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

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Abstract

Resource-rich developing countries increasingly restrict raw mineral exports to promote industrial upgrading, yet how far their effects extend along the value chain remains unclear. I develop a general equilibrium model with manufacturing scale externalities in which export restrictions improve the terms of trade while implicitly subsidizing downstream production. The direct cost advantage weakens along the value chain, potentially concentrating support in basic processing even when stronger scale externalities lie further downstream. Using 112 mineral export restrictions imposed by 28 countries during 2008–2023, I trace export responses across production stages. Restrictions reduce targeted mineral exports by 42 percent and raise their export prices by 14 percent. Downstream exports rise by 12 percent, but the gains are concentrated at the first processing stage and in technologically simple products, particularly base metals. Terms-of-trade gains justify restrictions by a few dominant suppliers, while the industrial-policy rationale fails as expansion occurs in activities with below-average scale economies. Thus, mineral export restrictions stimulate basic processing but fall short of delivering the broad-based industrial upgrading that policymakers seek.

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—from taxes and quotas to outright bans—as part of their industrialization strategies (OECD, 2025). These restrictions follow an industrial-policy logic: by redirecting raw minerals toward domestic markets, governments aim to expand downstream production and cultivate competitive industries in higher value-added activities (Harrison and Rodríguez-Clare, 2010; Juhász et al., 2024). However, these potential gains come at the cost of restricting trade in sectors where these countries already have an export advantage. Despite the growing use of these policies, it remains unclear whether they can foster downstream expansion beyond basic processing and support the development of more sophisticated industries.

This paper examines the scope and limits of mineral export restrictions as industrial policy, combining a normative theoretical framework with global empirical evidence. I develop a general equilibrium model with external economies of scale across downstream production stages. In the model, export restrictions serve both trade- and industrial-policy objectives: they raise the world price of the mineral and implicitly subsidize domestic downstream producers through lower input costs. I study these restrictions as a second-best instrument when downstream employment subsidies are unavailable, characterize the optimal export tax, and establish the conditions under which it is equivalent to a tariff on downstream imports. The model also reveals a tension built into the instrument: the cost advantage attenuates along the value chain, so if scale externalities are stronger in more advanced activities, the largest gains from industrial policy may lie where the stimulus is weakest. To examine how far downstream the effects reach, I combine a global dataset of mineral export restrictions with product-level trade and production linkages. Restrictions reduce targeted mineral exports by 42 percent and increase downstream exports by 12 percent. However, the downstream gains are concentrated at the first processing stage and in technologically simple products, particularly base metals, with little evidence of comparable expansion further downstream. These findings reveal a limitation of mineral export restrictions as industrial policy: they raise mineral export prices and stimulate basic processing, but offer limited support for expansion into more advanced manufacturing.

Why have mineral export restrictions become so popular? I document three stylized facts to help explain their appeal. First, poorer countries specialize in exporting upstream, low value-added goods, creating incentives to climb up the value chain through industrial policy. Second, export restrictions are attractive for their low fiscal cost and administrative simplicity. Although developing countries adopt far fewer industrial-policy interventions overall, export restrictions

account for a disproportionately large share of their policy portfolios. Finally, raw minerals are natural targets: they occupy the earliest stages of the value chain, where intervention is predicted to generate the largest multiplier effects (Liu, 2019). Restricting countries typically have a strong revealed comparative advantage (RCA) in the targeted minerals but not in their downstream products, providing a rationale for using export restrictions to foster downstream industrial development and realize latent comparative advantages (Reed, 2024).

Theoretically, I embed mineral export restrictions in a parsimonious two-country, two-sector general equilibrium model. The mining sector combines exogenous mineral reserves and labor to produce minerals, which serve as an input to a manufacturing sector characterized by external economies of scale. I model mineral export restrictions as an *ad valorem* export tax imposed by the home country, which creates a wedge between domestic and world mineral prices. For the home country, the fall in the domestic price acts as an implicit subsidy for downstream manufacturing, while the rise in the world price improves the country's terms of trade. These two channels collectively exhaust the price wedge, with their relative strength determined by a pass-through coefficient reflecting the home country's mineral market power. As an industrial policy, the implicit subsidy boosts labor demand in manufacturing, bidding up domestic wages and reallocating labor into the sector, where output expands more than proportionally due to scale externalities.

In this two-sector benchmark, the welfare effect of mineral export restrictions decomposes into three terms: a terms-of-trade gain, a Pigouvian gain from the expansion of manufacturing employment, and a Harberger loss from diverting minerals away from exports. This decomposition distinguishes the policy's trade and industrial-policy motives. An export tax directly addresses the terms-of-trade motive but provides only second-best support for downstream manufacturing: a targeted employment subsidy can correct the production externality without distorting mineral trade. When direct subsidies are unavailable, the optimal export tax balances indirect industrial support against its trade-distortion cost, augmenting the conventional terms-of-trade term with an industrial-policy term that reflects scale externalities and the manufacturing employment response per unit of mineral exports forgone. The export tax also has an import-substitution interpretation: an appropriately calibrated tariff on manufacturing imports can generate the same production allocation and real consumption (Lerner, 1936).

I then extend the model to multiple manufacturing stages that form a vertical value chain. Firms at each stage combine domestic and imported intermediates from the preceding stage with labor, and scale externalities may differ across stages. The direct input-cost advantage attenuates along the chain: at each stage, intermediates account for only part of production costs, and

only the domestically sourced share transmits the upstream price reduction. Lerner symmetry no longer takes the simple two-sector form: once processed goods are also exported, replicating the mineral export tax requires a uniform tariff on all imports together with export subsidies on processed goods (McKinnon, 1966; Costinot and Werning, 2019). The welfare decomposition also changes. Lower processed-export prices can offset part of the terms-of-trade gain on minerals, while the Pigouvian effect depends on both aggregate manufacturing expansion and employment reallocation across stages. The Pigouvian effect can turn negative if workers move from activities with stronger scale externalities to those with weaker ones. If externalities are stronger in more advanced activities, the largest potential industrial-policy gains may therefore lie where the direct cost advantage is weakest. Ultimately, whether export restrictions can reach more advanced stages or remain confined to basic processing is an empirical question.

To test how far downstream these effects propagate, I assemble a cross-country product-level dataset combining three sources: (i) 112 mineral export restriction episodes imposed by 28 countries during 2008–2023, recorded by the Global Trade Alert database; (ii) HS6-level bilateral trade data from CEPII-BACI; and (iii) the AI-generated production network (AIPNET), which maps upstream–downstream linkages at the HS6 product level (Fetzer et al., 2024). A key challenge in measurement is to assign downstream products to production stages in a network with circular dependencies. I apply Tarjan's algorithm to group mutually dependent products into single nodes, producing an acyclic network in which production stages are defined by the longest directed path from the originating mineral. This construction distinguishes mineral-specific production chains at a finer resolution than conventional input-output tables and allows me to estimate how policy effects vary across stages. Exploiting variation across countries, products, and policy timing, I estimate effects on export value and quantity at the country–product–year level using Poisson pseudo-maximum likelihood (PPML) with country–product, country–year, and product–year fixed effects. Bilateral export unit-value regressions compare suppliers serving the same importer–product market in the same year. These regressions assess whether restrictions raise mineral export prices and whether downstream exporters pass cost reductions on to foreign buyers. Finally, I estimate both trade-flow and unit-value regressions separately by production stage to trace how price pass-through and export responses vary along the chain.

I first show that mineral export restrictions have bite: they substantially reduce targeted mineral exports and raise the prices paid by foreign buyers. Following policy announcements, restricting countries export 42 percent less of the targeted minerals by value and 56 percent less by quantity, while receiving unit values 14 percent higher relative to other suppliers. Importers

also face higher sourcing costs: those previously sourcing the mineral entirely from restricting countries pay 25 percent more on average than unexposed importers, reflecting both higher supplier prices and shifts toward more expensive suppliers. Turning to downstream industries, export values rise by 12 percent and quantities by 24 percent, with gains accumulating gradually over time. Event-study estimates show no evidence of differential pre-trends, and the results are largely robust to alternative sample constructions, estimation methods, and definitions of raw minerals.

However, the downstream expansion is concentrated at the first processing stage beyond raw minerals, where export values rise by 26 percent and quantities by 43 percent. At later production stages, the estimated effects on export value and quantity are statistically insignificant or even negative. Pooling stages 2 and beyond likewise yields no statistically significant export expansion. Event-study estimates reveal sharply different dynamics: at the first stage, export values and quantities rise shortly after restrictions take effect, and the gains strengthen over time; at stages 2 and beyond, post-treatment estimates remain statistically insignificant, with no evidence of sustained expansion. The unit-value results add a price dimension to this picture. First-stage export unit values fall by 2.2 percent relative to other suppliers serving the same importer–product market, potentially reflecting both the pass-through of lower input costs and shifts toward lower-unit-value varieties. No significant price changes are detected at later stages. Sectoral results reinforce this pattern: gains cluster in base-metal products, while other sectors show little or no positive response.

What limits the propagation of these gains further downstream? Beyond the attenuation of the input-cost advantage predicted by the model, export responses vary systematically across product characteristics. Gains accrue mainly to technologically simple products and largely disappear at higher levels of complexity. Expansion is also greatest in goods that use simpler complementary inputs. Moreover, downstream quantity responses are strongest in products where restricting countries already have a revealed comparative advantage, with little evidence of expansion where they lack an established competitive position. Cheaper minerals thus appear to reinforce existing strengths more readily than they create competitiveness in more advanced activities, which require more sophisticated capabilities and complementary inputs.

To evaluate whether these uneven gains improve aggregate welfare, I map the estimated responses into the model's welfare decomposition. The price responses imply a tariff equivalent of 20 percent and a pass-through coefficient of 0.60, with most of the price wedge appearing as a higher world mineral price. At this tariff equivalent, only 19 of 197 restricted country–mineral pairs meet the terms-of-trade welfare criterion, although they account for half of restricted

mineral exports. Across all pairs, the mineral terms-of-trade gain of $13.3 per $100 of pre-restriction mineral exports is nearly offset by a $5.3 loss on processed-export prices and an $8.2 Harberger loss. Labor reallocation is therefore decisive for aggregate welfare. Under the scale-elasticity estimates of Bartelme et al. (2025), welfare rises if downstream workers come from agriculture and mining, and falls if they come from other manufacturing. Although origin sectors are not directly observed in the data, the destination of the expansion is clear: expanding activities have an average scale elasticity of 0.17, below the manufacturing average of 0.22. Thus, even when reallocation increases welfare, restrictions channel labor into manufacturing activities with relatively weak externalities.

Taken together, the results distinguish an initial expansion of processing from broader industrial upgrading. While mineral export restrictions stimulate downstream exports, gains remain concentrated in basic activities and products where countries already hold a revealed comparative advantage. Terms-of-trade gains can independently justify intervention for a handful of dominant suppliers, though on trade-policy rather than industrial-upgrading grounds. For most restrictions, by contrast, the industrial-policy welfare case hinges on which sectors release the workers entering downstream production. The expansion of basic processing does not by itself establish a welfare case. Mineral export restrictions thus stimulate initial downstream activity but fall short of delivering the broad-based industrial upgrading that policymakers seek.

Related Literature. This paper contributes to four strands of literature. First, it speaks to the literature on trade and industrial policy (Harrison and Rodríguez-Clare, 2010; Juhász et al., 2024). Recent empirical work has revived the case for industrial policy by documenting substantial returns to targeted support in East Asia (Barwick et al., 2025; Choi and Levchenko, 2025; Lane, 2025), while quantitative trade models have begun to estimate sector-level scale economies and the gains from exploiting them (Lashkaripour and Lugovskyy, 2023; Bartelme et al., 2025). Most of this work studies support aimed directly at the industry the government seeks to grow. With multi-stage production, the question becomes where to target: Liu (2019) shows that distortions accumulating along the chain justify upstream subsidies, and Head et al. (2026) examine how interventions at one stage reshape production across the entire chain. This paper extends that work to mineral export restrictions. Unlike subsidies that directly target production externalities (Bhagwati and Ramaswami, 1963; Baldwin, 1969), these restrictions support downstream industries by lowering input costs while distorting upstream mineral trade. I characterize the optimal export tax and link its welfare implications to where along the chain downstream expansion occurs. Empirically, the gains are concentrated in basic processing and base metals, where existing estimates suggest relatively weak scale economies.

Second, it revisits the literature on export taxes and restrictions from an industrial-policy perspective. Existing work studies their use for domestic price stabilization and as a terms-of-trade instrument, focusing on world-price and aggregate welfare effects (Piermartini, 2004; Martin and Anderson, 2012; Ruta and Venables, 2012; Laborde et al., 2013). Theory shows that restricting raw-material exports can relocate processing toward the exporting country (Latina et al., 2011), but leaves open how the induced cost advantage propagates through a multi-stage production chain. Empirical work focuses largely on specific countries and minerals, including Indonesia's nickel export ban (Kee and Xie, 2025; Bosker et al., 2025), China's rare-earth export restrictions (Alfaro et al., 2025), and restrictions on selected critical minerals (Andrenelli et al., 2025). Using 112 restrictions across 28 countries, this paper provides, to my knowledge, the first cross-country causal evidence on their downstream effects and the first welfare assessment disciplined by estimated trade responses. The analysis traces export and price changes from targeted minerals through successive processing stages, examining how the input-cost advantage attenuates and how technological complexity and complementary inputs constrain its reach.

Third, this paper relates to the literature on natural resources and development, including the Dutch disease tradition (van der Ploeg, 2011; Venables, 2016; Mien and Goujon, 2021). Resource booms can crowd out manufacturing through exchange-rate appreciation and factor reallocation, especially where institutions are weak (Corden and Neary, 1982; Mehlum et al., 2006; Ross, 2015). The resource-based industrialization literature examines whether proximity to raw materials confers an advantage in downstream processing (Hausmann et al., 2008; Asche, 2018). This paper contributes to that debate by asking whether export restrictions can turn resource abundance into downstream competitiveness and how far that advantage extends along the value chain. The findings suggest that while export restrictions can foster initial downstream processing, the input-cost advantage associated with resource abundance does not readily translate into competitiveness in advanced manufacturing.

Finally, this paper connects to work on comparative advantage and its evolution (Costinot et al., 2012; Levchenko and Zhang, 2016). Atkin et al. (2021) formalize the "development ladder" metaphor, showing how trade can leave countries concentrated on its lower rungs. By lowering domestic input prices, export restrictions seek to move comparative advantage downstream. They are thus an input-side analogue of infant-industry protection and connect to the debate over whether protection can build lasting productive capabilities (Krueger and Tuncer, 1982; Head, 1994; Melitz, 2005; Juhász, 2018). The evidence here speaks to the first step of that process. Export gains are concentrated in products where countries already had a revealed comparative advantage and decline sharply as products and their inputs become more

complex. These patterns are more consistent with expanding established competitive activities than with developing new sources of downstream comparative advantage.

The remainder of the paper is organized as follows. Section 2 examines why developing countries increasingly adopt mineral export restrictions, and Section 3 develops the theoretical framework. Sections 4 and 5 describe the data and empirical strategy. Section 6 reports the main findings, while Section 7 presents the robustness checks. Section 8 quantifies the trade-policy and industrial-policy motives behind the observed restrictions, and Section 9 concludes.

2 Why Mineral Export Restrictions?

This section examines why developing countries increasingly adopt mineral export restrictions. Specializing in upstream segments of global value chains, developing countries have strong incentives to promote downstream industries through industrial policy. Export restrictions are particularly attractive among available instruments, as they are administratively simple and impose no direct fiscal burden. Raw minerals appear as natural targets: they occupy the earliest stages of the value chain, and restricting countries typically have a strong comparative advantage in the raw mineral but not in its downstream products. This asymmetry creates a compelling rationale for policies aimed at redirecting raw materials toward domestic processing.

2.1 Industrial Upgrading and the Appeal of Export Restrictions

A country's position in global value chains is closely tied to its level of development. As shown in Figure 1, richer countries export goods closer to final demand,[1] whereas poorer countries specialize in upstream products such as raw materials and basic intermediates: in the sample excluding oil exporters, a one-unit increase in log GDP per capita is associated with a 0.164-stage shift in average export composition toward final demand.

This pattern raises a classic question in development policy: should countries accommodate their current position, or should they actively promote downstream industries to move up the value chain? The rationale for intervention rests on the premise that downstream sectors are subject to unrealized Marshallian externalities that leave them inefficiently small, preventing countries from realizing their latent comparative advantage (Lin and Chang, 2009; Harrison and Rodríguez-Clare, 2010). While developing-country governments have increasingly embraced

[1] Upstreamness measures the average number of production stages between a product and final demand, so higher values indicate products further from final use (Antràs et al., 2012). The measure is computed at the industry level from input–output tables and mapped to HS6 products using Liao et al. (2020).

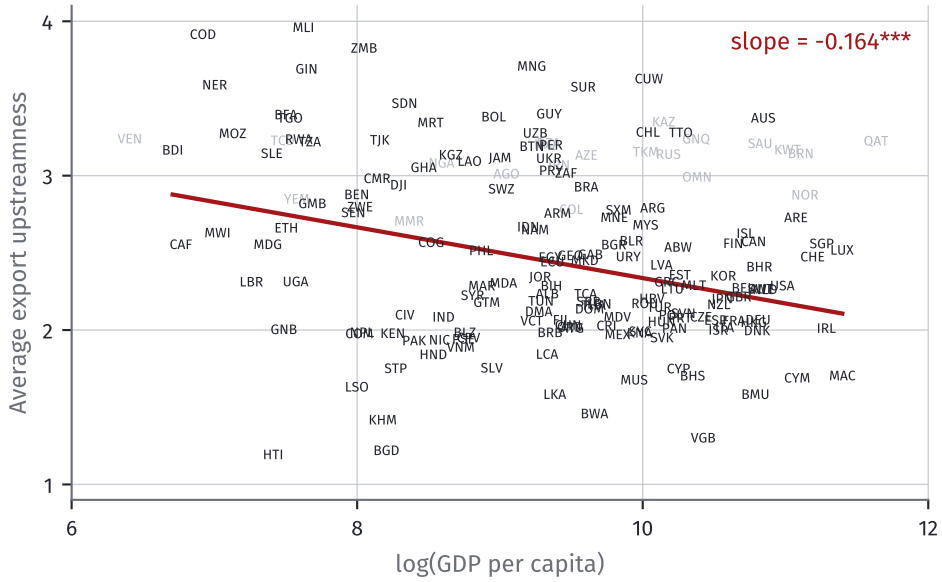


Figure 1. Income levels and trade specialization

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.

this approach, the instruments available to them differ markedly from those used by advanced economies. High-income countries rely on fiscally intensive tools such as direct subsidies and state loans, yet budget constraints and limited administrative capacity push developing countries toward lower-cost alternatives. In this context, export restrictions have become particularly prominent, and their use has surged in recent years.[2]

Figure 2 illustrates this contrast. While high-income countries account for the largest share of industrial-policy interventions, export restrictions constitute only 1 percent of their policy portfolio. By contrast, export restrictions account for more than 10 percent of industrial policies adopted by low-income countries. In absolute terms, most export restrictions recorded in the Global Trade Alert (GTA) database are implemented by lower-middle- and upper-middle-income countries. Export restrictions appeal to these developing-country governments as they require (seemingly) no fiscal outlay, demand only control at the border, and do not require governments to evaluate individual firms' productivity or potential.

[2]Appendix Figure A1 plots the time trends in export restrictions imposed by developing countries.

