{d\ln L_Y^*}{dt} = -\frac{\Gamma^*/\gamma}{1-\alpha-\Gamma^*}\cdot\frac{\Phi}{1-t} < 0.$$

□

B.1.4 Proof of Corollary 1

Home. Differentiating (10):

$$d\ln Y = \alpha(d\ln w - d\ln p_M) + (1+\gamma)\,d\ln L_Y.$$

From (A.2): $d\ln w - d\ln p_M = -d\ln p_M/(1-\alpha-\Gamma)$. Substituting (A.4):

$$d\ln Y = \frac{-\alpha}{1-\alpha-\Gamma}\,d\ln p_M - \frac{(1+\gamma)\Gamma/\gamma}{1-\alpha-\Gamma}\,d\ln p_M = \frac{-\mu}{1-\alpha-\Gamma}\,d\ln p_M,$$

where $\mu \equiv \alpha + \Gamma(1+1/\gamma) > 0$. Substituting $d\ln p_M/dt = (\Phi-1)/(1-t)$:

$$\frac{d\ln Y}{dt} = \frac{\mu}{1-\alpha-\Gamma}\cdot\frac{1-\Phi}{1-t} > 0.$$

Foreign. Analogously, with $\mu^* \equiv \alpha + \Gamma^*(1+1/\gamma)$:

$$\frac{d\ln Y^*}{dt} = -\frac{\mu^*}{1-\alpha-\Gamma^*}\cdot\frac{\Phi}{1-t} < 0.$$

□

B.1.5 Proof of Proposition 3

Since $W = \ln(I/p_Y)$ and $p_Y = \tau$ is fixed, $dW = d\ln I$. Differentiating Home income (7) and using the income share definitions (21):

$$\frac{dW}{dt} = s_w\frac{d\ln w}{dt} + s_R\frac{d(\ln p_M + \ln M)}{dt} + \frac{s_T}{t}.$$

The tax revenue term contributes s_T/t because $d\ln(t\cdot p_M^* X_M/\tau)/dt$ evaluated at the share level yields $1/t$ to leading order in s_T.

Wage term. From Proposition 1:

$$s_w \frac{d\ln w}{dt} = \frac{s_w(\alpha+\Gamma)}{1-\alpha-\Gamma}\cdot\frac{1-\Phi}{1-t}.$$

Rent term. From (A.3):

$$\frac{d(\ln p_M + \ln M)}{dt} = \left(1+\frac{1-\beta}{\beta(1-\alpha-\Gamma)}\right)\frac{d\ln p_M}{dt} = \frac{\beta(1-\alpha-\Gamma)+(1-\beta)}{\beta(1-\alpha-\Gamma)}\cdot\frac{\Phi-1}{1-t}.$$

Therefore:

$$s_R \frac{d(\ln p_M + \ln M)}{dt} = \frac{s_R[\beta(1-\alpha-\Gamma)+(1-\beta)]}{\beta(1-\alpha-\Gamma)}\cdot\frac{\Phi-1}{1-t}.$$

Combining. Summing the wage and rent terms and factoring out $(\Phi-1)/(1-t)$:

$$\frac{dW}{dt} = \frac{1-\Phi}{1-t}\cdot\frac{s_w(\alpha+\Gamma)-s_R[\beta(1-\alpha-\Gamma)+(1-\beta)]}{\beta(1-\alpha-\Gamma)} + \frac{s_T}{t} = \frac{\Lambda(1-\Phi)}{1-t}+\frac{s_T}{t}.$$

The Foreign expression follows analogously with $s_T^*=0$, yielding $dW^*/dt = -\Lambda^*\Phi/(1-t)$. □

B.1.6 Proof of Corollary 2

Setting $dW/dt > 0$ in Proposition 3:

$$\frac{\Lambda(1-\Phi)}{1-t}+\frac{s_T}{t} > 0.$$

Multiplying through by $t(1-t)>0$:

$$t\Lambda(1-\Phi)+s_T(1-t) > 0.$$

Substituting $s_T = [t/(1-t)]\cdot p_M X_M/I$ and simplifying:

$$t\Lambda(1-\Phi)+t\cdot\frac{p_M X_M}{I} > 0.$$

Dividing by $t>0$ and rearranging:

$$s_T = \frac{t}{1-t}\cdot\frac{p_M X_M}{I} > \frac{t}{1-t}\cdot\Lambda(\Phi-1).$$

□

B.2 Extension: Continuum of Sectors

This section extends the baseline two-sector model to a vertical production chain with a continuum of sectors $k \in [0,1]$, where $k = 0$ corresponds to mineral extraction and higher k corresponds to more processed goods. Each sector combines the output of the preceding stage with labor. The extension resolves the non-differentiability of welfare that arises in finite-sector models, where the production cutoff jumps discretely at critical tax rates.

Setup. A representative firm in sector k produces according to:

$$y_{jk} = A_k \cdot y_{j,k-\varepsilon}^{\alpha} \cdot l_{jk}^{1-\alpha} \cdot L_{Yk}^{\gamma}, \tag{26}$$

where $y_{j,k-\varepsilon}$ is the upstream input, l_{jk} is labor, and L_{Yk}^{γ} captures external economies of scale as in the baseline. We maintain: (i) comparative disadvantage is monotone, A_k/A_k^* strictly decreasing in k; (ii) external economies are homogeneous, $\gamma_k = \gamma$; and (iii) input intensity is homogeneous, $\alpha_k = \alpha$.

The endogenous cutoff $s^* \in [0,1]$ divides sectors between Home ($k \leq s^*$) and Foreign ($k > s^*$). Home exports minerals subject to the export tax t; all other trade is unrestricted. Consumers have symmetric log utility $U = \int_0^1 \ln C_k \, dk$, so spending is equalized across sectors.