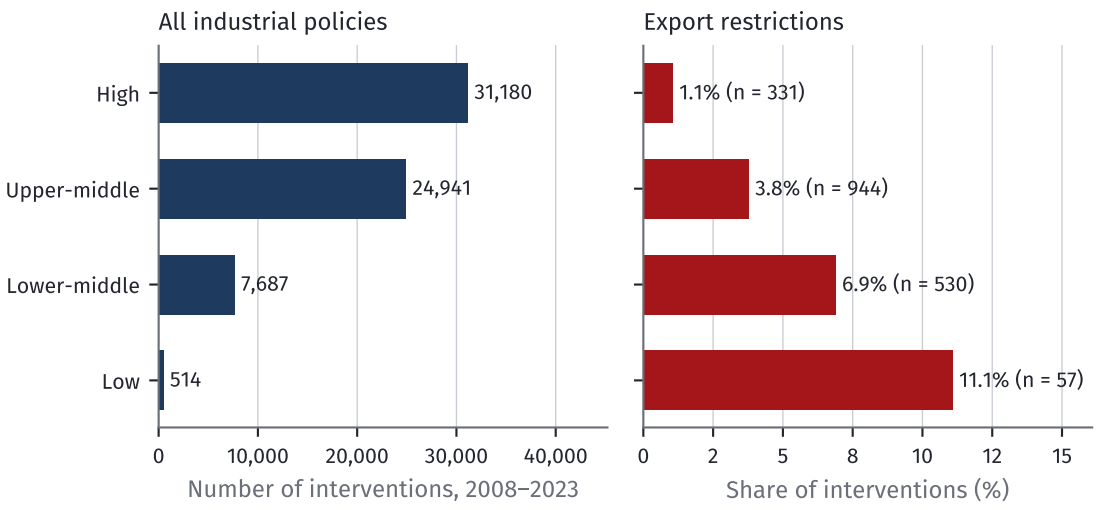


Figure 2. Industrial policies and export restrictions by income group

Notes: This figure presents the number of industrial-policy interventions (left panel) and the share of them that are export restrictions (right panel), by the income level of the implementing countries, as recorded in the GTA database from 2008 to 2023. Country income groups are based on the World Bank's 2015 classification.

2.2 Raw Minerals as Targets

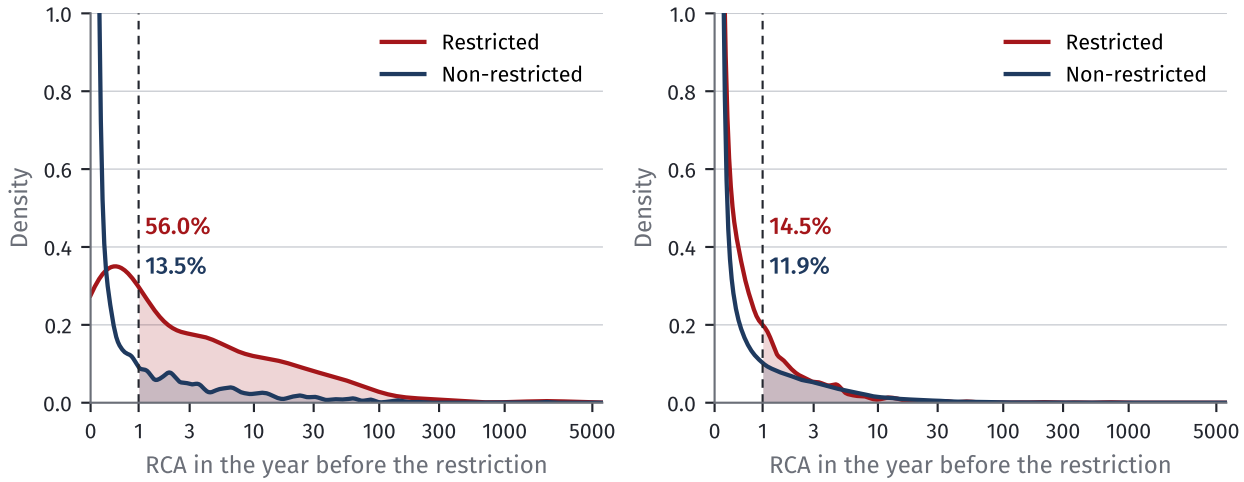
This paper focuses on export restrictions targeting raw minerals, defined as products in HS chapters 25 (non-metallic minerals) and 26 (metallic minerals).[3] Mineral export restrictions are widely used in practice: among all export restrictions recorded, raw minerals constitute the third most frequently targeted product category, after agricultural products and mineral fuels. Unlike restrictions on other products, mineral export restrictions are often adopted with explicit industrial objectives, offering a particularly suitable setting for examining whether industrial policy can promote downstream upgrading in developing countries.[4]

Raw minerals appear as natural targets for export restrictions with industrial objectives. First, they occupy the most upstream positions in global value chains, serving as inputs for exceptionally long downstream production chains. They account for 20 percent of global trade by quantity but only 1.4 percent by value, reflecting extremely low unit prices: most value

[3]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. I explore broader definitions of raw minerals that include some of these products in robustness checks.

[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. Appendix Figure A2 shows the distribution of export restrictions across product categories. Appendix F discusses agricultural export restrictions and their downstream effects in detail.

addition occurs in downstream processing. By restricting mineral exports, governments aim to redirect these materials toward domestic markets, encouraging investment in processing and stimulating downstream production. This upstream positioning also makes mineral sectors theoretically attractive targets for intervention: as market distortions accumulate in upstream sectors through backward demand linkages, intervening in these sectors should yield the largest aggregate multiplier effects (Liu, 2019).



(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) for products (or their upstream minerals) subject to export restrictions (red) versus those without (blue), measured one year before the restrictions take effect. Percentage labels indicate the share of products in each group with RCA greater than one. Appendix Table A1 reports t-test results for differences in mean RCA between the two groups.

Another motivation relates to patterns of revealed comparative advantage (RCA). For the restricting country, targeted minerals are often the products in which it holds the strongest RCA. However, this upstream advantage rarely translates into competitiveness in downstream export markets. Figure 3 illustrates this pattern using data from the year prior to export restrictions. The left panel shows that targeted raw minerals display substantially higher RCA than non-targeted minerals in the same country, with more than half greater than one and some exceeding one hundred. In contrast, the right panel reveals that downstream products of targeted minerals do not exhibit significantly higher RCA than other products. Amid rising global demand for mineral-intensive downstream goods, this asymmetry creates a compelling rationale for policies aimed at developing domestic downstream capabilities.

When used as an industrial-policy tool, mineral export restrictions deliberately run against a country's comparative advantage by curbing exports of products in which the country currently specializes.[5] If successful, such policies could enable developing countries to capture a greater share of value addition along the value chain, transforming resource wealth into industrial capacity. However, these potential gains are far from guaranteed. By discouraging mineral exports, the policy forgoes revenues from a sector in which the country is competitive, while redirecting resources toward downstream sectors where it has yet to establish competitiveness. At the same time, mineral export restrictions can benefit the restricting country through a distinct channel: by raising world mineral prices, they improve the country's terms of trade. The net welfare effect depends on the interplay among these competing forces. In the next section, I develop a theoretical framework to formalize these trade-offs and trace the effects of mineral export restrictions along the value chain.

3 Theory

In this section, I develop a parsimonious two-country, two-sector general equilibrium model to examine the dual role of mineral export restrictions as trade and industrial policy. An export tax improves the terms of trade by raising the world mineral price and implicitly subsidizes downstream manufacturing by lowering the domestic mineral price. The relative strength of these channels depends on how the tax is passed through to domestic and world prices. With external economies of scale in manufacturing, I decompose the domestic welfare effect into a terms-of-trade gain, a Pigouvian gain from manufacturing expansion, and a Harberger loss from distorted mineral trade. I then characterize the optimal export tax when direct employment subsidies are unavailable, compare it with the first-best policy, and establish its equivalence to a tariff on manufacturing imports. Finally, I extend the model to multiple production stages. The direct input-cost advantage attenuates along the value chain, while the Pigouvian effect depends on both aggregate manufacturing expansion and employment reallocation across stages with different scale externalities. This creates a potential *policy dilemma*: if externalities are stronger in more advanced activities, the largest industrial-policy gains may lie where the instrument's direct stimulus is weakest.

[5] Appendix Tables A2, A3, and A4 confirm that export restrictions disproportionately target upstream goods with stronger revealed comparative advantage. 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.

3.1 Setup

Environment. There are two countries, Home and Foreign, with Foreign variables denoted by asterisks. Each country is exogenously 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 fixed, the mining sector exhibits decreasing returns to labor, and mineral reserves earn economic rents.

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

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

where m_j is firm j's mineral input, ℓ_j is its labor input, L_Y is aggregate manufacturing employment, and A is country-specific total factor productivity. The term L_Y^{γ} captures Marshallian external economies of scale: aggregate productivity rises as employment in the sector expands.[6] Because each firm takes L_Y as given, production exhibits constant returns to scale at the firm level, consistent with perfect competition. Free entry then drives profits to zero.

Trade. The outputs of both sectors are homogeneous across countries and tradable subject to iceberg trade costs $\tau > 1$. I focus on equilibria in which Home exports minerals and imports manufactures. Let p_M and p_Y denote Home's domestic prices of minerals and manufactures, and p_M^* and p_Y^* their Foreign counterparts. Manufactures are traded without policy distortions, so the domestic price in Home follows the import-parity condition:

$$p_Y = \tau\, p_Y^*. \tag{3}$$

[6] Marshallian external economies of scale are the standard way to represent infant-industry externalities in a tractable general equilibrium framework (Bartelme et al., 2025). The specification preserves perfect competition and zero profits, allowing the welfare effects to operate solely through the externality rather than through markups or entry distortions (Lashkaripour and Lugovskyy, 2023).

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

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

Tax revenues are rebated lump-sum to Home residents.

Households. Representative consumers in both countries have logarithmic utility over manufactures: $U = \ln C$. Consumers spend their entire income on manufactures: $p_Y C = I$, where I denotes nominal income and p_Y the price of manufactures. Home residents' nominal income comprises labor income, mining rents, and tax revenues; Foreign's comprises labor income and mining rents only:

$$I = wL + \beta p_M M + t \frac{p_M^*}{\tau} X_M, \tag{5}$$

$$I^* = w^* L^* + \beta p_M^* M^*, \tag{6}$$

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:

$$p_M = \frac{w}{(1-\beta)R^\beta} L_M^\beta, \tag{7}$$

with mineral output $M = R^\beta L_M^{1-\beta}$ and mining rents 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 to unit cost:

$$p_Y = \frac{1}{\alpha^\alpha (1-\alpha)^{1-\alpha}} \cdot \frac{p_M^\alpha w^{1-\alpha}}{A L_Y^\gamma}. \tag{8}$$

Aggregating across firms, total manufacturing output is:

$$Y = \left(\frac{\alpha}{1-\alpha} \cdot \frac{w}{p_M} \right)^\alpha \cdot A L_Y^{1+\gamma}. \tag{9}$$

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

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

$$L_M + L_Y = L. \tag{10}$$

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

$$M = \frac{\alpha p_Y Y}{p_M} + X_M. \tag{11}$$

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

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

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

$$\frac{p_M^*}{\tau} X_M = \tau p_Y^* X_Y, \tag{13}$$

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 (7), manufacturing firms earn zero profits as in (8), labor markets clear as in (10) (with corresponding conditions in Foreign), and mineral markets clear as in (11)–(12).[7]

Given zero profits, balanced household budgets, and lump-sum redistribution of tax revenues, Walras' Law ensures the trade balance (13) holds automatically. The Foreign manufacturing price is taken as the numéraire, $p_Y^* = 1$, implying $p_Y = \tau$.

[7] Under external economies of scale, the competitive equilibrium need not be unique, and a corner equilibrium with $L_Y = 0$ may coexist with an interior equilibrium. Throughout the paper, I focus on the interior equilibrium with $L_Y > 0$. Kucheryavyy et al. (2023) show that gravity models with scale economies are well-behaved when the product of the trade elasticity and the scale elasticity is weakly below one in each sector, which corresponds to the stability condition introduced below.

3.3 Comparative Statics

3.3.1 Price and Quantity Responses

I analyze the effects of a marginal increase in the mineral export tax by totally differentiating the equilibrium conditions, expressing all responses as log-derivatives $d \ln x / dt$.

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

$$\frac{d \ln p_M}{dt} = \frac{\Phi - 1}{1 - t} < 0, \qquad \frac{d \ln p_M^*}{dt} = \frac{\Phi}{1 - t} > 0, \tag{14}$$

where $\Phi \equiv \varepsilon_M / (\varepsilon_M + \varepsilon_M^*) \in (0, 1)$ *is the pass-through coefficient, with* $\varepsilon_M > 0$ *denoting Home's mineral export supply elasticity with respect to the domestic mineral price and* $\varepsilon_M^* > 0$ *the absolute value of Foreign's mineral import demand elasticity with respect to the world mineral price.*

Proof. See Appendix B.1.1. ■

The pass-through coefficient Φ governs the *dual mandate* of the mineral export tax:

1. *Trade policy.* The rise in the world mineral price p_M^* improves Home's terms of trade, transferring rents from Foreign mineral consumers to Home.

2. *Industrial policy.* The fall in the domestic mineral price p_M acts as an implicit subsidy to Home's manufacturing sector, encouraging downstream expansion and activating the external economies of scale.

Since the two price responses jointly exhaust the tax wedge, the trade- and industrial-policy roles inherently compete: a higher Φ strengthens the trade-policy channel at the expense of the industrial-policy channel, and vice versa. Intuitively, when Home's export supply is elastic relative to Foreign's import demand, a larger share of the tax is passed through to the world price. The policy then operates more effectively at manipulating Home's terms of trade, but generates a smaller input cost reduction for domestic manufacturing firms.

As an industrial-policy tool, the mineral export tax triggers a global reallocation between mining and manufacturing. In Home, cheaper mineral inputs expand the manufacturing sector, strengthen external economies, and bid up wages. The opposite holds in Foreign, where higher mineral costs shrink manufacturing and depress wages.

Proposition 2 (Sectoral reallocation) *In Home, a mineral export tax raises wages, shifts labor from mining to manufacturing, and expands manufacturing output. The opposite holds in Foreign.*

$$\frac{d\ln w}{dt} = -\frac{\alpha\beta L_Y + \gamma L_M}{(1-\alpha)\beta L_Y - \gamma L_M} \cdot \frac{\Phi - 1}{1-t} > 0, \qquad \frac{d\ln w^*}{dt} < 0, \tag{15}$$

$$\frac{d\ln L_Y}{dt} = -\frac{L_M}{(1-\alpha)\beta L_Y - \gamma L_M} \cdot \frac{\Phi - 1}{1-t} > 0, \qquad \frac{d\ln L_Y^*}{dt} < 0, \tag{16}$$

$$\frac{d\ln Y}{dt} = -\frac{\alpha\beta L_Y + (1+\gamma) L_M}{(1-\alpha)\beta L_Y - \gamma L_M} \cdot \frac{\Phi - 1}{1-t} > 0, \qquad \frac{d\ln Y^*}{dt} < 0, \tag{17}$$

where the stability condition requires $\gamma < (1-\alpha)\beta L_Y / L_M$ for both countries.[8]

Proof. See Appendix B.1.2. ■

These results trace the full transmission of the mineral export tax from price wedge to sectoral reallocation to output expansion through external economies. The asymmetric effects on Home and Foreign set the stage for the welfare analysis that follows.

3.3.2 Welfare

Home welfare is measured by real consumption $W \equiv \ln C$. From the expenditure side, Home consumption consists of domestically produced manufactures and imports. By trade balance, the latter equals mineral export revenues net of iceberg trade costs:

$$C = Y + \frac{p_M^* X_M}{\tau^2}. \tag{18}$$

Taking log derivatives and using the fact that firms hire labor and purchase minerals at their private marginal products, all reallocations valued at private prices cancel out. The welfare effect of the export tax can therefore be decomposed into three wedges between private and social values: the terms-of-trade effect arising from Home's influence on world prices, the externality, and the export tax wedge.

Proposition 3 (Welfare decomposition) *A mineral export tax changes Home welfare by:*

$$\frac{dW}{dt} = \frac{1}{1-t}\left[(1-s_Y)\Phi + s_Y \gamma \varepsilon_L (1-\Phi) - (1-s_Y)\, t\, \varepsilon_M (1-\Phi)\right], \tag{19}$$

[8] This condition keeps the denominator $(1-\alpha)\beta L_Y - \gamma L_M$ positive, so that cheaper minerals raise manufacturing employment, wages, and output rather than yielding perverse signs. It requires γ to be weak enough that the expansion feedback converges rather than explodes.

where $s_Y \equiv Y/C$ is the share of domestic production in Home's final consumption, and $\varepsilon_L > 0$ and $\varepsilon_M > 0$ are the elasticities of Home's manufacturing employment and mineral exports with respect to the domestic mineral price, with ε_L defined in absolute value.

Proof. See Appendix B.1.3. ■

The three terms capture distinct channels through which the export tax affects Home welfare:

1. *Terms-of-trade gain* $(1-s_Y)\Phi$: The export tax raises the world mineral price, increasing the purchasing power of Home's mineral exports over imported manufactures. This gain is larger when Home has greater market power in mineral markets (higher Φ) and when the economy is more dependent on trade (lower s_Y).

2. *Pigouvian gain* $s_Y\,\gamma\,\varepsilon_L\,(1-\Phi)$: The decline in the domestic mineral price draws workers into manufacturing. Through the aggregate productivity externality L_Y^{γ}, each additional worker raises the productivity of all manufacturing firms, a benefit that individual firms do not internalize. This gain is larger when manufacturing employment is more responsive to the domestic mineral price (higher ε_L), the externality is stronger (higher γ), and domestic manufacturing accounts for a larger share of final consumption (higher s_Y).

3. *Harberger loss* $(1-s_Y)\,t\,\varepsilon_M\,(1-\Phi)$: The export tax drives a wedge between the world and domestic mineral prices, inducing an inefficient diversion of minerals from exports to domestic use. The resulting welfare loss increases with the tax rate and is larger when mineral exports are more responsive to the domestic mineral price (higher ε_M) and the economy is more dependent on trade (lower s_Y).

The welfare decomposition captures both trade- and industrial-policy motives, weighted by Φ and $1-\Phi$, respectively. The terms-of-trade and Pigouvian gains are non-negative, while the Harberger loss increases with the tax rate. The marginal welfare effect therefore depends on whether these gains outweigh the distortionary cost at the prevailing tax rate. A higher Φ strengthens the terms-of-trade motive but dampens the domestic mineral price response, weakening both the Pigouvian gain and the Harberger loss.

Corollary 1 (Optimal export tax) *Any interior welfare-maximizing mineral export tax satisfies*

$$t^* = \frac{(1-s_Y)\Phi + s_Y\,\gamma\,\varepsilon_L\,(1-\Phi)}{(1-s_Y)\,\varepsilon_M\,(1-\Phi)} = \frac{1}{\varepsilon_M^*} + \gamma\,\frac{s_Y}{1-s_Y}\,\frac{\varepsilon_L}{\varepsilon_M}. \tag{20}$$

Proof. See Appendix B.1.4. ■

Home's optimal export tax t^* satisfies the first-order condition $dW/dt = 0$, equating the marginal terms-of-trade and Pigouvian gains with the marginal Harberger loss. At $t = 0$, the Harberger loss vanishes, so a small export tax always raises Home welfare.

The optimal export tax does not implement the first-best allocation. By the targeting principle, a distortion is best corrected at its source (Bhagwati and Ramaswami, 1963). Here, external economies of scale in manufacturing create a wedge between the private and social marginal products of labor. The first-best policy therefore combines a manufacturing employment subsidy covering a share $s^{\text{FB}} = \gamma / (1-\alpha+\gamma)$ of the wage, financed by lump-sum taxation, with an export tax at rate $t^{\text{FB}} = 1 / \varepsilon_M^*$ to adjust Home's terms of trade. The subsidy delivers the Pigouvian gain without diverting minerals from export markets to support manufacturing, and thus avoids the associated Harberger loss. The optimal mineral export tax is therefore a second-best instrument when direct employment subsidies are unavailable, balancing terms-of-trade gains and indirect manufacturing support against mineral trade distortions.

The mineral export tax also has an import-substitution interpretation. In the two-sector model, Home exports only minerals and imports only manufactures, so the mineral export tax applies uniformly to all of Home's exports. By Lerner symmetry, it is equivalent to a uniform tariff on all of Home's imports (Lerner, 1936). Specifically, an *ad valorem* tariff on manufactures at rate $t' = t/(1-t)$, with revenue rebated lump-sum, generates the same equilibrium allocation and real consumption in both countries.

Finally, the optimal tax formula can be inverted to recover the strength of the productivity externality that would rationalize an observed export restriction.[9] Given the export-tax equivalent t of an observed restriction, the implied externality is

$$\gamma^{\text{implied}} = \left(t - \frac{1}{\varepsilon_M^*} \right) \frac{1-s_Y}{s_Y} \frac{\varepsilon_M}{\varepsilon_L}. \tag{21}$$

This expression distinguishes the two motives for restricting mineral exports. Countries with greater market power can justify higher export taxes through terms-of-trade gains alone, whereas smaller exporters must rely more heavily on downstream productivity externalities.

Foreign welfare is measured symmetrically by $W^* \equiv \ln C^*$. As an exporter of manufactures, Foreign's real consumption equals domestic manufacturing output net of exports to Home:

$$C^* = Y^* - \frac{p_M^* X_M}{\tau}. \tag{22}$$

[9] Although both elasticities depend on the productivity externality γ, their common amplification term cancels in the ratio $\varepsilon_M/\varepsilon_L$. The terms-of-trade term depends only on Foreign's import demand. Conditional on the observed equilibrium allocation, the optimal tax is linear in γ, allowing the implied externality to be recovered directly.

A mineral export tax unambiguously lowers Foreign welfare: it raises the world mineral price p_M^*, contracting Foreign manufacturing through higher input costs and worsening Foreign's terms of trade. Combined with the ambiguous sign of Home welfare, the global welfare implications of mineral export restrictions remain theoretically indeterminate.

3.4 Multiple Production Stages

The baseline model features a single downstream sector, so the mineral export tax subsidizes all of Home's manufacturing uniformly. In practice, minerals pass through multiple processing stages before reaching final consumption, and the implicit subsidy may attenuate along the way. To examine this, I extend the framework to a multi-stage production structure.

Production. Suppose the manufacturing sector consists of N discrete production stages in both countries, each combining output from the preceding stage with labor under external economies of scale. Individual firm j at stage k produces:

$$y_{j,k} = A_k \, y_{j,k-1}^{\alpha} \, \ell_{j,k}^{1-\alpha} \, L_{Y,k}^{\gamma_k}, \quad k = 1, \ldots, N, \tag{23}$$

where $y_{j,k-1}$ is the intermediate input from stage $k-1$, and $y_{j,0} = m_j$ is the mineral input. I assume Armington differentiation, with Home and Foreign varieties of processed goods at each stage substitutable at a constant elasticity σ.[10] Minerals remain homogeneous, as in the baseline model, so first-stage producers purchase mineral inputs at the domestic price p_M. Accordingly, for $k \geq 2$, $y_{j,k-1}$ is a symmetric CES aggregate of Home and Foreign varieties:

$$y_{j,k-1} = \left(\tilde{y}_{j,k-1}^{\frac{\sigma-1}{\sigma}} + \tilde{y}_{j,k-1}^{*\frac{\sigma-1}{\sigma}} \right)^{\frac{\sigma}{\sigma-1}}. \tag{24}$$

Preferences and trade. Consumers have logarithmic utility over a symmetric CES aggregate of Home and Foreign final-stage varieties, and goods at every stage are tradable subject to iceberg trade costs $\tau > 1$. The mineral export tax is as in the baseline model.

[10] Armington differentiation allows the domestic mineral price wedge to propagate beyond the first processing stage. With homogeneous goods, producers at stage $k \geq 2$ would be indifferent between domestic and foreign intermediates at equal delivered prices, limiting transmission along the value chain. For simplicity, I hold α and σ constant across stages, while allowing γ_k to vary. This heterogeneity matters for welfare, as the gains from reallocating workers depend on the distribution of scale externalities across stages.

3.4.1 Comparative Statics

To isolate the transmission of the domestic mineral price reduction along the value chain, I consider the limiting case in which Home has no market power in the world mineral market ($\Phi = 0$) and is small in each processed-goods market. Foreign prices and aggregate demand are therefore unaffected by the policy, while demand for each Home variety is iso-elastic, allowing downstream responses to be characterized recursively.

Let $\rho_k \equiv d\ln p_k / d\ln p_M$ denote the pass-through of the domestic mineral price to Home's stage-k output price, with $\rho_0 = 1$, and let $\rho_w \equiv d\ln w / d\ln p_M$ denote the response of the wage. Let $\varepsilon_{L,k} \equiv -d\ln L_{Y,k} / d\ln p_M$ denote the employment elasticity at stage k, which is positive when employment expands as the domestic mineral price falls. For mining ($k = 0$), define $\varepsilon_{L,0} \equiv -d\ln L_M / d\ln p_M$. Mineral exports respond with elasticity $\varepsilon_M \equiv d\ln X_M / d\ln p_M$.

Proposition 4 (Recursive structure) *Downstream price and employment responses follow a recursive structure along the value chain:*

$$\rho_{k+1} = \alpha s_k \rho_k + (1-\alpha)\rho_w + \gamma_{k+1}\varepsilon_{L,k+1}, \tag{25}$$

$$(1-\phi_k)\varepsilon_{L,k+1} = \varepsilon_{L,k} - \phi_k \rho_w + (1-\sigma)\big(1 - s_k(1-\phi_k)\big)\rho_k, \tag{26}$$

where $s_k \equiv p_k^{1-\sigma} / \big(p_k^{1-\sigma} + (\tau p_k^*)^{1-\sigma}\big)$ is Home's expenditure share in the Armington composite at stage k and $\phi_k \equiv X_k / Y_k$ is Home's export share of output at stage k.

At the mineral stage, $s_0 = 1$, and with $\phi_0 \equiv X_M / M$ denoting the export share of mineral output, the employment recursion replaces $-\sigma$ with ε_M:

$$(1-\phi_0)\varepsilon_{L,1} = \varepsilon_{L,0} - \phi_0 \rho_w + \phi_0(1+\varepsilon_M). \tag{27}$$

Proof. See Appendix B.2.1. ■

The direct pass-through of the mineral price attenuates along the value chain. At each stage, the upstream price signal is diluted twice: first because the intermediate input accounts for only a fraction α of production costs, and second because only a fraction s_k of the intermediate input is sourced domestically and thus affected by the export tax. Abstracting from wage and employment feedback, the direct effect on the final-good price after N stages is proportional to $\prod_{i=0}^{N-1} \alpha s_i$, which declines geometrically with N. This attenuation weakens the direct stimulus to downstream employment, while demand linkages across stages can amplify the response. How far downstream the resulting expansion extends is therefore an empirical question.

3.4.2 Welfare

I now extend the welfare decomposition to the multi-stage production structure, allowing for market power in the world mineral market and price adjustments in both Home and Foreign. Unlike the preceding comparative statics, the decomposition holds for any Φ.

Proposition 5 (Welfare effects along the value chain) *A mineral export tax changes Home welfare by:*

$$\frac{dW}{dt} = \frac{1}{1-t}\Bigg[\underbrace{\Phi\left(\xi_0 - \sum_k \mu_k \rho_k^*\right) - (1-\Phi)\sum_k \xi_k \rho_k}_{\textit{Terms of trade}} + \underbrace{(1-\Phi)\sum_k \gamma_k \lambda_k \varepsilon_{L,k}}_{\textit{Pigouvian}} - \underbrace{(1-\Phi)\,\xi_0\, t\, \varepsilon_M}_{\textit{Harberger}}\Bigg]. \tag{28}$$

Here,

$$\xi_0 \equiv \frac{p_M^* X_M}{\tau I}, \qquad \xi_k \equiv \frac{p_k X_k}{I}, \qquad \mu_k \equiv \frac{\tau\, p_k^* X_k^*}{I}, \qquad \lambda_k \equiv \frac{p_k Y_k}{I}$$

denote, respectively, Home's mineral exports, stage-k exports, stage-k imports, and stage-k gross sales, each expressed relative to national income I, and $\rho_k^* \equiv d\ln p_k^*/d\ln p_M^*$ is the pass-through of the world mineral price to Foreign's stage-k price. With $N = 1$ and homogeneous manufactures, (28) *reduces to* (19).

Proof. See Appendix B.2.2. ■

Proposition 5 extends the welfare decomposition in Proposition 3 to multiple production stages. The three terms retain their interpretations, but neither the terms-of-trade nor the Pigouvian effect is necessarily positive. In the baseline model, manufactures are homogeneous and priced at import parity, so the terms-of-trade gain arises solely from mineral exports. With differentiated processed goods, a mineral export tax also lowers Home's downstream export prices, transferring part of the cost reduction to foreign buyers.[11] This loss may offset the terms-of-trade gain from mineral exports, even as the tax approaches zero. The Pigouvian effect likewise depends on the distribution of employment responses across stages. An expansion of downstream production may generate limited welfare gains or even losses if workers move from stages with stronger scale externalities to those with weaker ones. Proposition 6 decomposes this effect into manufacturing expansion and employment reallocation across stages.

[11] The processed-export price term also illustrates how Lerner symmetry changes in the multi-stage model. When Home exports both minerals and processed goods, the mineral export tax no longer applies uniformly to all exports. A uniform tariff at rate $t/(1-t)$ on all imports, including intermediates, is equivalent to a uniform tax at rate t on all exports, including processed goods. Replicating the mineral export tax alone therefore requires combining this tariff with an export subsidy at rate $t/(1-t)$ on all processed exports (McKinnon, 1966; Costinot and Werning, 2019). The decline in processed-export prices reflects the export-subsidy component of this equivalent policy.

Proposition 6 (Decomposing the Pigouvian effect) *Let $n_k \equiv L_{Y,k}/L$ denote stage k's share of total employment, $\theta_L \equiv wL/I$ the labor share of national income, and $\bar{\gamma} \equiv \sum_k n_k \gamma_k / \sum_k n_k$ the employment-weighted average scale elasticity across manufacturing stages. With a common input share α, the Pigouvian effect in Proposition 5 can be decomposed as*

$$\sum_k \gamma_k \lambda_k \varepsilon_{L,k} = \frac{\theta_L}{1-\alpha}\Bigg[\underbrace{\bar{\gamma} \sum_k n_k \varepsilon_{L,k}}_{\text{Aggregate expansion}} + \underbrace{\sum_k (\gamma_k - \bar{\gamma}) n_k \varepsilon_{L,k}}_{\text{Across-stage reallocation}} \Bigg]. \tag{29}$$

Proof. See Appendix B.2.3. ■

The first term measures the welfare gain from expanding manufacturing at its existing employment composition, evaluated at the average scale elasticity $\bar{\gamma}$. Since $\sum_k n_k \varepsilon_{L,k}$ measures the increase in manufacturing employment relative to the total labor force as domestic mineral prices fall, this term is positive whenever manufacturing employment expands. The second term captures the additional gain or loss from changes in employment composition across stages. Because $\sum_k (\gamma_k - \bar{\gamma}) n_k = 0$, it can be written as $\sum_k n_k (\gamma_k - \bar{\gamma})(\varepsilon_{L,k} - \bar{\varepsilon}_L)$, where $\bar{\varepsilon}_L \equiv \sum_k n_k \varepsilon_{L,k} / \sum_k n_k$. This term reflects the covariance between scale externalities and employment growth, weighted by stage employment shares. It vanishes when employment grows proportionally across stages and is positive when employment growth is concentrated in stages with stronger externalities. If the sector from which workers are drawn also exhibits scale externalities with elasticity γ_o, the relevant welfare effect depends on the difference $\gamma_k - \gamma_o$, provided both sectors have the same labor cost share.

The decomposition highlights a potential limitation of mineral export restrictions as industrial policy. While lower domestic mineral prices stimulate downstream production, the direct cost advantage attenuates along the value chain. If scale externalities increase with production stages, employment growth concentrated in early processing may generate smaller welfare gains than an equivalent expansion in more advanced manufacturing activities. The welfare effects of mineral export restrictions therefore depend not only on the magnitude of aggregate manufacturing expansion, but also on the alignment between employment responses and scale externalities across stages. The empirical analysis that follows examines how far the effects of these restrictions propagate along the value chain.

4 Data

This section describes the data sources and construction of key variables used in the empirical analysis. I combine data on mineral export restrictions, international trade, and product-level production linkages to construct measures of downstream exposure and production stages. While the model yields testable predictions about employment responses along the value chain, employment data at the granularity needed to link specific minerals to their downstream products are not available globally. Therefore, I use downstream exports as the empirical counterpart. As export responses are driven by the same upstream price signal, their pattern along the value chain provides useful evidence on how far the policy's effects propagate through downstream production. Appendix E provides indirect evidence on whether these export responses reflect shifts in domestic production.

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 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 focus on mineral export restrictions recorded through 2023. Minerals are defined as products in HS chapters 25 (non-metallic minerals) and 26 (metallic minerals), covering 109 six-digit HS codes. In the GTA database, export restrictions are classified as distortionary measures—including export bans, quotas, taxes, licensing requirements, and other export-related interventions—that limit the export of certain goods. To distinguish broadly applicable trade- and industrial-policy interventions from targeted or exceptional measures, I retain only restrictions that apply to all trading partners, excluding bilateral measures and country-specific economic sanctions. I further exclude firm-specific interventions, measures applying exclusively to processing trade, and restrictions introduced in response to the COVID-19 pandemic. I use the announcement date as the policy onset to account for potential anticipatory responses by exporters.

The final dataset comprises 112 mineral export restrictions imposed by 28 countries, covering 200 country–mineral pairs. China, India, and Indonesia are the most frequent implementers, although the use of such measures is geographically widespread. Restrictions are imposed almost exclusively by developing countries, with Hungary and Oman as the only exceptions. Appendix Tables A5 and A6 provide details on implementing countries and the most frequently targeted minerals. Most restrictions are narrowly targeted, with a median policy covering only

two six-digit HS products. The minerals targeted, however, vary considerably across countries, reflecting differences in natural resource endowments and policy priorities.

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 to all destinations. Since reported quantities in BACI are occasionally missing or erroneous, I adjust aggregate quantities using information from valid trade flows.[12]

Upstream–Downstream Linkages. To link each mineral to its specific downstream products, 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.[13] To illustrate, Appendix Figure A3 traces all downstream products linked to iron ores in AIPNET along the iron–steel value chain. Appendix Table A7 reports the number of products and mineral-related downstream products by sector. Minerals are most frequently linked to sectors including base metals, machinery and electronics, chemicals, and stone and glass. In constructing downstream exposure, I exclude restrictions on slag, ash, and other industrial residues (HS 2618–2621), restricting treatment to mined minerals.

Production Stages. While AIPNET identifies upstream–downstream connections between products, it does not directly measure how far a downstream product is from its originating mineral. Existing measures such as the upstreamness index of Antràs et al. (2012) locate

[12]BACI contains missing quantities (2.1 percent of flows) and occasional unit errors. I flag quantities as erroneous when their log unit values deviate by more than ln 100 from both the exporter–importer–product median across years and the product–year median, using the exporter–product median for links with fewer than three observations. For each exporter–product–year cell, I scale valid quantities by the ratio of total trade value to the value of flows with valid quantities. Cells without valid quantities remain missing. Export values are unaffected. I also exclude China's exports of four boron-added steel products (HS 722530, 722540, 722790, 722830) from the downstream estimation sample, as their reported export quantities were distorted by the reclassification of carbon steel as alloy steel to obtain export VAT rebates.

[13]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). Appendix D provides a detailed comparison.

products relative to final demand, whereas my analysis requires distance from a specific upstream mineral input. A key complication is that the downstream production network contains circular dependencies, so simple path-based distances are not well defined. To address this, I apply Tarjan's algorithm (Tarjan, 1972) to collapse mutually dependent products into single nodes, yielding a directed acyclic graph in which each product's *downstreamness*—its production stage relative to the originating mineral—can be defined as the longest directed path from that mineral. Figure 4 illustrates this procedure. Appendix C provides full construction details, including the definition of strongly connected components and the resulting network decomposition. Because 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.

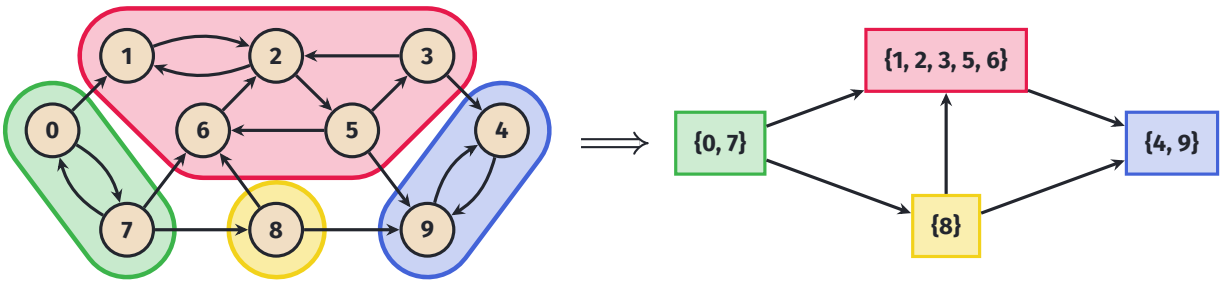


Figure 4. Collapsing cycles into production stages: illustration

Notes: The left panel shows a directed network with cycles; nodes that can reach one another form a strongly connected component (shaded). The right panel applies Tarjan's algorithm and collapses each component into a single node, yielding a directed acyclic graph in which the longest-path distance from any node is well defined. Applied to the AIPNET subgraph downstream of a mineral, this distance is the product's production stage.

Figure 5 presents the distribution of production stages across mineral-related products. The distribution is skewed toward earlier stages: most downstream products are located at stage 1, followed by stages 2 and 3. The number of products declines at higher stages, with relatively few products appearing at stage 5 and above. Raw mineral products are shown separately at stage 0. Part of this distribution reflects the structure of the HS classification system rather than underlying economic variety. 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 later production stages,

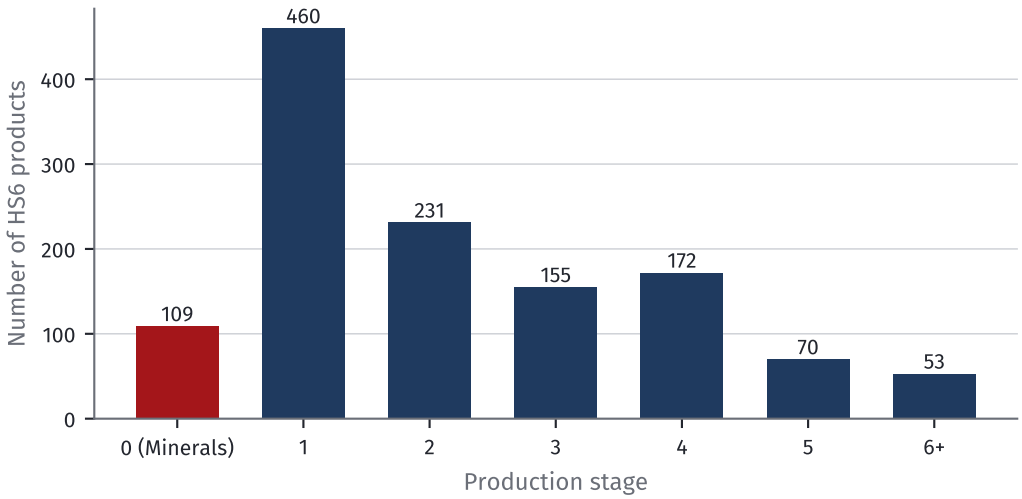


Figure 5. Distribution of production stages

Notes: This figure reports the distribution of downstream production stages across mineral-related products. Production stages are constructed by applying Tarjan's algorithm to the AIPNET network to eliminate circular dependencies. Minerals are shown at stage 0 for reference.

even when economic variety may be substantial. This classification feature should be kept in mind when interpreting the stage-level empirical results.