Price transmission. Taking the continuum limit of the zero-profit condition across sectors, the Home domestic price satisfies the ODE:

$$\frac{d \ln p(s)}{ds} = -N \left[(1-\alpha) \ln \frac{p(s)}{w} + \gamma \ln L_Y(s) + \ln \tilde{A}(s) - \ln \tau \right], \tag{27}$$

with boundary condition $p(0) = p_M = (1-t)p_M^*/\tau$. Linearizing with respect to t and solving:

$$\frac{d \ln p(s)}{dt} = e^{-N(1-\alpha)s} \frac{d \ln p_M}{dt} + \left(1 - e^{-N(1-\alpha)s}\right) \frac{d \ln w}{dt} + (\text{external economy terms}). \tag{28}$$

The key structural feature is the exponential attenuation factor $e^{-N(1-\alpha)s}$: the mineral price shock decays geometrically with processing depth. Define the cumulative attenuation coefficient:

$$\mathscr{A}(s) \equiv \int_0^s e^{-N(1-\alpha)u} \, du = \frac{1 - e^{-N(1-\alpha)s}}{N(1-\alpha)}. \tag{29}$$

As $N(1-\alpha) \to 0$, $\mathscr{A}(s) \to s$ (no attenuation); as $N(1-\alpha) \to \infty$, $\mathscr{A}(s) \to 0$ (full attenuation).

Endogenous cutoff. The cutoff s^* is determined by the condition that Home and Foreign are equally competitive at the margin. Under monotone comparative disadvantage, s^* exists and is unique. Differentiating the cutoff condition with respect to t:

$$\frac{ds^*}{dt} > 0 \iff e^{-N(1-\alpha)s^*}\delta > \left(1-e^{-N(1-\alpha)s^*}\right)\left(\frac{d\ln w}{dt} - \frac{d\ln w^*}{dt}\right) - \Delta_{\text{EE}}(s^*), \tag{30}$$

where $\Delta_{\text{EE}}(s^*)$ denotes the net external economy effect at the margin. The export tax raises s^* — expanding Home's production chain into more processed sectors — when the price-chain advantage at the margin outweighs the wage and externality effects. This condition is easier to satisfy when α is large (slow attenuation) or when s^* is small (the margin is close to the mineral stage).

Wage determination. The wage equation retains the same structural form as in the baseline model:

$$\frac{d\ln w}{dt} = \frac{\alpha+\tilde{\Gamma}}{1-\alpha-\tilde{\Gamma}} \cdot \frac{1-\Phi}{1-t} > 0, \tag{31}$$

where $\tilde{\Gamma} \equiv \gamma\lambda_M/(\beta\tilde{\lambda}_Y)$ now aggregates over all Home downstream sectors, with $\tilde{\lambda}_Y \equiv \int_0^{s^*} \lambda_Y(k)\,dk$. The continuum extension changes only the interpretation of $\tilde{\lambda}_Y$ as an integral over the production chain.

Welfare. Home welfare is $W = \int_0^1 \ln C_k\,dk = \ln I - \int_0^1 \ln p_k\,dk$. Differentiating and integrating the price index over Home-produced ($k \le s^*$) and imported ($k > s^*$) sectors separately yields:

$$\frac{dW}{dt} = \frac{\tilde{\Lambda}(\Phi-1)}{1-t} - \frac{\tilde{\Lambda}^*\Phi}{1-t} + \frac{s_T}{t}, \tag{32}$$

where $\tilde{\Lambda}$ captures the net welfare effect of a fall in the domestic mineral price on Home income and the domestic price index, and $\tilde{\Lambda}^*$ captures the welfare loss from higher world mineral prices raising the cost of imported goods:

$$\tilde{\Lambda} \equiv \bar{\Lambda} - \mathscr{A}(s^*) + (s^* - \mathscr{A}(s^*))\,\frac{\alpha+\tilde{\Gamma}}{1-\alpha-\tilde{\Gamma}}, \tag{33}$$

$$\tilde{\Lambda}^* \equiv (\mathscr{A}(1) - \mathscr{A}(s^*)) - ((1-s^*) - (\mathscr{A}(1) - \mathscr{A}(s^*)))\,\frac{\alpha+\tilde{\Gamma}^*}{1-\alpha-\tilde{\Gamma}^*}. \tag{34}$$

Here $\bar{\Lambda}$ is the baseline Λ with $\tilde{\Gamma}$ replacing Γ, and $\tilde{\Gamma}^*$ is the Foreign analogue. Relative to the baseline, $\tilde{\Lambda}$ contains an additional domestic price index benefit $-\mathscr{A}(s^*) < 0$: lower mineral prices reduce the cost of all Home-produced goods, benefiting consumers. This term is partially offset by a wage cost. Since $\tilde{\Lambda} < \bar{\Lambda}$, the continuum model strengthens the case for export taxes relative to the baseline.

Welfare sufficiency condition. Setting $dW/dt > 0$ and rearranging:

$$s_T > \frac{t}{1-t}\left[\tilde{\Lambda}(1-\Phi) - \tilde{\Lambda}^*\Phi\right]. \tag{35}$$

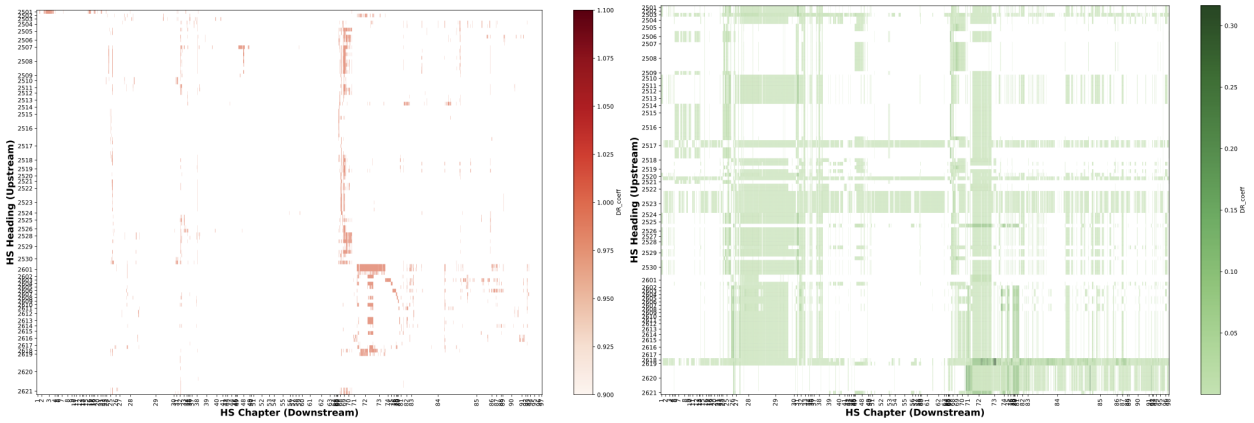
This generalizes condition (22). The qualitative structure is unchanged: the fiscal dividend on the left must exceed the net domestic cost on the right. The two modifications are: (i) $\tilde{\Lambda}$ replaces Λ, incorporating the domestic price index benefit; and (ii) the term $\tilde{\Lambda}^*\Phi > 0$ is a new cost from higher import prices that tightens the condition. On net, since the domestic price index benefit reduces $\tilde{\Lambda}$ relative to $\bar{\Lambda}$, the continuum extension weakly relaxes the sufficiency condition relative to the baseline.

C Comparing AIPNET with BEA IO Tables

In this section, I compare the upstream–downstream linkages identified by the AI-Generated Production Network (AIPNET) with those derived from input–output tables compiled by the U.S. Bureau of Economic Analysis (BEA).

C.1 Overview of AIPNET and BEA Structures

The AIPNET dataset, developed by Fetzer et al. (2024), uses large language models (GPT-4o) to predict product-level input–output linkages at the six-digit HS level. For comparison, I use a conventional input–output table harmonized to the same HS classification by Conconi et al. (2018), based on the 1997 BEA Benchmark Input–Output Accounts. While the BEA table provides quantitative direct requirement coefficients at the industry level, AIPNET offers binary product-level linkages with greater resolution.



(a) AIPNET (b) BEA IO Table

Figure C1. Full downstream linkages of raw minerals

Figure C1 compares the full set of downstream linkages for raw minerals identified by the two datasets and highlights two systematic differences. First, AIPNET offers substantially more disaggregated information on the mapping between upstream raw minerals and downstream products. At the HS-6 level, there are 109 distinct raw mineral products in the trade data, yet these are aggregated into only 15 industries in the BEA input–output table. This coarse aggregation implies that many minerals in the BEA system mechanically share identical downstream input coefficients. By contrast, AIPNET constructs upstream–downstream linkages directly at the product level, preserving variation across individual minerals and allowing downstream exposure to be measured with much finer granularity.

Second, the nature of the linkage information differs. AIPNET records whether a downstream product uses a given raw mineral through a binary indicator, while the BEA table provides continuous direct requirement coefficients that reflect input intensity. The absence of weights in AIPNET limits its applicability for conventional input–output analysis, such as computing the Leontief inverse matrix. However, AIPNET linkages are not restricted to immediate input–output relationships; instead, they capture broader production-relatedness along the value chain. For example, iron and steel products close to final demand (e.g., car bodies and tableware) are also linked to iron ores. This perspective is particularly useful for mapping the full value chain associated with each raw mineral.

Table C1. Predicting AIPNET linkages using BEA coefficients

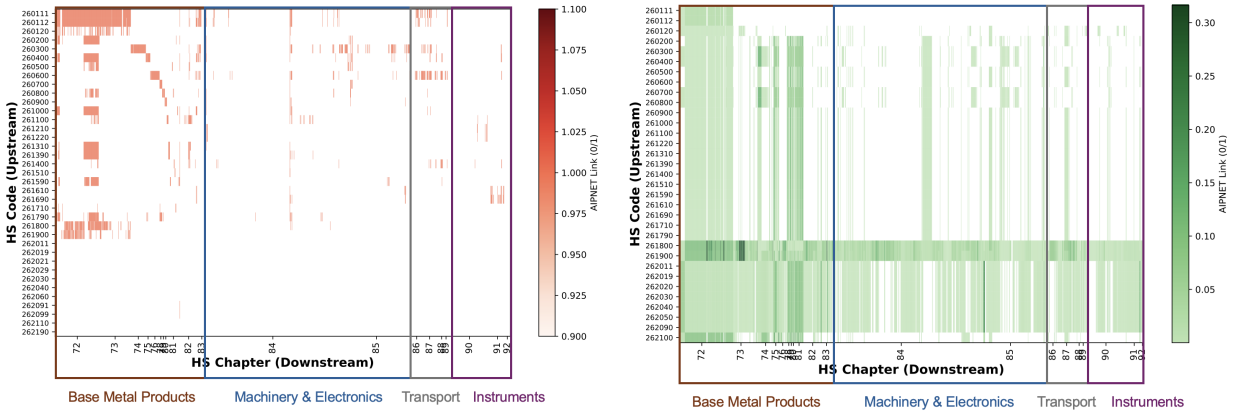
	$Link_{ij}$	$Link_{ij}$	$Link_{ij}$	$Link_{ij}$	$Link_{ij}$
DR_{ij}	14.902***	0.753***	0.740***	0.723***	0.738***
	(1.541)	(0.154)	(0.141)	(0.180)	(0.158)
Input FE			✓		✓
Output FE				✓	✓
Estimator	Logit	OLS	OLS	OLS	OLS
(Pseudo-)R^2	0.0375	0.0152	0.0969	0.194	0.256
# of Obs.	123,089	123,089	123,089	123,082	123,082