5 Empirical Strategy

My empirical strategy consists of two parts. First, I examine the direct effects of mineral export restrictions on exports of the targeted minerals. Second, I analyze their downstream effects along the value chain, testing whether upstream restrictions stimulate exports of downstream products and how these effects vary across production stages.

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 may undercount restrictions, particularly in low-income countries where policy changes are not always publicly documented. If some restrictions go unrecorded, treated observations are misclassified as controls, biasing the estimated effect toward zero. Second, enforcement varies widely across countries and products: politically connected exporters, for instance, may automatically receive the licenses required to continue exporting. Therefore, establishing that restrictions indeed reduce mineral exports is a necessary first step before analyzing their downstream consequences.

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:

$$Y_{ikt} = \exp\left[\alpha + \beta \cdot ER_{ikt} + \mu_{ik} + \delta_{it} + \eta_{kt}\right] + \varepsilon_{ikt}, \tag{30}$$

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; μ_{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 the relevant country–product pair 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 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 invalidate most, if not all, recent DiD estimators designed for heterogeneous treatment effects (de Chaisemartin and D'Haultfœuille, 2023). Second, the GTA database provides limited information on policy removal: many governments do not report when a policy becomes inactive, and in some cases the original measure is replaced by another type of restriction, creating multiple entries for the same country–product pair.[14] Third, the GTA database does not track export restrictions enacted before 2008. Treatment for each country–product pair starts with the announcement year of its first recorded measure, which captures the first observable tightening of export controls within the sample period; the estimated effects should therefore be interpreted as a lower bound of the true impact.

I estimate the equation using the Poisson pseudo-maximum likelihood (PPML) estimator proposed by Santos Silva and Tenreyro (2006), now standard in the trade literature. Unlike traditional OLS estimators applied to log-linearized models, PPML naturally accommodates zero trade flows, which account for 48 percent of country–product–year observations for raw minerals. PPML also addresses the heteroskedasticity that can bias log-linear regressions.

[14] Among the 112 mineral export restrictions in my sample, 60 have no recorded removal dates. 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.

5.2 Downstream Effects Across Production Stages

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

$$Y_{ikt} = \exp\left[\alpha + \beta_1 \cdot ER^{\text{up}}_{ikt} + \beta_2 \cdot ER_{ikt} + \mu_{ik} + \delta_{it} + \eta_{kt}\right] + \varepsilon_{ikt}, \tag{31}$$

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 (30). Both export restriction indicators are constructed under the absorptive assumption discussed above, and the equation is again estimated via PPML.

Equation (31) is estimated on all country–product–year observations for downstream products. I exclude agricultural products (Chapters 1–24) and mineral fuels (Chapter 27), since they do not use raw minerals as inputs and are therefore irrelevant for tracing downstream effects.[15] I also exclude arms and ammunition (Chapter 93) and artwork and antiques (Chapter 97) due to their unique characteristics.

To examine how downstream effects vary across production stages, I estimate Equation (31) separately for each production stage, restricting the sample to downstream products assigned to that stage. Within each stage, products that are never exposed to an upstream restriction serve as controls. The model predicts that the direct price signal attenuates along the value chain, but demand linkages across stages may partially offset this attenuation. Comparing the estimated β_1 across stages therefore reveals how far the policy's effects reach downstream.

Appendix Figure A4 illustrates how treatment status evolves across all country–product pairs over time. Treatment coverage is limited: by the end of the sample period, only 1.21 percent of raw mineral pairs are subject to export restrictions and 0.95 percent of downstream pairs are exposed to upstream restrictions. While treatment timing is staggered, the large share of never-treated observations mitigates concerns about bias in the two-way fixed effects (TWFE) estimator. Section 7 further verifies robustness using heterogeneity-robust difference-in-differences estimators.

[15] 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.

6 Results

This section empirically evaluates the effects of mineral export restrictions, following them from the targeted minerals downstream along the value chain. I begin by examining whether the restrictions indeed reduce exports of the targeted minerals. I then estimate whether they stimulate exports of downstream products in the aggregate. Using the production stages constructed above, I trace how far these effects propagate along the value chain. Finally, I discuss whether the restrictions lead to industrial upgrading by promoting the production of more downstream and technologically complex goods, and the conditions under which the downstream effects materialize.

6.1 Effects on Targeted Minerals

Table 1 reports estimates of Equation (30), which tests whether mineral export restrictions in fact reduce exports of the targeted raw minerals. The results confirm that they do. Column (1) shows that imposing a restriction lowers export value by 42.1 percent, and Column (2) reveals a larger contraction in export quantity, of 56.4 percent.[16] All regression specifications include country–product, country–year, and product–year fixed effects. Identification therefore comes from how a restricted country–product pair evolves relative to the same product in other countries that year and to other products in the same country that year.[17]

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 6 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 estimated effects build gradually, becoming statistically significant only after a lag. Part of this pattern likely reflects well-known biases in TWFE estimation under staggered treatment timing.[18] The gradual phase-in of restrictions, as countries often begin with lenient measures and tighten them as

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

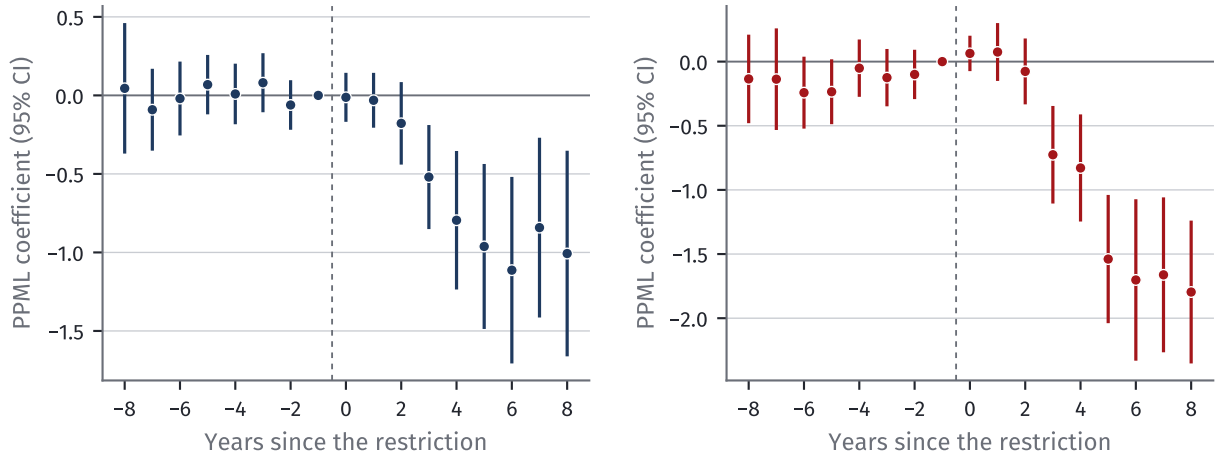
[17] Appendix Table A8 examines the effects on export participation and destination concentration. Restrictions reduce the probability of exporting by 2.4 percentage points and the number of export destinations by 7.8 percent, with no significant changes in export concentration. These results suggest that the contraction occurs primarily within existing export relationships.

[18] Section 7 reports event-study estimates from heterogeneity-robust difference-in-differences estimators, corroborating that the lag is partly an artifact of standard TWFE estimation.

Table 1. Direct effects of mineral export restrictions

	Export Value	Export Quantity	Unit Value
Export Restriction	-0.547***	-0.831***	0.107**
	(0.172)	(0.173)	(0.0486)
Unit of observation	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	PPML	PPML	OLS
# of Clusters	16,512	16,377	14,139
# of Obs.	357,198	351,749	188,004

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). Fixed effects are indexed by country i, product k, and year t. 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 6. 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.

domestic processing capacity expands, may also contribute. The absence of pre-trends and the sustained post-treatment decline reinforce a causal interpretation of the baseline estimates.

Because export quantity falls by more than export value, the restriction raises the unit value of the remaining exports. Column (3) of Table 1 confirms this pattern, showing an 11.3 percent increase in the restricting country's export unit value. However, country–product unit values may also reflect changes in the composition of export destinations and mineral grades. Table 2 therefore turns to bilateral trade flows. Column (1) compares changes in the restricting

country's export unit values with those of other suppliers selling the same mineral to the same importer in the same year, controlling for exporter–importer–product, importer–product–year, and exporter–importer–year fixed effects. The estimate shows a 14.2 percent increase, indicating that restricting exporters receive higher prices from foreign buyers. The increase in relative export prices is consistent with the terms-of-trade mechanism in Proposition 1.

Columns (2)–(4) examine the effects on importing countries. The dependent variable is the average unit value an importer pays for a mineral across all origins, while the explanatory variable is the importer's exposure E_{jkt}, defined as the share of its 2002–2007 imports of mineral k sourced from countries restricting that mineral in year t. Column (2) shows that an importer previously sourcing entirely from restricting countries pays 24.6 percent more than an unexposed importer. Columns (3) and (4) distinguish two channels underlying this increase: a composition component, which values current sourcing shares at each supplier's pre-period price, and a within-supplier component, which values pre-period sourcing shares at current prices. The two components are of similar magnitude, suggesting that exposed importers both shift toward more expensive suppliers and face higher prices from existing suppliers, although the latter effect is estimated imprecisely. The increase in import costs thus extends beyond purchases from restricting exporters to the alternative suppliers that importers turn to.

Table 2. Direct effects: prices of targeted minerals

	Restricting country's	Importers' average price paid		
	export price	All origins	Composition	Within supplier
Export Restriction (ER_{ikt})	0.133***			
	(0.0287)			
Exposure to Restrictions (E_{jkt})		0.220***	0.126***	0.121
		(0.0756)	(0.0360)	(0.0790)
Unit of observation	$ijkt$	jkt	jkt	jkt
Fixed Effects	ijk, jkt, ijt	jk, kt, jt	jk, kt, jt	jk, kt, jt
Estimator	OLS	OLS	OLS	OLS
# of Clusters	11,909	109	109	109
# of Obs.	1,545,470	267,207	266,023	239,723

Notes: This table reports the estimated effects of export restrictions on the prices of targeted raw minerals. In Column (1) the dependent variable is the log unit value of bilateral export flows, so the restricting country's price is compared with other suppliers of the same mineral to the same importer in the same year, net of exporter–importer–year shocks. In Columns (2)–(4) the dependent variable is the log average unit value an importer pays for a mineral across all origins, with Columns (3) and (4) holding supplier prices and sourcing shares, respectively, at their 2002–2007 levels; the regressor is the share of the importer's 2002–2007 imports that came from countries restricting the mineral in that year. Fixed effects are indexed by exporter i, importer j, product k, and year t. Standard errors are clustered at the exporter–product level in Column (1) and at the product level in Columns (2)–(4). * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Appendix Figure A5 reports event-study estimates corresponding to Columns (1) and (2). No pre-treatment coefficient is statistically significant at the 5 percent level in either panel. The restricting country's export unit value rises by 9.3 percent one year after the restriction and remains 10–15 percent higher in most subsequent years. Importers' average unit values adjust more gradually, showing little response in the first four years before increasing from year five onward, by up to 35 percent per unit of exposure. Taken together, the price effects of mineral export restrictions extend beyond restricting exporters, raising import costs for exposed countries through both supplier price increases and changes in sourcing patterns.

6.2 Effects on Downstream Products

I now examine whether upstream restrictions stimulate exports of downstream products. Table 3 reports estimates of Equation (31). In contrast to the negative effects on targeted minerals, upstream export restrictions significantly increase exports of downstream products. Columns (1) and (3) show that downstream export value rises by 12.3 percent and export quantity by 23.5 percent. The larger effect on quantity than on value is consistent with the negative unit-value estimate in Column (5), although the latter is small and statistically insignificant, potentially reflecting the smaller estimation sample. To isolate the upstream channel, Columns (2), (4), and (6) additionally control for export restrictions imposed directly on downstream products. These direct restrictions reduce export quantity by 10.9 percent, while the estimated 2.2 percent decline in export value is statistically insignificant. Importantly, accounting for direct restrictions leaves the estimated upstream effects virtually unchanged, with downstream export value increasing by 12.3 percent and quantity by 24.7 percent. Taken together, these findings suggest that restrictions on raw mineral exports encourage a reallocation of export activity toward downstream products, consistent with the manufacturing expansion predicted by Proposition 2.[19]

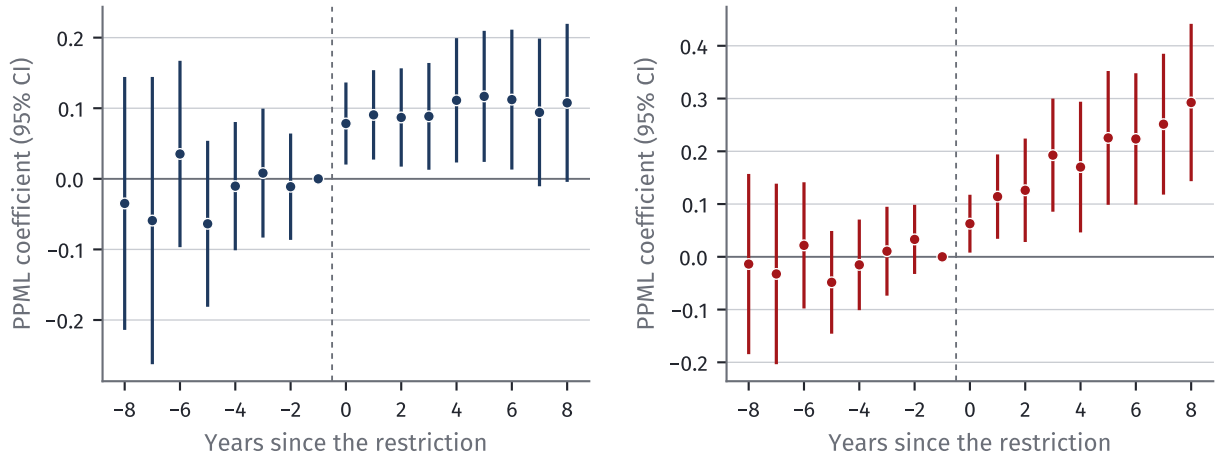
Figure 7 extends the event study analysis to downstream products. None of the pre-treatment coefficients are statistically significant, consistent with the increase in downstream exports being driven by upstream restrictions. In contrast to targeted minerals, downstream exports respond more quickly, with positive effects emerging almost immediately after the policy takes effect. This faster export response likely reflects the ability of existing domestic firms to scale

[19] Appendix Table A9 examines changes in downstream export participation and destination concentration. Upstream restrictions increase the probability of exporting a downstream product by 0.5 percentage points and the number of export destinations by 2.9 percent, while reducing export concentration. These results suggest that downstream expansion occurs primarily among products already exported, rather than through entry into previously unexported products.

Table 3. Downstream effects of mineral export restrictions

	Export Value		Export Quantity		Unit Value	
Export Restriction (Up)	0.116**	0.116**	0.211***	0.221***	-0.00799	-0.00817
	(0.0511)	(0.0510)	(0.0580)	(0.0579)	(0.00832)	(0.00832)
Export Restriction (Own)		-0.0227		-0.115**		0.00994
		(0.0227)		(0.0470)		(0.00810)
Unit of observation	ikt	ikt	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	PPML	PPML	PPML	PPML	OLS	OLS
# of Clusters	724,742	724,742	718,339	718,339	646,489	646,489
# of Obs.	15,714,045	15,714,045	15,433,472	15,433,472	9,401,797	9,401,797

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). Fixed effects are indexed by country i, product k, and year t. 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 7. 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.

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

A natural concern is that higher downstream exports reflect a diversion of sales from domestic to foreign markets rather than an expansion of domestic production. Appendix E provides two indirect empirical checks. Mining output in restricting countries does not decline following the restriction, consistent with minerals being redirected from export markets to domestic

processors rather than remaining unextracted. Downstream imports also do not fall, offering no evidence of significant import substitution. Neither result, however, rules out a decline in domestic sales of downstream products.

6.3 Propagation along the Value Chain

The preceding results establish that mineral export restrictions stimulate downstream exports in the aggregate. However, Proposition 4 shows that the direct input-cost advantage attenuates along the value chain, while Proposition 6 establishes that the welfare gains from downstream expansion depend on the distribution of employment responses and scale externalities across stages. If these externalities are stronger in more advanced activities, the policy dilemma arises when the stimulus is concentrated in early processing stages. Whether this is the case—and whether restrictions can deliver the industrial upgrading governments seek—depends on how far their effects propagate along the value chain. To examine this, I estimate stage-specific treatment effects on downstream exports using the production stages constructed in Section 4.

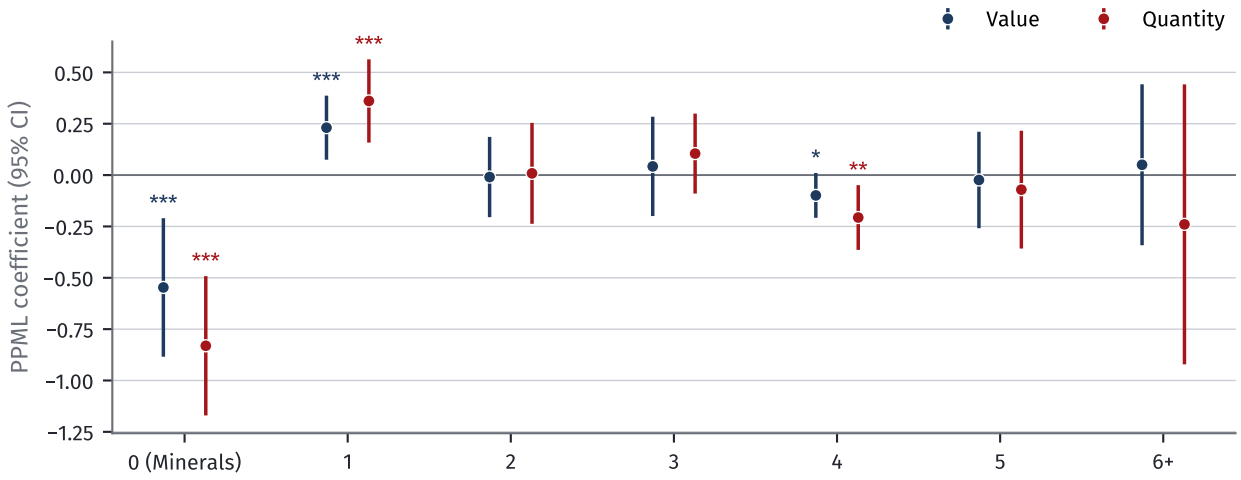
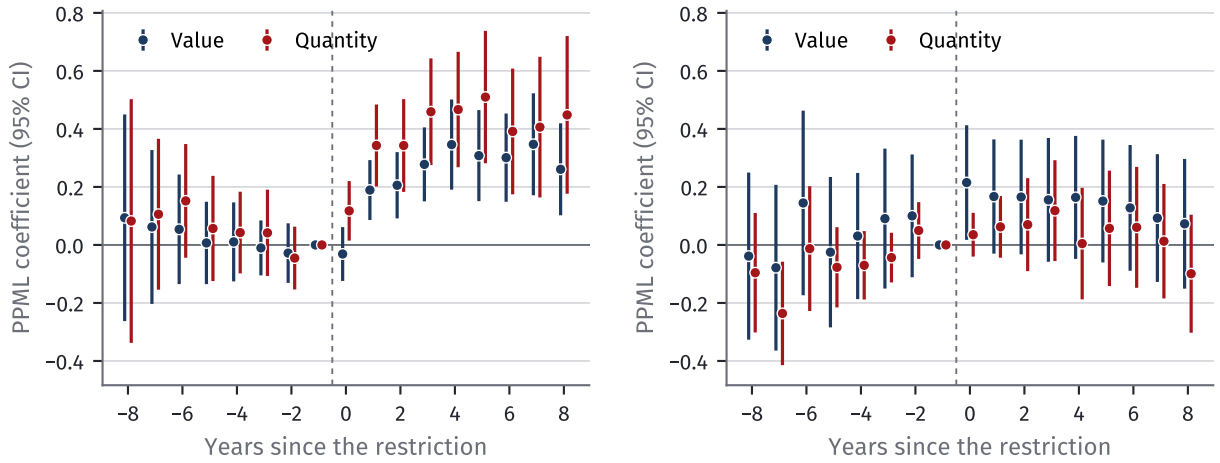


Figure 8. Downstream effects of mineral export restrictions by production stage

Notes: This figure plots the estimated effects of upstream mineral export restrictions on exports at each downstream production stage. The direct effects on targeted minerals (stage 0), reported in Table 1, are included for comparison. Bars denote 95% confidence intervals, with standard errors clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Figure 8 shows that the export-stimulating effects of upstream mineral export restrictions are concentrated at the first processing stage. At this stage, export values and quantities increase by 26.0 percent and 43.5 percent, respectively. Beyond the first stage, the pattern is less systematic.

At stages 2, 3, 5, and 6+, the estimated effects on both export value and quantity are statistically insignificant, while at stage 4, both decline significantly. Thus, instead of exhibiting a gradual attenuation along the value chain, the results show a sharp contrast between the substantial gains at the first stage and the absence of consistent positive effects further downstream. The sharp decline is consistent with the recursive structure in Proposition 4, where the direct cost advantage is attenuated by a factor αs_k at each stage. When this factor is small, the cost advantage can dissipate rapidly. This pattern suggests that mineral export restrictions stimulate basic processing activities but provide little evidence of broader expansion into more advanced stages of production.[20]



(a) Stage 1

(b) Stages 2 and beyond

Figure 9. Downstream effects by production stage: event study

Notes: This figure plots the dynamic effects of upstream mineral export restrictions on exports of downstream products at the first processing stage and at stages 2 and beyond, based on PPML event-study regressions on the sample of Figure 8. Stages 2 and beyond are pooled in a single regression with a common exporter–year effect. Bars represent 95% confidence intervals, with standard errors clustered at the country–product level.

Figure 9 further examines the dynamic responses at the first processing stage and at stages 2 and beyond. At the first stage, the pre-treatment coefficients are small and statistically insignificant, while the effects on both export value and quantity emerge shortly after the restriction and strengthen over time. In contrast, at stages 2 and beyond, the estimates exhibit some pre-treatment fluctuations, and the post-treatment coefficients remain statistically insignificant, with no clear evidence of sustained expansion. These dynamic results reinforce the finding that

[20]Appendix Table A10 reports results using terciles of the upstreamness measure as an alternative. Because upstreamness reflects a product's relative position along the full value chain rather than its distance from a specific mineral, estimates are less precise; the qualitative pattern nonetheless corroborates the stage-level findings.

downstream export gains are concentrated in the first processing stage rather than propagating along the value chain. Appendix Table A11 reports the corresponding static estimates. Pooling stages 2 and beyond, the export quantity response is close to zero and significantly smaller than at the first stage. The export value response is also smaller, although the difference is not statistically significant.

Table 4. Downstream effects on bilateral export prices by production stage

	All Stages	Stage 1	Stages 2+
Export Restriction (Up)	-0.00810	-0.0220***	0.00213
	(0.00568)	(0.00782)	(0.00728)
Unit of observation	$ijkt$	$ijkt$	$ijkt$
Fixed Effects	ijk, jkt, ijt	ijk, jkt, ijt	ijk, jkt, ijt
Estimator	OLS	OLS	OLS
# of Clusters	160,941	157,617	157,624
# of Obs.	50,167,448	48,263,523	48,619,917

Notes: This table reports the estimated effects of upstream mineral export restrictions on the bilateral export prices of downstream products. The dependent variable is the log unit value of exporter–importer–product–year flows in BACI, so the exposed country's price is compared with other suppliers of the same product to the same importer in the same year, net of exporter–importer–year shocks. Column (1) uses all downstream products. Columns (2) and (3) restrict the sample to products at the indicated production stage (stage 1, or stages 2 and beyond) together with downstream products never exposed to a restriction, which serve as controls in every column. Fixed effects are indexed by exporter i, importer j, product k, and year t. Standard errors are clustered at the exporter–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 4 examines whether downstream export expansion is accompanied by changes in export prices. Following Column (1) of Table 2, I use bilateral trade flows to compare exposed exporters' unit values with those of other suppliers selling the same product to the same importer, controlling for exporter–importer–product, importer–product–year, and exporter–importer–year fixed effects. The pooled effect across all downstream stages is small and statistically insignificant. However, export unit values decline significantly at the first processing stage, consistent with exposed exporters passing part of their input-cost advantage on to foreign buyers. At subsequent stages, the estimated price effects are small and statistically insignificant, consistent with the attenuation of upstream cost advantages along the value chain. Together, the price and quantity results indicate that mineral export restrictions primarily stimulate basic processing, increasing export volumes while modestly reducing export prices, with limited evidence of similar responses further downstream.

To see which products drive the gains, Figure 10 breaks the effects down by sector. The export-stimulating effects are concentrated almost entirely in base metals, the sector that sits

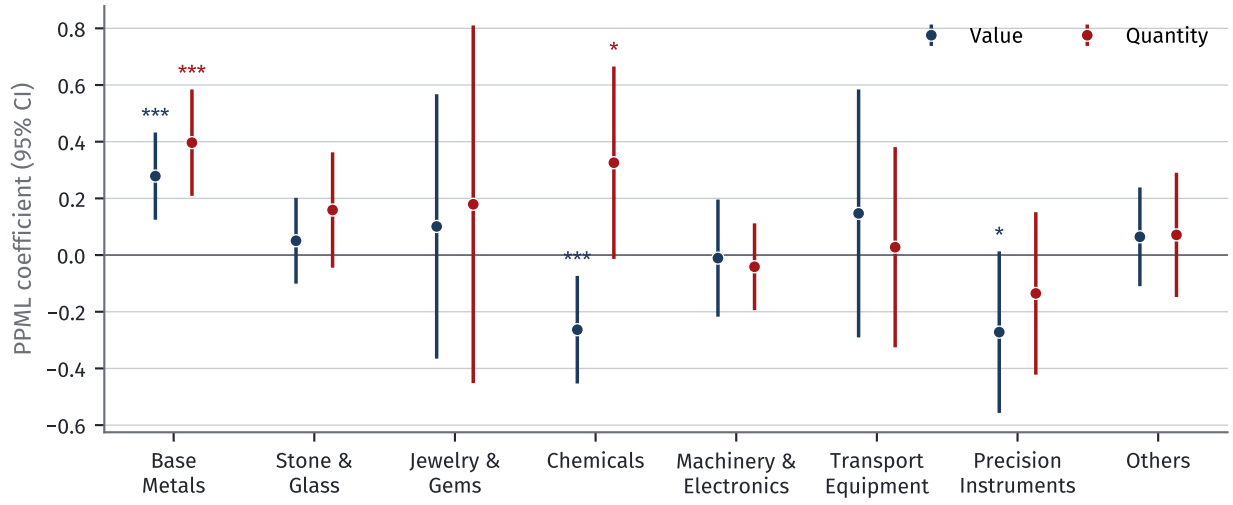


Figure 10. Downstream effects of mineral export restrictions by sector

Notes: This figure plots the estimated effects of upstream mineral export restrictions on exports of downstream products by 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 Appendix Table A12. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

immediately downstream of raw minerals and absorbs them with minimal further transformation. By contrast, no comparable gains appear 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, consistent with an expansion in lower-value processing rather than in more advanced segments.

Taken together, the stage-level and sectoral evidence points to the same conclusion: the export gains from mineral restrictions are concentrated in basic processing closely tied to raw material inputs, with little expansion into more sophisticated downstream activities. This concentration leaves two questions open. The stage- and sector-level estimates are averages across heterogeneous restricting countries, so whether the gains reflect a broad response or one confined to a particular subset of exporters is unclear. In addition, the abrupt truncation beyond basic processing implies that some barrier halts the policy's reach short of the more sophisticated, higher-value stages. The next subsection takes up both questions, asking under what conditions the downstream effects arise and what confines them to basic processing.

6.4 Conditions and Limits of Downstream Upgrading

Restricting attention to mineral-related downstream products, for which upstream market share is well defined and cross-product RCA comparisons are meaningful, I first ask which exporters the downstream gains accrue to.

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)	0.106	0.0201	0.149**	0.282**	0.477**	0.548***
	(0.105)	(0.0741)	(0.0654)	(0.120)	(0.198)	(0.210)
Unit of observation	ikt	ikt	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	PPML	PPML	PPML	PPML	PPML	PPML
# of Clusters	178,855	177,128	27,196	27,144	1,913	1,913
# of Obs.	3,886,744	3,811,574	593,895	589,978	41,520	41,292

Notes: This table reports the estimated effects of upstream mineral export restrictions on exports of downstream products, with the sample split by the restricting country's pre-treatment market share in the upstream mineral, averaged over 2005–2007. Dependent variables are export value and quantity, both in levels. Fixed effects are indexed by country i, product k, and year t. Standard errors are clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table 5 re-estimates the downstream effects after splitting the sample by the restricting country's pre-treatment market share in the upstream mineral: negligible (below 1 percent), moderate (1 to 30 percent), and dominant (above 30 percent). The point estimates increase across the three groups. Among countries with a market share below 1 percent, export value and quantity rise by 11.2 and 2.0 percent, respectively, but neither effect is statistically significant. For countries with market shares between 1 and 30 percent, the effects are larger and statistically significant, with export value increasing by 16.1 percent and quantity by 32.6 percent. The largest estimates are found among countries holding more than 30 percent of the upstream market, where export value and quantity increase by 61.1 and 73.0 percent, respectively. These latter estimates, however, are based on only four countries, reflecting the rarity of such high upstream market shares, and should therefore be interpreted with caution. Overall, the results suggest that downstream export gains are more pronounced when restricting countries have a non-negligible presence in the upstream mineral market. This pattern need not imply a stronger domestic input-cost subsidy among countries with greater market power. Because the estimates compare restricting countries with other exporters, larger relative effects may also reflect the contraction of foreign competitors as higher world mineral prices raise their input costs.

Table 6. Downstream effects: heterogeneity by downstream RCA

	Low RCA (≤ 1)		High RCA (> 1)	
	Value	Quantity	Value	Quantity
Export Restriction (Up)	0.00927	0.0357	0.112	0.219**
	(0.0549)	(0.0630)	(0.0825)	(0.101)
Unit of observation	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	PPML	PPML	PPML	PPML
# of Clusters	184,852	183,087	23,510	23,495
# of Obs.	4,021,653	3,944,817	511,137	508,941

Notes: This table reports the estimated effects of upstream mineral export restrictions on exports of downstream products, with the sample split by whether the restricting country's revealed comparative advantage (RCA) in the downstream product, averaged over 2005–2007, was above one. Pairs without exports in 2005–2007 are in the low-RCA group. Dependent variables are export value and quantity, both in levels. Fixed effects are indexed by country i, product k, and year t. Standard errors are clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

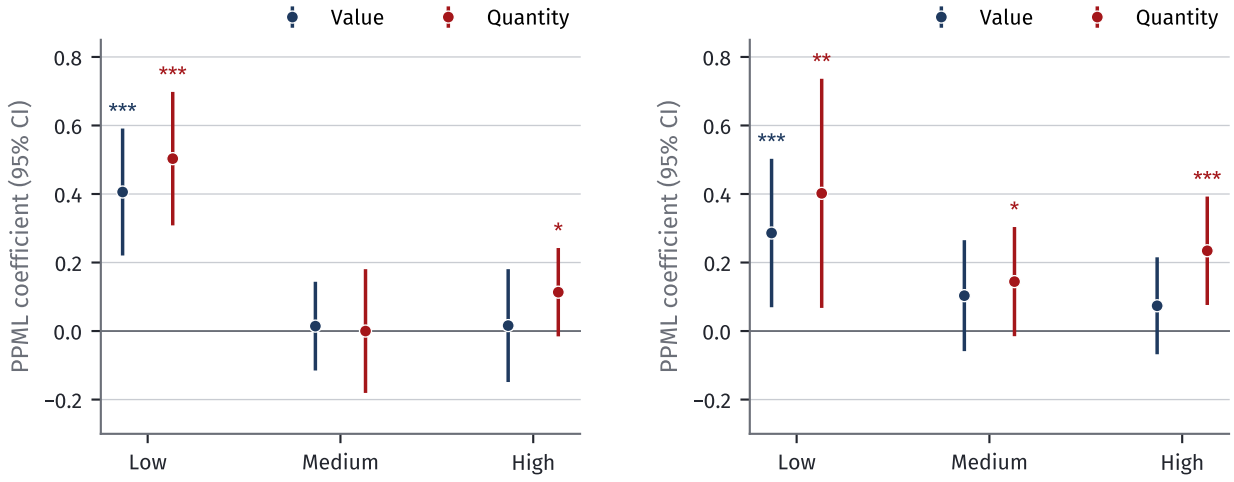
Even where a country holds upstream market power, do restrictions work as policymakers envision—expanding downstream exports into products that the country could not previously produce competitively? I examine whether downstream gains depend on pre-existing comparative advantage. Table 6 divides country–product pairs according to whether their pre-treatment revealed comparative advantage (RCA) exceeds one.[21] Among initially high-RCA products, export quantity increases by 24.5 percent, statistically significant at the 5 percent level, while the estimated 11.9 percent increase in export value is not significant. By contrast, the estimates for low-RCA products are small and statistically insignificant for both outcomes. These results suggest that downstream export gains are more readily realized in products where countries already possess a comparative advantage. Lower mineral input costs may help expand existing competitive activities, but provide less evidence of stimulating exports in products without an established comparative advantage.

If this is the case, what determines whether a developing country becomes competitive in a downstream product, and why does that capacity erode as products move downstream? Part of the answer lies in the product itself. I focus on two characteristics that are higher at later stages of the value chain and, I argue, hold the effects back: technological complexity and the complexity of complementary inputs. As production moves downstream, processes grow more complex, demanding capabilities and specialized knowledge that cheaper raw materials cannot

[21] As Figure 3 showed, restricting countries are not competitive in most mineral-related downstream products: only 14.5 percent of country–product pairs had a pre-treatment RCA above one.

supply. Downstream production also relies on increasingly sophisticated intermediate inputs from other sectors, which may be difficult to source competitively even when domestic mineral inputs become cheaper. Cheaper minerals may thus facilitate basic processing, but become less effective as production requires more sophisticated technologies and complementary inputs.

I measure product-level technological complexity using the Product Complexity Index (PCI) (Simoes and Hidalgo, 2011), and measure the complexity of complementary inputs by the average PCI of the upstream products linked to each downstream product in AIPNET. As Appendix Figure A6 shows, both measures are higher at later production stages. Partitioning the sample directly by product complexity and input complexity provides a sharper test: if these barriers bind, downstream gains should be concentrated in technologically simpler products and those relying on less complex upstream inputs.



(a) Complexity

(b) Input complexity

Figure 11. Downstream effects: heterogeneity by product and input complexity

Notes: This figure plots the estimated effects of upstream mineral export restrictions on exports of downstream products, with products divided into terciles by technological complexity (panel a) and by input complexity, measured as the average complexity of the upstream inputs linked to each product (panel b); effects are estimated separately within each tercile for export value and quantity. Bars denote 95% confidence intervals, with standard errors clustered at the country–product level. Corresponding regression results are reported in Appendix Tables A13 and A14. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Figure 11 shows that, under both classifications, downstream gains are concentrated in the lowest tercile, particularly in export value. The two characteristics, however, differ in how sharply the effects diminish. Among the least complex products (panel a), export value rises by 50.1 percent and quantity by 65.4 percent, both highly significant. In the middle and top terciles, the effects are close to zero, apart from a modest and marginally significant quantity

response in the top tercile. Input complexity (panel b) shows a more gradual attenuation. Products with the least complex inputs again respond strongly, rising by 33.1 percent in value and 49.5 percent in quantity. Above the lowest tercile, the effects are substantially smaller: the value estimates become statistically insignificant, while the quantity effects remain positive and significant at 15.5 percent and 26.4 percent in the middle and highest terciles, respectively. This difference is consistent with the proposed mechanisms: more sophisticated complementary inputs may limit the benefits of cheaper minerals, whereas technological complexity reflects production capabilities that lower mineral costs cannot readily provide. Overall, the results suggest that both characteristics help explain why downstream export gains are concentrated in relatively simple processing activities.

Across these results, mineral export restrictions reduce exports of targeted minerals and stimulate downstream expansion, but the gains are concentrated in the first processing stage and in base metals. The effects are stronger among countries with a substantial upstream market share and for downstream products with an established comparative advantage, while diminishing with product and input complexity. These patterns suggest that cheaper mineral inputs can support existing domestic processing activities but are insufficient on their own to promote broad-based upgrading into more technologically sophisticated manufacturing industries. They also highlight the potential welfare implications of Proposition 6: if export gains in early processing are accompanied by similar patterns of employment growth, the resulting welfare benefits may be limited when scale externalities are stronger in more advanced production stages. Existing sector-level estimates support this possibility, suggesting stronger scale externalities at later production stages.[22]

7 Robustness Checks

This section examines the robustness of the baseline results to alternative estimation methods, sample definitions, and classifications of minerals. Across these specifications, export restrictions reduce exports of targeted minerals and increase downstream exports, with the downstream gains concentrated in the first processing stage.

[22] Bartelme et al. (2025) and Lashkaripour and Lugovskyy (2023) estimate stronger scale externalities in advanced manufacturing than in base metals. Section 8 maps their estimates to the production stages used here and evaluates this possibility quantitatively.