Notes: This table reports estimates from regressions predicting AIPNET linkages using BEA direct requirement coefficients. Standard errors, clustered at the input level, are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Despite these structural differences, AIPNET linkages remain strongly correlated with BEA direct requirement coefficients. As shown in Table C1, the two datasets exhibit a significant positive association at the HS-6 level, even after controlling for both input and output fixed effects. This correlation supports the validity of using AIPNET as a proxy for product-level input–output relationships. Moreover, AIPNET offers distinctive advantages in tracing the specific downstream uses of raw minerals, which I now discuss in greater detail.

C.2 Tracing Downstream Uses of Metal Ores

This paper investigates the downstream effects of mineral export restrictions. To illustrate the advantages of using AIPNET for this purpose, I focus on a particular category of raw minerals: metal ores. Due to differences in their chemical composition, metal ores are associated with distinct downstream uses, with limited substitutability across types. This product-level specificity is critical when evaluating the effects of export restrictions targeting particular ores.

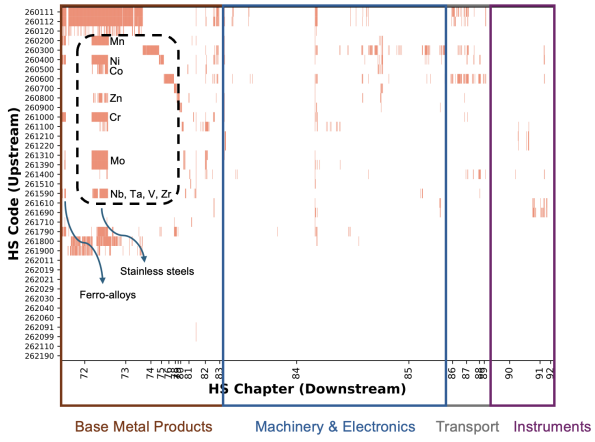


(a) AIPNET (b) BEA IO Table

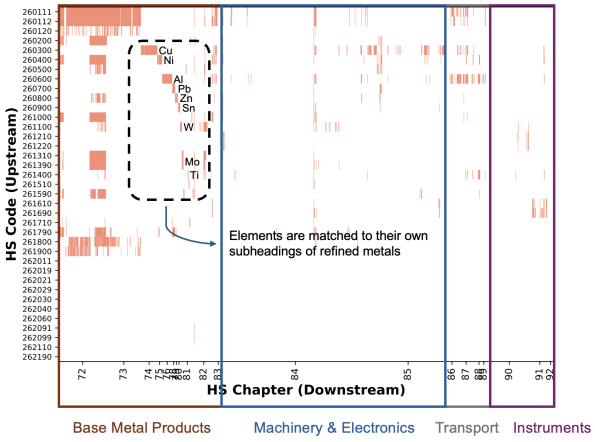
Figure C2. Downstream linkages of metal ores in selected industries

Figure C2 compares a subset of the AIPNET production network with the BEA input–output table, focusing on downstream linkages from metal ores (Chapter 26) to four broad product sections: base metal products (Chapters 72–83), machinery and electronics (Chapters 84–85), transport equipment (Chapters 86–89), and precision instruments (Chapters 90–92). These sections occupy adjacent ranges in the HS classification and correspond to progressively more downstream product categories. As documented in Table A7, they capture the most common downstream uses of metal ores. Collectively, these four sections account for more than 85 percent of all downstream products linked to metal ores in AIPNET.

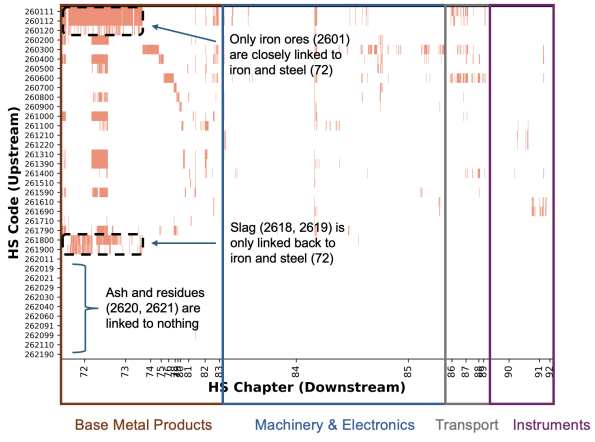
AIPNET continues to provide substantially more disaggregated product-level linkage information than the BEA input–output table, even within this targeted subset of downstream industries. In particular, it outperforms along four key dimensions:



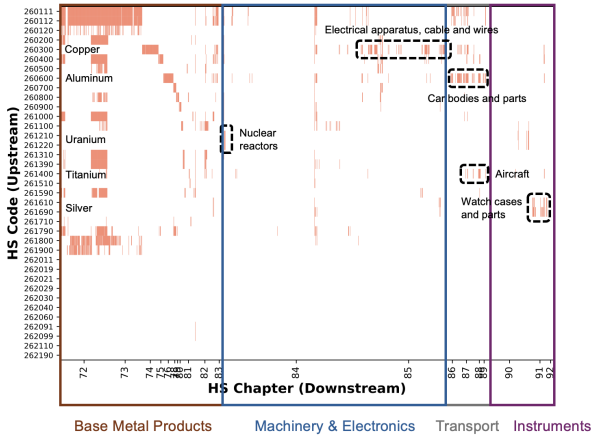
1. Identifying ferro-alloy elements.
Ferro-alloys and stainless steels constitute a substantial share of base metal products. Consequently, elements that form commercially viable alloys with iron exhibit distinct downstream linkages compared to those that do not. AIPNET clearly identifies such elements from common alloying agents like chromium and nickel to less common ones such as niobium and tantalum.