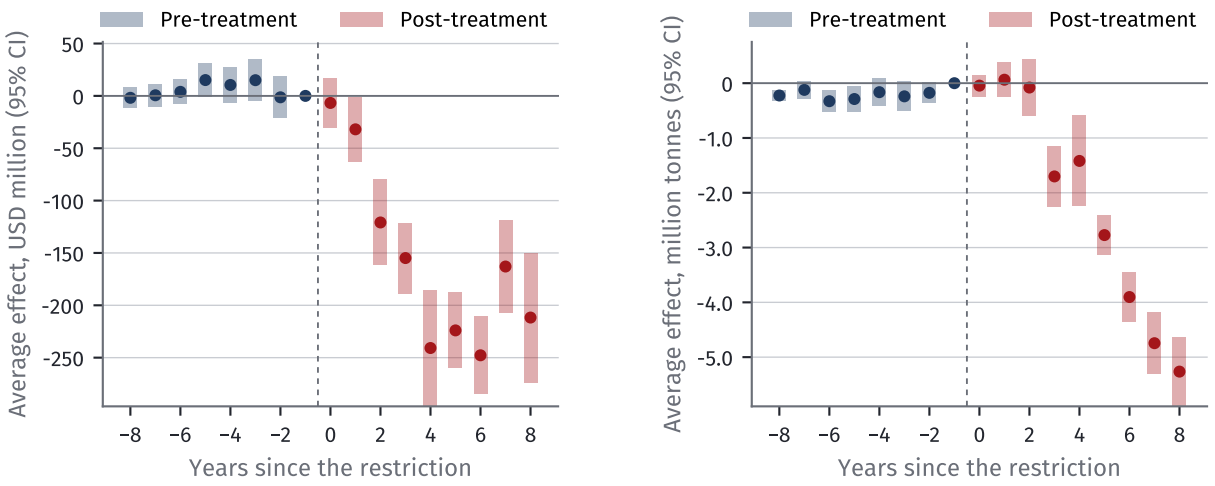
7.1 Alternative Estimation Methods

Due to the prevalence of zero trade flows in the data, all baseline regressions are estimated using PPML in levels. As a first check, I re-estimate Equations (30) and (31) using log-linear OLS specifications, weighting country–product pairs by their 2008 export values so that larger flows receive more weight, as in PPML. These regressions exclude zero trade flows and provide a comparison under a different functional form and weighting scheme. As Appendix Table A15 shows, the OLS estimates remain consistent with the baseline in sign and significance for both targeted minerals and downstream products.

TWFE estimators for difference-in-differences models produce biased estimates when treatment effects are heterogeneous and treatment timing varies (de Chaisemartin and D'Haultfœuille, 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. To assess whether staggered treatment timing affects the baseline results, I first employ the extended two-way fixed effects (ETWFE) estimator of Wooldridge (2023). Unlike conventional linear DiD estimators, ETWFE accommodates treatment-effect heterogeneity within a nonlinear framework, allowing a direct comparison with the PPML baseline. Figures 12 and 13 report estimates obtained using the `jwdid` command (Rios-Avila et al., 2022), following its application to gravity settings by Nagengast and Yotov (2025) and Nagengast et al. (2025). The estimates show no systematic pre-treatment trends for either targeted minerals or downstream products, while the post-treatment effects are broadly similar to the PPML baseline, lending further support to the main findings. For targeted minerals, the baseline PPML event study (Figure 6) shows a roughly three-year lag before the export decline emerges, whereas the ETWFE estimates indicate that the decline begins one to two years earlier. This suggests that the gradual phase-in under TWFE may partly reflect the contamination of event-study coefficients under staggered treatment timing, rather than a delayed policy response.

As a further check, I re-estimate the event-study specifications using three alternative estimators that accommodate staggered treatment timing and heterogeneous treatment effects: `csdid` (Callaway and Sant'Anna, 2021), `did_imputation` (Borusyak et al., 2024), and `did_multiplegt_dyn` (de Chaisemartin and D'Haultfœuille, 2024). I use the log-linear OLS specifications in Appendix Table A15 as the benchmark for these estimators.[23] Because these specifications exclude zero trade flows and differ from the nonlinear PPML baseline, I

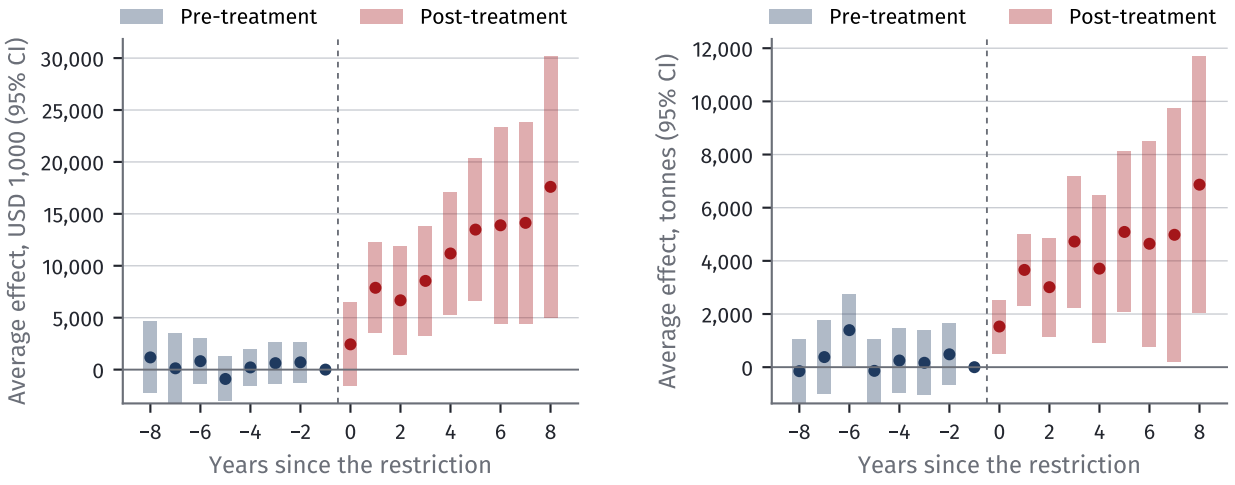
[23] In these estimators, the country–product pair is the panel unit and the year is the time dimension. Country–year and product–year fixed effects are included as controls where supported by the estimator.



(a) Export Value (b) Export Quantity

Figure 12. ETWFE estimates: targeted minerals

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



(a) Export Value (b) Export Quantity

Figure 13. ETWFE estimates: downstream products

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

report the results in Appendix Figures A7 and A8. The targeted-mineral analysis uses the full sample. For downstream products, because `csdid` and `did_multiplegt_dyn` cannot directly absorb country–year and product–year fixed effects, I restrict the analysis to countries that have ever imposed a mineral export restriction and products that have ever been exposed to one. This allows comparisons within a more relevant set of countries and products, reducing the risk that differences in export growth across countries and products are confounded with treatment effects. Overall, the long-run effects remain consistent with the OLS benchmark. A Goodman-Bacon decomposition (Goodman-Bacon, 2021) of linear TWFE regressions with country–product and year fixed effects (Appendix Table A16) shows that comparisons with never-treated units account for over 90 percent of the estimation weight in each regression, with little weight assigned to comparisons between treatment cohorts.

7.2 Alternative Samples and Mineral Definitions

I next examine the sensitivity of the baseline estimates to alternative sample restrictions. Because mineral export restrictions are almost exclusively imposed by developing countries, treated and control observations may not be comparable; I therefore re-estimate Equations (30) and (31) on a sample limited to developing (non-high-income) countries. A related concern is that countries or products never exposed to restrictions may differ systematically from those affected at least once, so I also narrow the sample to countries that have ever imposed a mineral export restriction and to products that have ever been targeted. To assess the influence of China, which accounts for the largest number of restrictions in the sample, I exclude it. Finally, I drop broad-based restrictions covering more than 100 products or more than 10 raw minerals, since such sweeping measures likely reflect policy motives different from those behind more targeted interventions. As Figure 14 shows, the estimates remain closely aligned with the baseline across all of these sample constructions.

Another set of robustness checks examines the definition of raw minerals. As the baseline definition (HS Chapters 25 and 26) aggregates products with heterogeneous industrial applications, I report three variations. First, I estimate the regressions separately for metallic and non-metallic minerals. Second, I drop slag, ash, and residues (HS 2618–2621) from the sample. Because the baseline already does not count restrictions on these by-products as mineral restrictions, this variation only removes them from the comparison group. Third, 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 metals (Asian

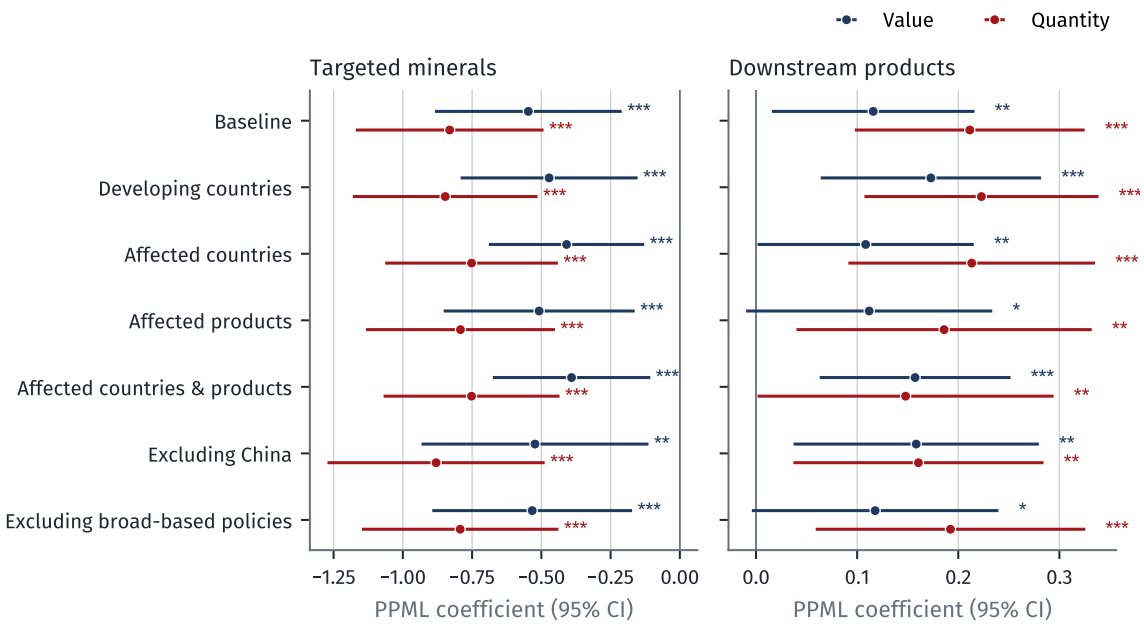


Figure 14. Robustness checks: alternative samples

Notes: This figure shows the estimated effects of mineral export restrictions on exports of both targeted minerals and downstream products 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. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

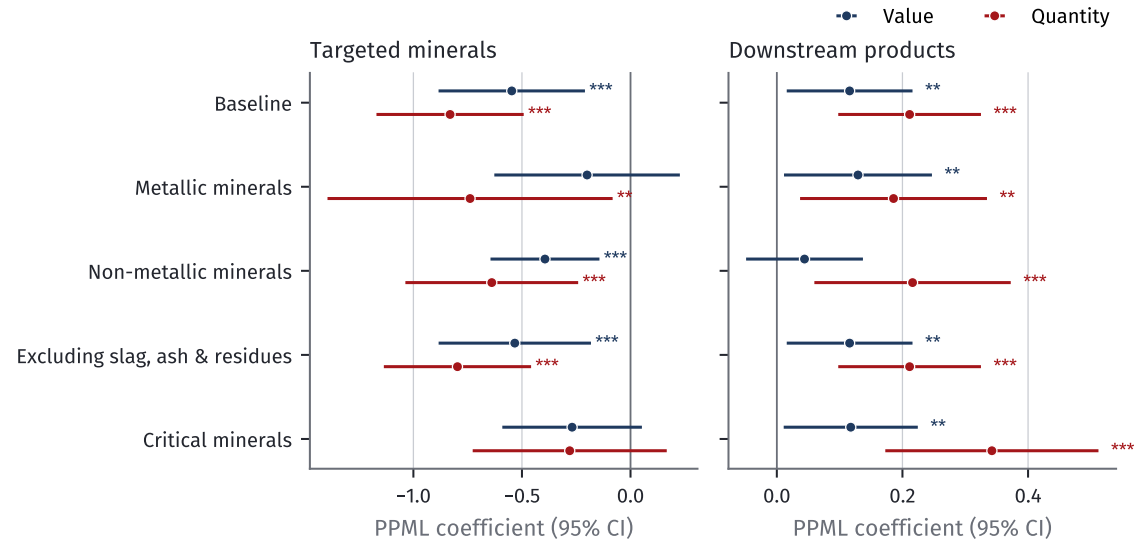


Figure 15. Robustness checks: alternative mineral definitions

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

Development Bank and World Trade Organization, 2024).[24] Figure 15 presents the results. The first two variations reproduce the baseline pattern in quantities, while the value estimates are less precise within each subset. The results remain qualitatively consistent for critical minerals, although the direct export-curbing effect becomes smaller and statistically insignificant, while the downstream quantity response becomes larger. One possible explanation lies in the different trade profiles of critical minerals and their downstream products. Critical minerals generally account for smaller trade flows, which receive less weight in PPML estimation and may contribute to the lower precision of the direct estimates. At the same time, these minerals are linked to a broader range of downstream products, potentially involving larger aggregate trade flows. The stronger downstream response may therefore reflect their extensive connections within production networks, despite their relatively limited direct trade volumes.

Finally, I examine whether the contrast between the first and subsequent stages is driven by particular minerals or policies. I re-estimate the specification in Appendix Table A11, sequentially excluding each targeted HS4 mineral or export restriction and recomputing downstream exposure. Appendix Figure A9 shows that the first-stage effects remain positive and statistically significant in nearly all cases, while the effects at subsequent stages remain small and generally insignificant. These results indicate that the concentration of downstream export gains in the first processing stage is not driven by any individual mineral or policy measure.

8 Quantification

This section evaluates how well trade-policy and industrial-policy motives explain the observed mineral export restrictions. For the trade-policy motive, I compare a common tariff equivalent inferred from the estimated price responses with pair-specific terms-of-trade optimal taxes, computed from world market shares and the elasticities of world demand and rest-of-world supply. For the industrial-policy motive, I compare the welfare cost of each restriction with the Pigouvian gain implied by its estimated downstream response and sector-level scale elasticity. I use scale elasticity estimates from Bartelme et al. (2025) and Lashkaripour and Lugovskyy (2023), hereafter BCDR and LL.

[24] 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).

8.1 The Trade-policy Motive

For each restricted pair, the terms-of-trade optimal tax is

$$t_i^{\mathrm{FB}} = \frac{1}{\varepsilon_{M,i}^*} = \frac{q_i}{\varepsilon_D + (1-q_i)\varepsilon_S}, \tag{32}$$

where ε_D and ε_S are the long-run elasticities of world demand and rest-of-world supply, and q_i is the restricting country's share of world mineral exports in the three years before the restriction was first announced. An export restriction can raise welfare even when its tariff equivalent exceeds the terms-of-trade optimal tax. Absent downstream externalities, it does so when the terms-of-trade gain exceeds the loss from reduced exports. For a restriction with tariff equivalent t, a second-order approximation yields the welfare criterion $t < 2\, t_i^{\mathrm{FB}}$.[25]

For calibration, I interpret the ratio of the estimated decline in mineral export quantities to the rise in export prices, $0.831/0.133 = 6.2$, as an approximate elasticity of foreign import demand. The inverse of this elasticity, 16.0 percent, provides a benchmark for the terms-of-trade optimal tax. I start from the demand and supply elasticities of 0.4 and 0.6 in Fally and Sayre (2018) and scale both by a common factor so that the export-weighted mean of t_i^{FB} matches this benchmark. This yields $\varepsilon_D = 0.50$ and $\varepsilon_S = 0.75$.

Since the tariff equivalent is not observed for bans, quotas, and licensing requirements, I infer a common value from the estimated price responses. The equivalent tax rate is the gap between the foreign and domestic mineral prices as a share of the foreign price. My estimates indicate that the restricting country's mineral export price rises by 14.2 percent. I set the mineral input share in first-stage processing costs to $\alpha = 0.25$.[26] Abstracting from wage and scale feedback, Equation (25) implies that the 2.2 percent fall in first-stage export prices corresponds to an 8.4 percent fall in the domestic mineral price. The two log price changes imply a pass-through coefficient of $\Phi = 0.60$: roughly three-fifths of the price wedge appears as a higher world mineral price, and the remainder as a lower domestic price. The price incidence is therefore tilted toward the trade-policy channel. Combining the changes also gives a tariff equivalent of $t = 0.20$, which I apply to all pairs. At this value, the welfare criterion requires a world market share above 11.6 percent.

Table 7 shows that the optimal terms-of-trade tax is small for most restricted pairs, with a median of 0.9 percent. None of the 175 pairs with world market shares below 10 percent

[25] Appendix G derives this criterion from a second-order approximation of the welfare decomposition.

[26] In the WIOD data, purchases from mining and quarrying account for 13 percent of basic-metals output worldwide, 17 percent in China, and 28 percent in Indonesia. These averages include later processing stages, so the share at the first processing stage is higher.

Table 7. Terms-of-trade motive by world market share

	Optimal Tax (%)		All Restricted Pairs		Meeting ToT Criterion	
World Market Share	Mean	Median	Pairs	% Exports	Pairs	% Exports
Below 1%	0.4	0.2	97	8	0	0
1% to 10%	4.1	2.0	78	24	0	0
10% to 30%	13.5	17.2	13	58	10	41
Above 30%	74.5	50.6	9	10	9	10
All	16.0	0.9	197	100	19	51

Notes: This table reports the trade-policy motive for restricted country–mineral pairs, grouped by the restricting country's share of world exports of the mineral over the three years before the restriction was first announced. For the optimal tax, the mean weights the pairs in each group by their mineral exports, and the median is unweighted. A pair meets the ToT criterion when twice its optimal tax exceeds the common tariff equivalent of 0.20, in which case the restriction raises welfare without downstream externalities to a second-order approximation. Export percentages are shares of total restricted mineral exports over the three years before the restriction.

meets the approximate terms-of-trade welfare criterion under the assumed tariff equivalent of $t = 0.20$. These pairs account for 89 percent of restricted pairs and 32 percent of restricted mineral exports. By contrast, 19 pairs across 7 countries meet the criterion. They represent only 10 percent of restricted pairs but account for 51 percent of restricted mineral exports. The trade-policy motive can therefore justify restrictions by a few large mineral suppliers, but it does not show that they promote downstream industrialization. For most restricted product pairs, terms-of-trade gains alone are insufficient; the welfare case for using restrictions as industrial policy depends on the benefits generated by downstream expansion.

8.2 The Industrial-policy Motive

The industrial-policy case for a restriction depends on whether the gains from downstream expansion outweigh its welfare costs. I evaluate the welfare decomposition in Proposition 5 for each restricted pair. The restriction raises the world mineral price and reduces mineral exports, while lower domestic mineral prices stimulate downstream production. In the multi-stage model, lower prices for processed exports offset part of the mineral terms-of-trade gain. The Pigouvian effect depends on where downstream employment expands and on the scale externalities in the activities from which workers are drawn, as shown in Proposition 6.

The calculation maps the estimated trade responses into the welfare decomposition, using the tariff equivalent and market-power parameters calibrated above. It draws on the estimated decline in mineral exports and the change in first-stage export prices from Tables 1 and 4. To capture downstream expansion, I apply the estimated stage-specific export quantity responses to

the output of products linked to each restricted mineral, assigning sector-level scale elasticities from BCDR and LL.[27] Since the data do not identify which sectors supply the additional downstream workers, I consider two labor sources: other manufacturing, assigned each country's average manufacturing scale elasticity, and agriculture and mining, assigned LL's estimate of 0.14 throughout, since BCDR do not estimate scale elasticities outside manufacturing.

Figure 16 decomposes the welfare effect across the 197 restricted country–mineral pairs with positive pre-restriction exports, expressed per $100 of those exports. Higher mineral export prices generate a terms-of-trade gain of $13.3, while lower processed-export prices and distorted mineral trade generate losses of $5.3 and $8.2, respectively. These three effects nearly cancel. Using BCDR's scale elasticities, the Pigouvian effect is a gain of $10.4 when downstream workers come from agriculture and mining, resulting in a net welfare gain of $10.2. When workers instead come from other manufacturing sectors, the Pigouvian effect is a loss of $19.7. Combined with the other channels, this yields a net welfare loss of $20.0.[28]

The Pigouvian effect changes sign because the scale elasticity of the expanding activities lies between those of the two potential labor sources. Under BCDR, weighting the scale elasticities of downstream products by their estimated expansion gives 0.17, above the 0.14 for agriculture and mining and below the manufacturing average of 0.22. LL gives the same ranking: 0.19 for expanding activities, compared with 0.14 for agriculture and mining and 0.26 for manufacturing. The scale elasticity of the expanding activities is relatively low because growth is concentrated at the first processing stage, where scale economies are weak: restricting the calculation to that stage yields only 0.16 under BCDR. The sector-level estimates point in the same direction. Base metals, with a BCDR scale elasticity of 0.13, are the only sector with a statistically significant increase in export value. By contrast, machinery and electronics, at 0.26 under the same estimates, exhibit no significant export response.

Which sectors supply the additional downstream workers remains uncertain. Domestic mine production does not fall following a restriction, while exports of precision instruments decline. These patterns are consistent with some reallocation within manufacturing, but neither identifies the workers' sectors of origin. The aggregate welfare conclusion therefore depends on the labor source: it is positive when workers come from agriculture and mining, and negative

[27] Appendix G derives the welfare calculation and describes the data. Because scale economies cause output to rise more than employment, proxying employment responses with output responses favors the restrictions.

[28] Appendix Table G2 reports pair-level results. Net welfare is positive for 20–21 of the 197 pairs when workers come from other manufacturing, for 83–97 when they come from agriculture and mining with a scale elasticity of 0.14, and for 136 when scale elasticities outside manufacturing are set to zero, where the ranges span the BCDR and LL estimates. These calculations apply pooled downstream responses to every pair and may overstate gains for small exporters, for whom Table 5 finds no statistically significant downstream response.

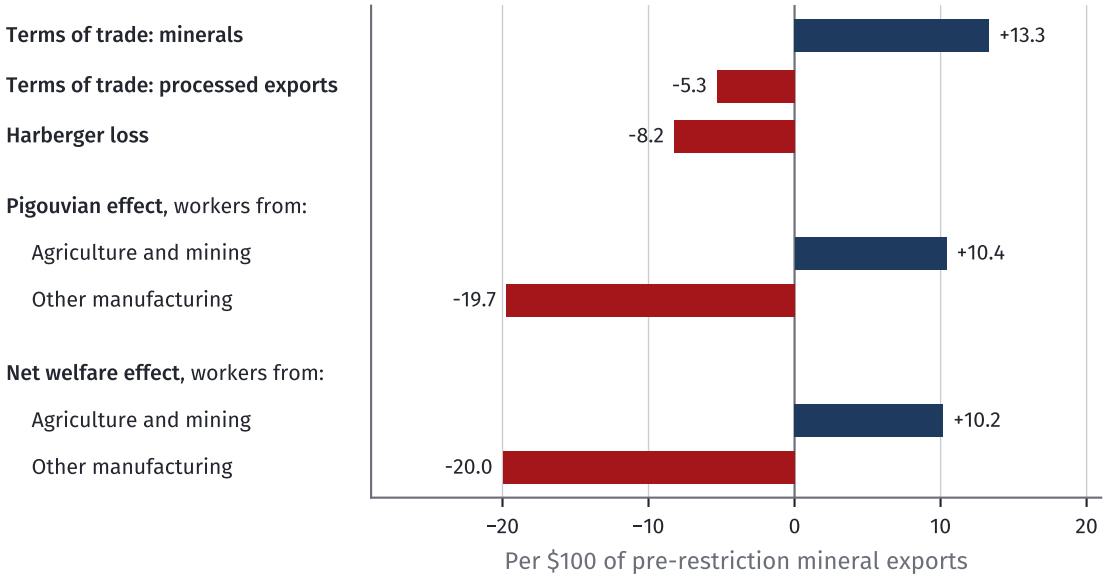


Figure 16. Welfare effect of mineral export restrictions by channel

Notes: This figure decomposes the welfare effect across 197 restricted country–mineral pairs, expressed per $100 of their aggregate pre-restriction mineral exports. The Pigouvian and net effects are reported under two assumptions about the source of downstream workers: other manufacturing, or agriculture and mining. Both calculations use BCDR's sector-level scale elasticities; the corresponding results using LL's estimates are shown in Appendix Figure A10.

when they come from other manufacturing. The destination of the expansion is clearer. Even when a shift out of agriculture and mining raises welfare, it draws workers into basic processing activities with scale economies below the manufacturing average. The restrictions can thus stimulate initial processing, but the observed expansion provides little evidence of movement toward manufacturing activities with stronger externalities.

9 Conclusion

This paper examines the scope and limits of mineral export restrictions as instruments of industrial policy. I develop a general equilibrium framework in which restrictions can improve the restricting country's terms of trade while implicitly subsidizing downstream manufacturing through lower domestic mineral prices. The welfare effect decomposes into terms-of-trade gains, Pigouvian gains from manufacturing expansion, and Harberger losses from distorted mineral trade. The optimal export tax combines a conventional terms-of-trade component with an industrial-policy component reflecting downstream scale externalities and the manufacturing employment response relative to mineral exports forgone. With multiple production stages, the direct input-cost advantage attenuates along the value chain, while the Pigouvian effect depends

on both aggregate manufacturing expansion and employment reallocation across stages. If scale externalities are stronger in more advanced activities, the largest potential industrial-policy gains may lie where the direct cost advantage is weakest.

Using a dataset of 112 mineral export restrictions imposed by 28 countries during 2008–2023, combined with product-level production linkages, I find that restrictions reduce targeted mineral exports by 42 percent and raise their export prices by 14 percent. Downstream exports increase by 12 percent, but the gains are concentrated at the first processing stage and in base metals. They largely disappear beyond the lowest tercile of technological complexity and are strongest among products relying on simpler complementary inputs. Export responses are also more pronounced in products where restricting countries already have a revealed comparative advantage, suggesting that cheaper mineral inputs primarily reinforce existing strengths.

The quantification separates the trade-policy and industrial-policy rationales. At the inferred tariff equivalent of 20 percent, 19 of 197 restricted country–mineral pairs meet the approximate terms-of-trade welfare criterion; these pairs account for half of restricted mineral exports. Across all pairs, however, the terms-of-trade gain on minerals is nearly offset by lower processed-export prices and the distortion of mineral trade, leaving the Pigouvian effect decisive for aggregate welfare. Welfare rises if downstream workers come from agriculture and mining, and falls if they come from other manufacturing. Although the available data do not identify which sectors release these workers, the destination of the expansion is clear: expanding activities have scale economies below the manufacturing average. Thus, even when reallocation raises welfare, growth remains concentrated in activities with relatively weak scale economies. Nevertheless, the static framework used here cannot determine whether expansion in these activities generates learning-by-doing effects and capabilities that later support entry into more advanced industries. Tracing that dynamic transition and its long-run welfare consequences is left for future research.

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

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University of Oxford

November 19, 2026

ONLINE APPENDIX

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A Additional Figures and Tables

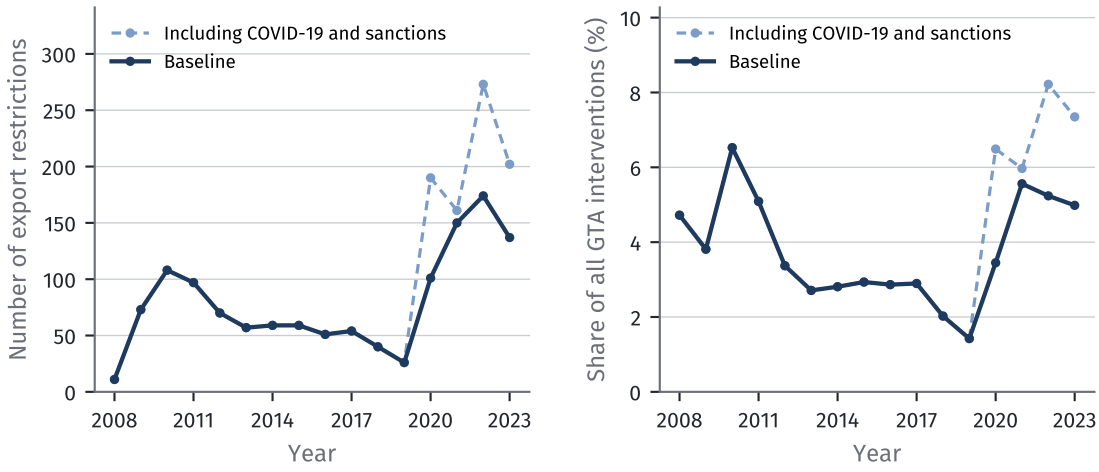


Figure A1. Export restriction usage by year

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.

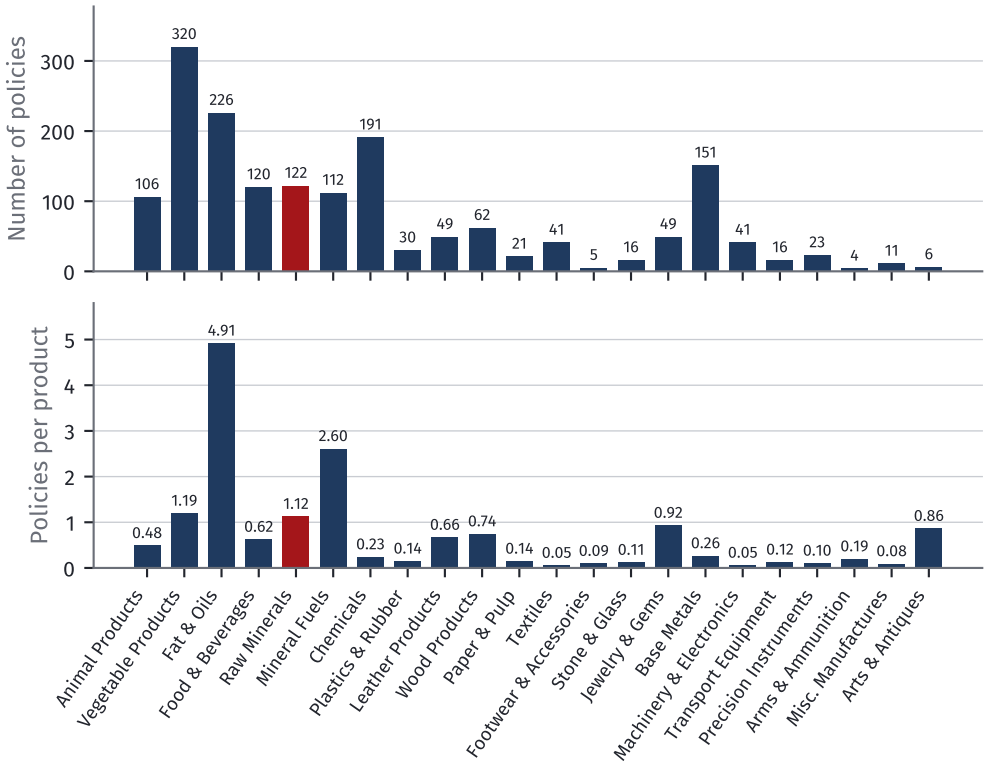


Figure A2. Export restrictions by product category

Notes: This figure displays the number of export restriction policies implemented between 2008 and 2023, excluding COVID-19-related measures and sanctions, 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.

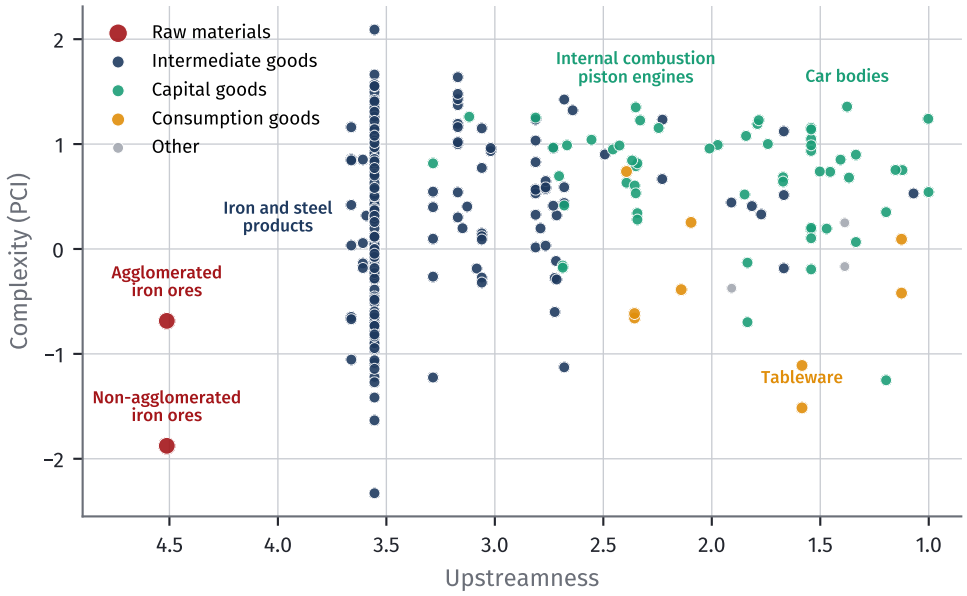
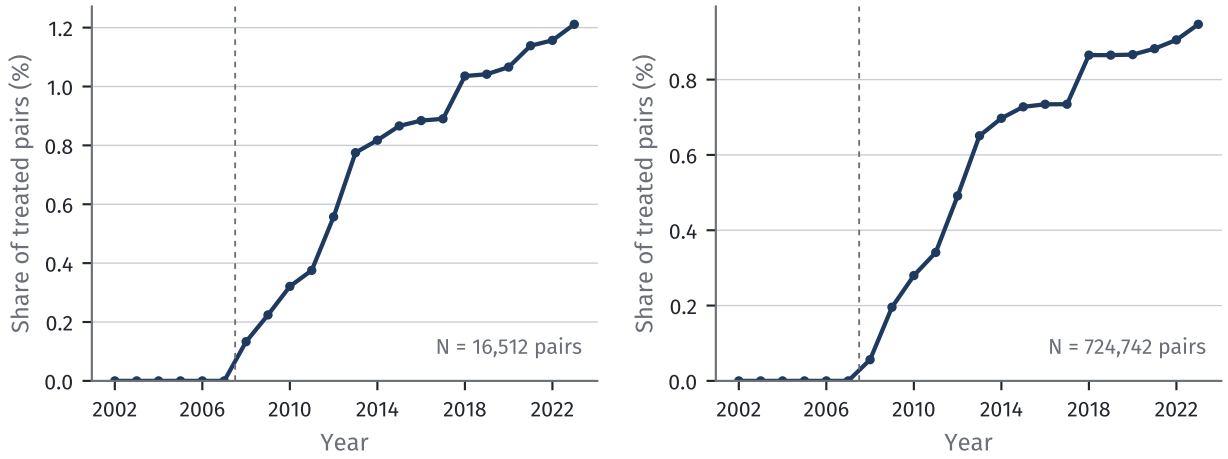


Figure A3. Products on the iron–steel value chain

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.

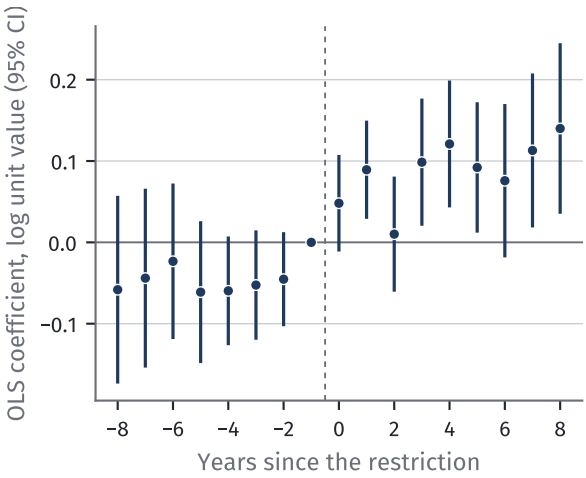


(a) Raw minerals

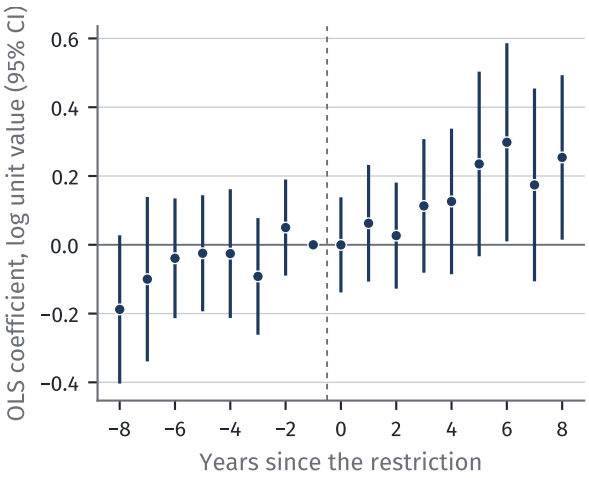
(b) Downstream products

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.



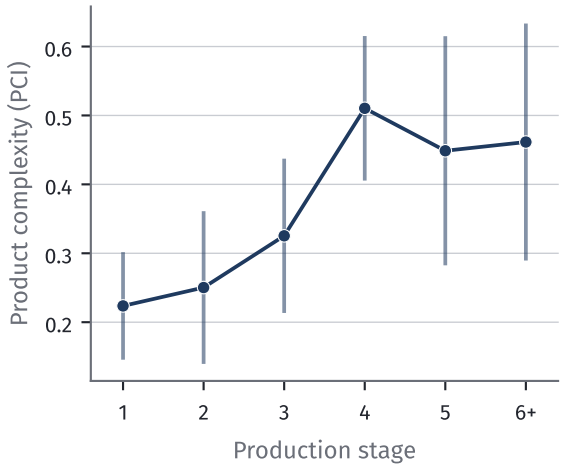
(a) Restricting country's export price



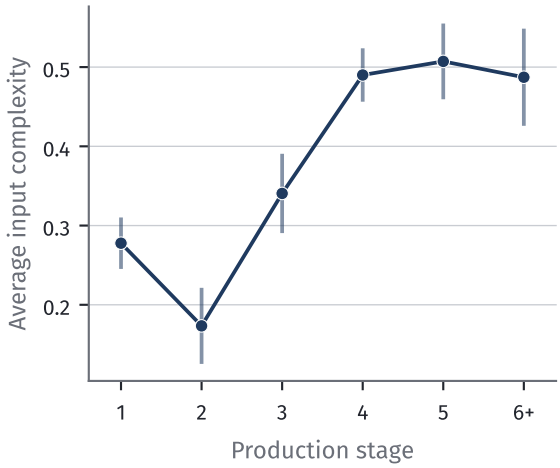
(b) Importers' average price paid

Figure A5. Direct effects on prices of targeted minerals: event study

Notes: This figure plots the estimated dynamic effects of export restrictions on the prices of targeted raw minerals. Panel (a) is the event-study version of Column (1) of Table 2: the restricting country's bilateral export price, with standard errors clustered at the exporter–product level. Panel (b) is the event-study version of Column (2): the importer's average unit value across all origins, where the exposure E_{jkt} is split by years since the restriction, so coefficients are per unit of exposure; standard errors are clustered at the product level. Event time is binned at −8 and 8. Bars represent 95% confidence intervals.