2. Matching elements with refined metal products. Some metal elements are assigned individual chapters in the HS classification system for refined metals and their products, such as copper (Chapter 74) and nickel (Chapter 75). AIPNET correctly matches these chapters with the corresponding metal ores, without any misclassification across elements.



3. Filtering out slag, ash, and residues. Slag, ash, and residues containing metal elements are widely linked to downstream products in the BEA IO table. By contrast, in AIPNET, slag from iron and steel production is linked only back to iron and steel, while ash and residues are largely unconnected to other products. This cleaner linkage structure improves the interpretability of policy impact estimates.



4. Tracing specific downstream uses. Certain downstream applications of metal elements are highly specific and offer little scope for substitution. AIPNET successfully traces such relationships, as illustrated on the left: copper in electrical wiring, uranium in nuclear reactors, and titanium in aircraft manufacturing, among others.

Taken together, AIPNET provides a more detailed and purpose-built linkage structure for analyzing the downstream effects of mineral export restrictions. At the same time, it is not designed to provide information on input cost shares or value-added decomposition, which are central to many analyses of global value chains. For applications that require such information, conventional input–output tables remain the appropriate benchmark.

D Export Restrictions on Agricultural Products

In this section, I examine the effects of export restrictions on agricultural products.[1] These products are excluded from the main analysis since they are not directly linked to mineral value chains and thus lie outside the core empirical focus. Nevertheless, they account for the largest number of export restrictions observed in the data, warranting a separate investigation.

D.1 Overview

Agricultural products constitute the most frequently targeted category in export restriction policies. Between 2008 and 2023, there are 678 export restrictions imposed on agricultural products by 94 countries, affecting 1,660 unique country–product pairs. As Figure A1 shows, all four major subcategories of agricultural products were heavily affected by such measures. Motivations for agricultural export restrictions are diverse and reflect both political and economic considerations. For instance, restrictions on cereals are often introduced in response to concerns over domestic food security and price stabilization during periods of adverse supply shocks; restrictions on live animals are frequently associated with disease outbreaks or animal welfare regulations; and restrictions on vegetable oils may be aimed at promoting domestic downstream processing or shielding local industries from external competition.

A key distinction between agricultural products and raw minerals lies in the structure of their respective value chains. In agriculture, upstream–downstream linkages are typically contained within the sector itself, as the downstream use of a given agricultural product most often involves another agricultural product rather than a manufacturing good. Reflecting this sectoral closure, I use the same sample of products (HS Chapters 1–24) to estimate Equation 24 and Equation 25. In this setting, properly accounting for whether a downstream product is itself subject to an export restriction is particularly important when estimating indirect effects, as policy measures frequently apply simultaneously at multiple stages of the agricultural production chain.

D.2 Direct Effects

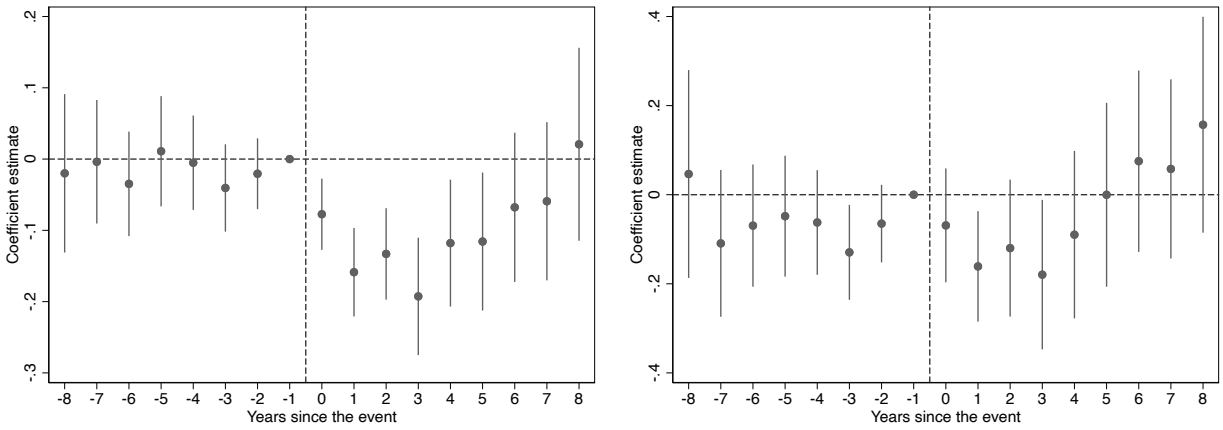
Table D1 reports the direct effects of export restrictions on the targeted agricultural products. While the restrictions do lead to a reduction in exports, the estimated effects are smaller in magnitude and less statistically significant compared to those reported in Table 1.

[1] Agricultural products refer to all products classified under HS Chapters 1–24. They are further divided into four subcategories: animal products (Chapters 1–5), vegetable products (Chapters 6–14), fats and oils (Chapter 15), and prepared foodstuffs and tobacco (Chapters 16–24).

Table D1. Direct Effects of Mineral Export Restrictions

	Export Value	Export Quantity	Unit Value
Export Restriction	-0.0988***	-0.0216	-0.00762
	(0.0376)	(0.0835)	(0.0130)
Country-Product FE	✓	✓	✓
Country-Year FE	✓	✓	✓
Product-Year FE	✓	✓	✓
Estimator	PPML	PPML	OLS
# of Clusters	122,516	121,956	109,438
# of Obs.	2,669,699	2,657,691	1,579,548

Notes: This table reports the estimated effects of export restrictions on exports of targeted agricultural products. Dependent variables include export value and quantity (in levels) and unit values (in logs). Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.



(a) Export Value (b) Export Quantity

Figure D1. Direct Effects of Agricultural Export Restrictions: Event Study

Notes: This figure plots the estimated dynamic effects of export restrictions on exports of targeted agricultural products, based on coefficient estimates from event-study regressions. Bars represent 95% confidence intervals, with standard errors clustered at the country–product level.

On the other hand, the event-study estimates reported in Figure D1 reveal a key difference in the dynamic effects of export restrictions on agricultural products relative to minerals. Following the implementation of an export restriction, exports of the targeted agricultural products decline immediately. However, the magnitude of this initial decline diminishes within a few years, and export volumes gradually revert to their pre-restriction levels. This largely transitory response contrasts with the pattern observed for mineral export restrictions, where the effects on targeted minerals are more persistent and extend over a substantially longer horizon.

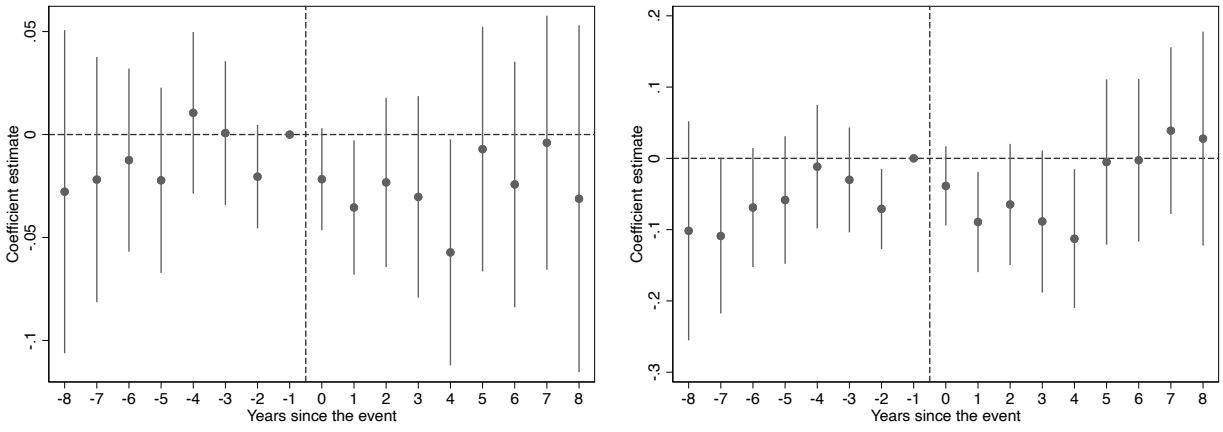
D.3 Downstream Effects

I then examine whether export restrictions on agricultural products generate export-stimulating effects for downstream products. The estimates reported in Table D2 provide a clear negative answer: all coefficients are statistically insignificant, and those associated with export values are even negative. In short, export restrictions on agricultural products do not give rise to any measurable downstream export effects.

Table D2. Downstream Effects of Mineral Export Restrictions

	Export Value		Export Quantity		Unit Value	
Export Restriction (Up)	-0.0162	-0.00496	0.00796	0.0119	0.00656	0.00687
	(0.0295)	(0.0295)	(0.0583)	(0.0588)	(0.00697)	(0.00698)
Export Restriction (Own)		-0.0980**		-0.0235		-0.00871
		(0.0383)		(0.0847)		(0.0131)
Country-Product FE	✓	✓	✓	✓	✓	✓
Country-Year FE	✓	✓	✓	✓	✓	✓
Product-Year FE	✓	✓	✓	✓	✓	✓
# of Clusters	122,516	122,516	121,956	121,956	109,438	109,438
# of Obs.	2,669,699	2,669,699	2,657,691	2,657,691	1,579,548	1,579,548

Notes: This table reports the estimated effects of upstream agricultural export restrictions on downstream exports. Dependent variables include export value and quantity (in levels) and unit values (in logs). Standard errors are clustered at the country-product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.



(a) Export Value (b) Export Quantity

Figure D2. Downstream Effects of Agricultural Export Restrictions: Event Study

Notes: This figure plots the dynamic effects of upstream agricultural export restrictions on downstream exports, based on coefficient estimates from event-study regressions. Bars represent 95% confidence intervals, with standard errors clustered at the country–product level.

The event-study estimates presented in Figure D2 reveal a markedly different pattern from that observed for mineral export restrictions. Instead of increasing, exports of downstream agricultural products *decline* in the years immediately following the introduction of the policy, although the magnitude of the contraction is smaller than that observed for the restricted agricultural products themselves. These negative downstream responses are concentrated in the short run and fade relatively quickly, with estimated effects becoming economically small and statistically indistinguishable from zero after a few years. This dynamic mirrors the transitory nature of the direct effects documented for agricultural export restrictions.

Taken together, these findings point to fundamentally different policy objectives underlying agricultural export restrictions. Rather than being designed to foster domestic processing, such measures primarily serve as short-term tools for market stabilization and food security during periods of supply stress. As many downstream products are themselves food-related, their export dynamics largely move in tandem with those of the directly restricted goods during food crises. Once the underlying shock subsides and domestic conditions normalize, exports across the agricultural value chain tend to revert to their pre-crisis levels. By contrast, the persistent downstream effects associated with mineral export restrictions underscore their distinct role as a longer-term industrial policy instrument aimed at reshaping production structures rather than addressing temporary market imbalances.

E Measure Relative Downstreamness in AIPNET

This appendix details the construction of the relative downstreamness measure used in the empirical analysis. The objective is to characterize the internal structure of production stages among mineral-related downstream products associated with a given upstream mineral input, and to establish a well-defined notion of "distance" along which the effects of upstream export restrictions may transmit through downstream production activities.

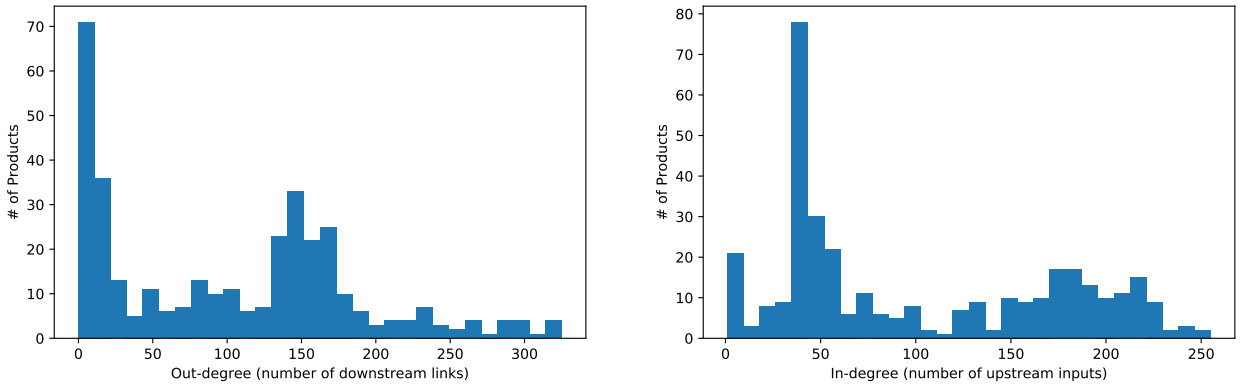
E.1 Methodology

Products are defined at the six-digit Harmonized System (HS6) level. The AIPNET dataset provides detailed information on upstream–downstream linkages, mapping each upstream product to a set of downstream products that use it as an input. These linkages are interpreted as global technological or physical input–output relationships and are treated as invariant across countries and over time. Formally, I distinguish between upstream products, indexed by u, and downstream products, indexed by d. Let $u \to d$ denote that downstream product d uses upstream product u as an input according to the AIPNET concordance.

Downstream-Induced Subgraph. The AIPNET network can be represented as a directed graph. As the analysis focuses exclusively on mineral-related downstream products, the mineral products themselves lie outside the scope of this construction. For any given upstream mineral product u, define its associated set of downstream products as

$$D(u) = \{d : u \to d\}.$$

Rather than operating on the full global input–output network, the analysis restricts attention to the production structure starts from each upstream mineral product w. Specifically, a *downstream-induced subgraph* associated with upstream mineral u, denoted by $\mathscr{D}(u)$, is defined as follows: the *nodes* consist of all downstream products $d \in D(u)$, and the *directed edges* are given by $d_1 \to d_2$ whenever product d_1 is used as an input into product d_2 according to the AIPNET linkage structure, with $d_1, d_2 \in D(u)$. This construction isolates the internal layering of downstream products that are jointly linked to the same upstream input, while excluding any additional upstream stages beyond u itself, as well as unrelated production linkages. Downstream products are restricted to manufacturing goods, consistent with the sample restrictions imposed in the main analysis.



(a) Out-degree (b) In-degree

Figure E1. Degree distributions of downstream products for iron ores

Notes: This figure reports the distributions of out-degree and in-degree in the downstream-induced subgraph associated with non-agglomerated iron ores (HS 2601.11). Nodes correspond to downstream HS6 products, and directed edges represent linkages identified by AIPNET.

Cycles and Strongly Connected Components. Figure E1 reports the distributions of out-degree and in-degree in the downstream-induced subgraph associated with an example mineral, non-agglomerated iron ores (HS 2601.11). The subgraph contains a total of 356 nodes. Both degree distributions indicate a highly dense network structure, with extensive reciprocity across downstream products. As a result, the subgraph contains a large number of directed cycles, reflecting mutually dependent intermediate inputs or tightly integrated production stages rather than a simple hierarchical supply chain. In such an environment, downstream products cannot be unambiguously ordered along a single production chain, as many products simultaneously act as both inputs and outputs within the subgraph. Consequently, simple path-length–based notions of distance are no longer well defined, motivating the need for an alternative measure of relative downstreamness that remains meaningful in the presence of cycles.

To address this issue, I identify *strongly connected components* (SCCs) within the downstream-induced subgraph. An SCC is defined as a maximal set of products in which each product is reachable from every other product through directed paths. Once identified, each SCC is collapsed into a single composite node, which can be interpreted as a tightly integrated production module whose internal sequencing cannot be meaningfully ordered or decomposed. This transformation yields a *directed acyclic graph* (DAG) with SCCs as its nodes, allowing upstream–downstream ordering and layer depth to be uniquely and consistently defined.

SCCs are identified separately for the downstream-induced subgraph associated with each upstream mineral using the Tarjan algorithm (Tarjan, 1972). The algorithm performs a depth-first search (DFS) over the directed graph, assigning to each node a discovery index and a

low-link value. The discovery index records the order in which nodes are first visited, while the low-link value captures the smallest discovery index reachable from that node via the DFS tree and at most one back edge. During traversal, nodes are maintained on a stack until their SCC membership is determined. When the algorithm encounters a node whose low-link value equals its discovery index, that node is identified as the root of an SCC, and all nodes on the stack up to that point are popped and assigned to the same component. This procedure correctly aggregates all nodes that are mutually reachable, even when the SCC contains multiple distinct cycles. The Tarjan algorithm runs in linear time, with worst-case complexity $O(|N|+|E|)$, where $|N|$ and $|E|$ denote the number of nodes and directed edges in the graph.

Definition of Relative Downstreamness. Edges in the SCC-DAG are constructed as follows. Let S and S' be two distinct SCCs. A directed edge $S \to S'$ exists if at least one product in S is an upstream input to at least one product in S'. SCCs with no incoming edges are assigned downstreamness 1. These components correspond to downstream products that do not depend on any other downstream products within $D(u)$ and therefore constitute the most upstream layer of production immediately following raw minerals. For any other SCCs, the distance is defined recursively as

$$\text{distance}(u,S) = 1 + \max_{S' \in U(S)} \text{distance}(u,S'),$$

where $U(S)$ denotes the set of SCCs with directed edges pointing into S. Since the SCC-DAG is acyclic, this longest-path distance is well defined and unique. Each downstream product inherits the distance of the SCC to which it belongs. I denote by $\text{distance}(u,d)$ the distance assigned to downstream product d in the downstream-induced subgraph associated with upstream mineral u. For reference, the upstream mineral u itself is assigned downstreamness 0.

Multiple Upstream Exposures. For each downstream product, the downstreamness measure constructed above is defined relative to a specific upstream mineral. The baseline regressions, however, are conducted at the country–product–year level. Although downstreamness is assumed to be time-invariant, this difference in aggregation levels nonetheless raises two related issues, which I address sequentially.

First, within a given country–year, a downstream product may be simultaneously exposed to export restrictions on multiple upstream minerals that differ in their relative distance along the supply chain. In this case, I assign the minimum distance as the relevant exposure level for the downstream product. This choice reflects the assumption that restrictions imposed on upstream

inputs that are closer to the downstream product exert more direct and stronger effects on production costs, and therefore dominate the influence of more distant upstream restrictions.

Second, across countries, the same downstream product may face different minimum exposure distances, reflecting cross-country variation in the set of upstream minerals subject to export restrictions. At the same time, downstream products in the never-treated group must also be assigned an exposure level in order to serve as controls in regressions. To obtain a single, stable measure of downstreamness for each product, I collapse this cross-country variation by assigning the modal distance (using the maxmode) observed in the sample. The intuition is that the modal distance captures the most representative policy exposure level for a given downstream product across countries. The main results are robust to alternative tie-breaking rules such as using the minmode or excluding these products altogether.

E.2 Results

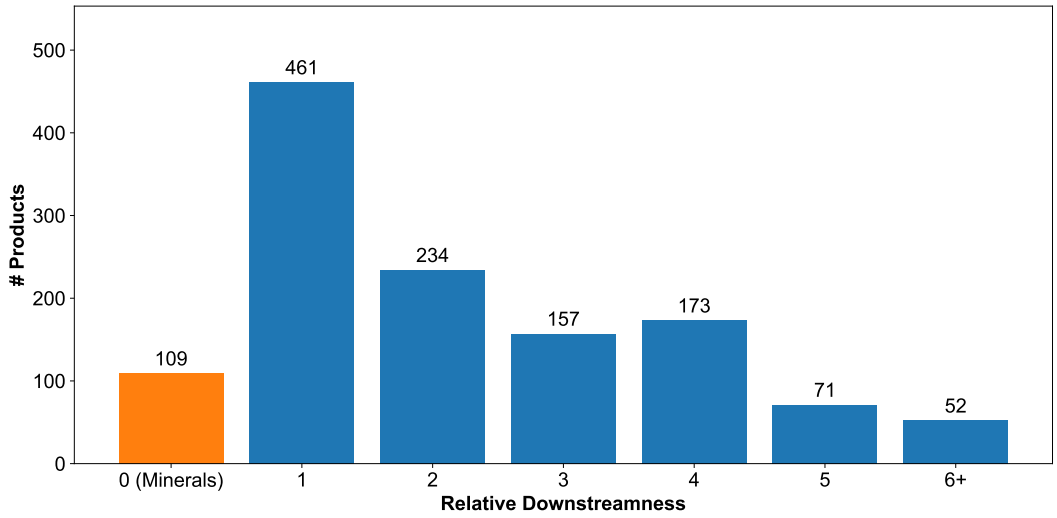


Figure E2. Distribution of relative downstreamness

Notes: This figure reports the distribution of relative downstreamness across mineral-related downstream products. The measure is constructed by eliminating circular dependencies using the Tarjan algorithm applied to the AIPNET dataset. Minerals are also shown for comparison.

Figure E2 presents the distribution of relative downstreamness across mineral-related downstream products. The distribution is skewed toward lower downstream layers: most downstream products are located at distance 1, followed by distances 2 and 3. The number of products declines as downstreamness increases, with relatively few products appearing at distances 5 and above. Raw mineral products are shown separately at downstreamness 0.

Part of this distribution reflects the structure of the HS classification system rather than underlying economic variety *per se*. Upstream goods linked to raw minerals, such as base metal products, tend to be classified in finer detail, with distinct HS codes assigned to products that differ only in physical form or basic processing stage. By contrast, downstream manufactured goods are classified more coarsely, such that a single HS code often aggregates a broad range of differentiated products. As a result, fewer HS codes are observed at more downstream stages, even when economic variety may be substantial. For the empirical part of the paper, I do not attempt to assess or correct for the implications of this classification feature.