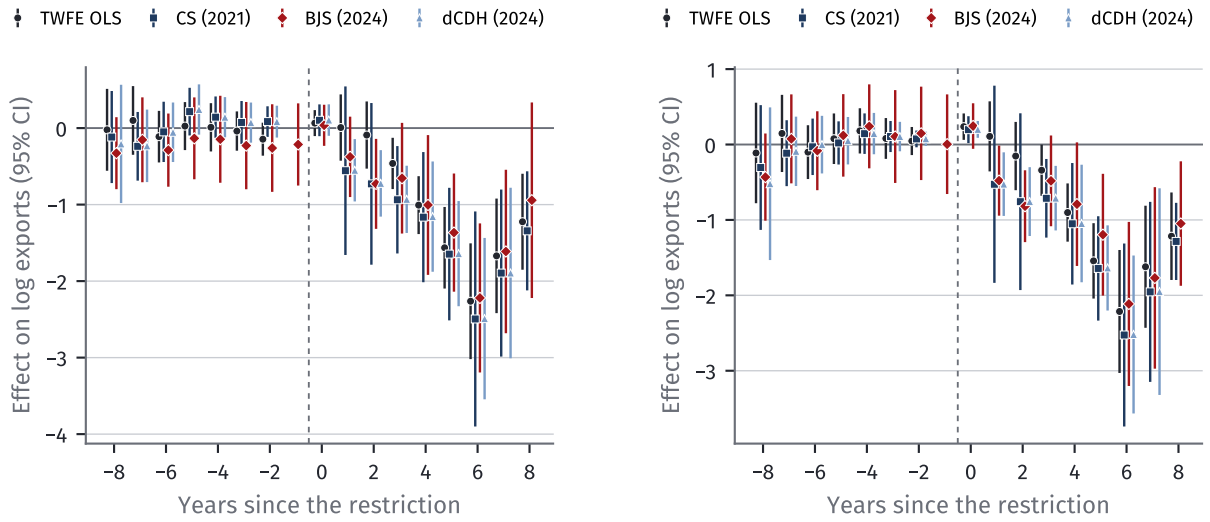
(a) Complexity



(b) Input complexity

Figure A6. Value chain position and product-level characteristics

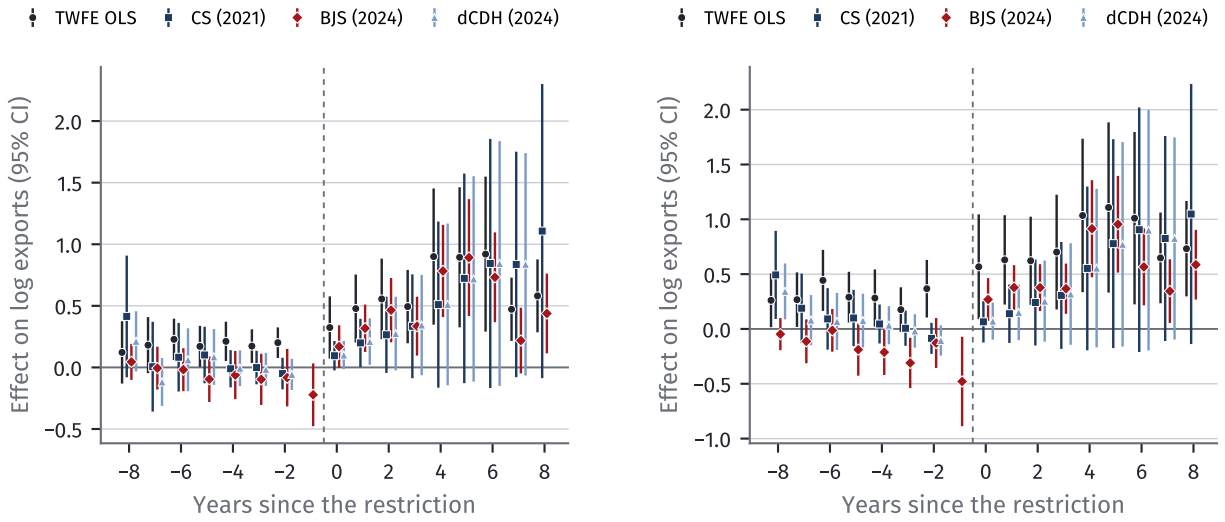
Notes: This figure summarizes key product characteristics across value-chain positions defined by AIPNET. Panel (a) plots average product complexity (PCI), and Panel (b) plots the average input PCI (a proxy for input sophistication) by production stage. Bars represent 95% confidence intervals. Products located further downstream tend to exhibit higher complexity and rely on more complex inputs.



(a) Export Value (b) Export Quantity

Figure A7. Heterogeneous DiD 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.



(a) Export Value (b) Export Quantity

Figure A8. Heterogeneous DiD 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.

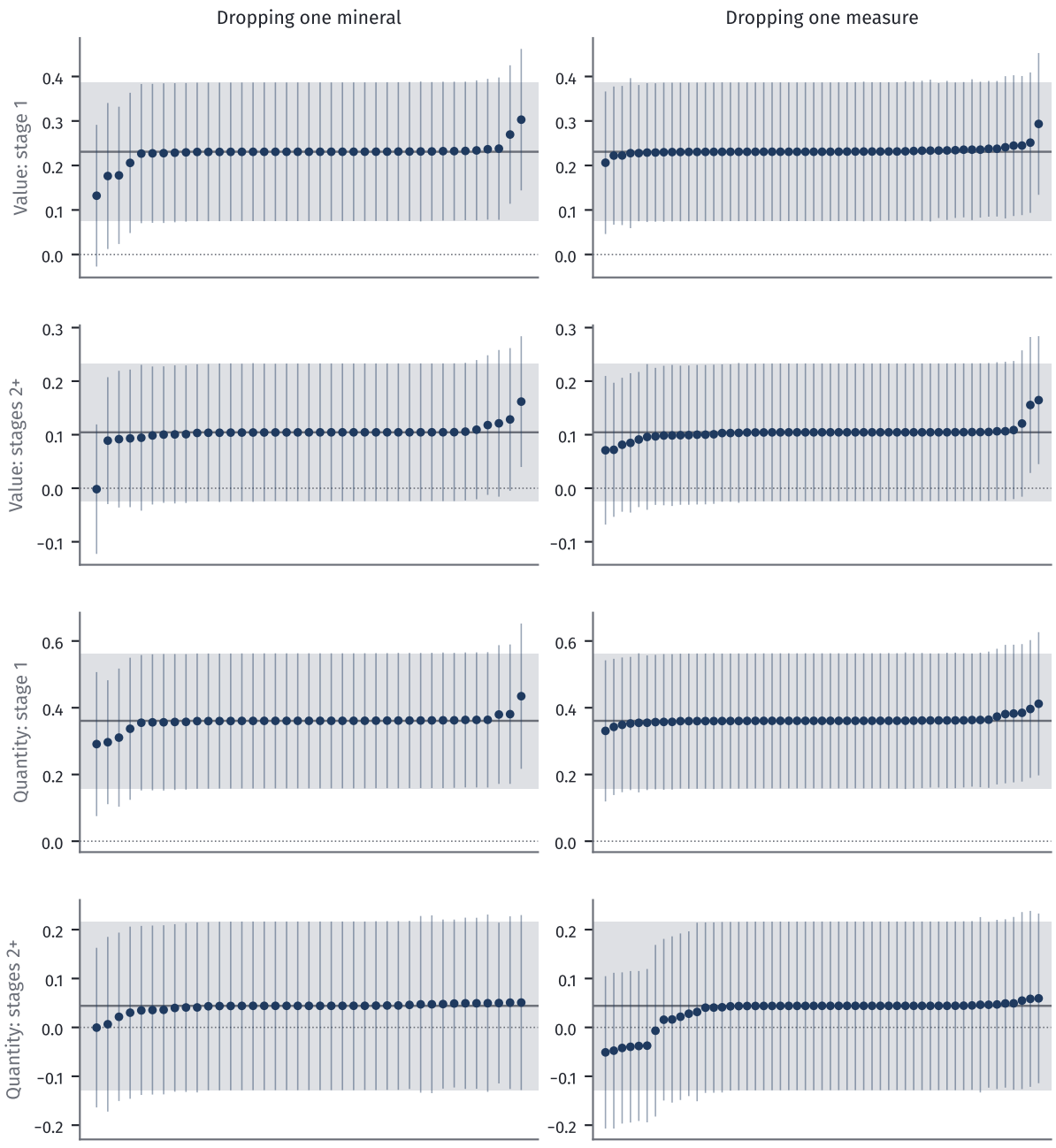


Figure A9. Leave-one-out estimates by production stage

Notes: This figure reports leave-one-out estimates of the specification in Appendix Table A11. The left column drops one targeted HS4 mineral at a time; the right column drops one of the 53 export restriction measures whose removal changes the treatment of at least one downstream country–product pair. When a mineral or measure is dropped, each downstream product's exposure is recomputed from the remaining restrictions, and products linked only through the dropped restriction become controls. Rows report the coefficients for the first stage and for stages 2 and beyond, for export value and quantity. Scenarios are sorted by the estimate. Lines show 95% confidence intervals, with standard errors clustered at the country–product level. The horizontal line and shaded band show the full-sample estimate and its 95% confidence interval.

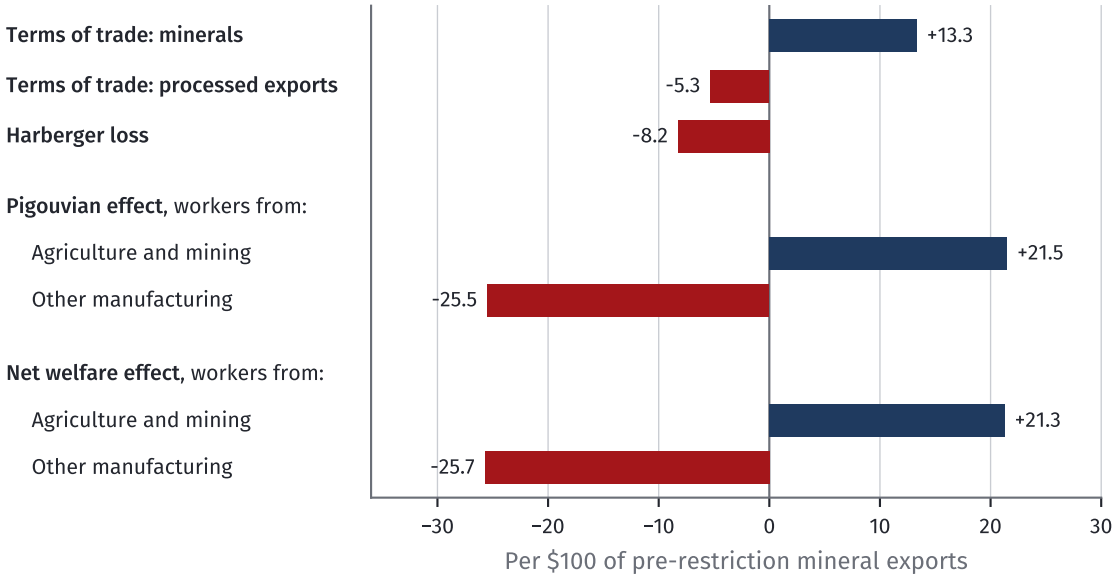


Figure A10. Welfare effect of mineral export restrictions by channel: LL

Notes: This figure repeats Figure 16 using the sector-level scale elasticities of Lashkaripour and Lugovskyy (2023) in place of those of Bartelme et al. (2025). It decomposes the welfare effect across 197 restricted country–mineral pairs, expressed per $100 of their aggregate pre-restriction mineral exports. The Pigouvian and net effects are reported under two assumptions about the source of downstream workers: other manufacturing, or agriculture and mining. The terms-of-trade effects and the Harberger loss do not depend on the scale elasticities.

Table A1. Revealed comparative advantage: restricted vs. non-restricted

		RCA (Balassa Index)			% RCA > 0	% RCA > 1	p-value
		# of Obs.	Mean	Median			
Raw Minerals	Restricted	200	20.57	1.21	97.00	56.00	0.000
	Non-Restricted	2,615	2.42	0.0061	63.14	13.50	
Downstream Products	Restricted	6,838	1.11	0.087	84.66	14.54	0.406
	Non-Restricted	104,603	0.95	0.013	71.09	11.92	

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 A2. Motives behind export restrictions: product-level

	ER_k	ER_k	ER_k	ER_k	ER_k	ER_k
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 logit and 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 A3. 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)
Unit of observation	ik	ik	ik	ik	ik
Fixed Effects			i	k	i, k
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 logit and linear probability models predicting the imposition of export restrictions based on revealed comparative advantage (RCA). Fixed effects are indexed by country i and product k. Robust standard errors are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A4. 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)
Unit of observation	ik	ik	ik	ik	ik
Fixed Effects			i	k	i, k
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 logit and linear probability models predicting the imposition of export restrictions based on revealed comparative advantage (RCA). Fixed effects are indexed by country i and product k. Robust standard errors are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A5. Number of export restriction policies and affected minerals by country

Country	# Policies	# Minerals
China	24	22
India	19	9
Indonesia	16	23
Egypt	8	13
Vietnam	6	15
Zimbabwe	5	10
Kyrgyzstan	4	2
Türkiye	3	8
Uganda	3	8
Russia	3	3
Afghanistan, Argentina, DR Congo, Dominican Republic, Sri Lanka	2	—
Belarus, Ecuador, Honduras, Hungary, Iran, Kazakhstan, Laos, Malaysia, Mexico, Mozambique, Namibia, Oman, Venezuela	1	—
Total	112	66

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. Some restrictions are jointly implemented by multiple countries (e.g., EAEU members), so the per-country policy counts do not sum to the total number of distinct policies reported in the final row. The mineral total reports the number of *distinct* HS6 minerals affected; because the same mineral is often restricted by several countries, the per-country counts exceed this total as well. HS Chapters 25 and 26 consist of 109 mineral products in total.

Table A6. Number of export restriction policies by mineral product

HS Code	Description	Category	# Policies	Lead Country
260111	Iron ores and concentrates, non-agglomerated	Metallic	29	India
260112	Iron ores and concentrates, agglomerated	Metallic	28	India
253090	Mineral substances n.e.s.	Non-Metallic	16	China
260300	Copper ores and concentrates	Metallic	16	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	10	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	Non-Metallic	9	China
260600	Aluminium ores and concentrates	Metallic	8	Indonesia
261400	Titanium ores and concentrates	Metallic	8	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 A7. Distribution of mineral-linked downstream products by sector

Sector	HS Chapter	# of Products	Mineral Downstream Products			Share (%)
			Metallic	Non-Metallic	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		4,315	832	562	1,207	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. Direct effects: export status and destination

	Export Status	# of Destinations	Top Destination Share	Destination HHI
Export Restriction	-0.0237*	-0.0815***	0.0120	0.0126
	(0.0135)	(0.0282)	(0.0101)	(0.0119)
Unit of observation	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	OLS	PPML	OLS	OLS
Pre-treatment Mean	0.970	18.5	0.656	0.553
# 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. Fixed effects are indexed by country i, product k, and year t. Standard errors are clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A9. Downstream effects: export status and destination

	Export Status	# of Destinations	Top Destination Share	Destination HHI
Export Restriction (Up)	0.00466**	0.0289***	-0.00738***	-0.00856***
	(0.00216)	(0.00432)	(0.00185)	(0.00200)
Unit of observation	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	OLS	PPML	OLS	OLS
Pre-treatment Mean	0.843	24.2	0.583	0.471
# of Clusters	724,742	724,742	653,627	653,627
# of Obs.	15,944,324	15,714,045	9,553,122	9,553,122

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. Fixed effects are indexed by country i, product k, and year t. Standard errors are clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A10. Downstream effects: heterogeneity by value-chain position

	Upstream		Midstream		Downstream	
	Value	Quantity	Value	Quantity	Value	Quantity
Export Restriction (Up)	0.142**	0.352***	0.0615	0.111	0.169	0.0213
	(0.0599)	(0.0841)	(0.0623)	(0.0753)	(0.164)	(0.158)
Unit of observation	ikt	ikt	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	PPML	PPML	PPML	PPML	PPML	PPML
# of Clusters	209,278	207,003	236,284	234,538	227,736	225,893
# of Obs.	4,547,377	4,461,528	5,128,569	5,048,124	4,936,749	4,844,842

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. Fixed effects are indexed by country i, product k, and year t. Standard errors are clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A11. Downstream effects: stage 1 versus stages 2 and beyond

	Export Value			Export Quantity		
	Stage 1	Stages 2+	Difference	Stage 1	Stages 2+	Difference
Export Restriction (Up)	0.231***	0.104	0.126	0.361***	0.044	0.317**
	(0.080)	(0.066)	(0.103)	(0.103)	(0.088)	(0.136)
Unit of observation	ikt	ikt		ikt	ikt	
Fixed Effects	ik, it, kt	ik, it, kt		ik, it, kt	ik, it, kt	
Estimator	PPML	PPML		PPML	PPML	
# of Obs.	1,675,297	2,628,948		1,653,040	2,577,336	

Notes: This table reports the estimated effects of upstream mineral export restrictions on exports of downstream products at the first processing stage and at stages 2 and beyond, the static counterpart of Figure 9. Stages 2 and beyond are pooled in a single regression with common fixed effects. The difference column reports the stage-1 coefficient minus the stages-2+ coefficient; because the two groups contain different products, the two estimates are independent under country–product clustering. Dependent variables are export value and quantity, both in levels. Fixed effects are indexed by country i, product k, and year t. Standard errors are clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A12. Sectoral patterns of downstream export response

Sector	HS Chapters	Value	Quantity	Average Upstreamness	Average Complexity	Average Input Complexity
Base Metals	72-83	0.279***	0.397***	3.11	0.249	0.315
		(0.0785)	(0.0957)			
Stone & Glass	68-70	0.0505	0.159	2.48	0.207	0.523
		(0.0773)	(0.104)			
Jewelry & Gems	71	0.101	0.179	2.41	-0.408	0.414
		(0.238)	(0.322)			
Chemicals	28-38	-0.263***	0.326*	3.22	0.446	0.336
		(0.0968)	(0.173)			
Machinery & Electronics	84-85	-0.0107	-0.0412	1.87	0.609	0.522
		(0.105)	(0.0781)			
Transport Equipment	86-89	0.147	0.0277	1.51	0.287	0.402
		(0.223)	(0.180)			
Precision Instruments	90-92	-0.272*	-0.135	1.50	0.723	0.531
		(0.145)	(0.146)			
Others	—	0.0645	0.0712	2.31	-0.602	0.146
		(0.0889)	(0.112)			

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 A13. Downstream effects: heterogeneity by complexity

	Low		Medium		High	
	Value	Quantity	Value	Quantity	Value	Quantity
Export Restriction (Up)	0.406***	0.503***	0.0143	-0.0000	0.0159	0.113*
	(0.0945)	(0.0994)	(0.0661)	(0.0921)	(0.0840)	(0.0658)
Unit of observation	ikt	ikt	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	PPML	PPML	PPML	PPML	PPML	PPML
# of Clusters	168,335	167,265	221,328	219,546	246,499	243,956
# of Obs.	3,646,859	3,595,980	4,807,217	4,727,238	5,354,983	5,244,986

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. Fixed effects are indexed by country i, product k, and year t. Standard errors are clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A14. Downstream effects: heterogeneity by input complexity

	Low		Medium		High	
	Value	Quantity	Value	Quantity	Value	Quantity
Export Restriction (Up)	0.286***	0.402**	0.103	0.144*	0.0738	0.234***
	(0.110)	(0.171)	(0.0826)	(0.0813)	(0.0722)	(0.0807)
Unit of observation	ikt	ikt	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	PPML	PPML	PPML	PPML	PPML	PPML
# of Clusters	160,314	159,134	254,606	252,626	261,539	258,807
# of Obs.	3,464,532	3,412,216	5,527,538	5,438,412	5,679,791	5,561,481

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. Fixed effects are indexed by country i, product k, and year t. Standard errors are clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A15. Effects of export restrictions: OLS estimation

	Targeted Minerals		Downstream Products			
	Value	Quantity	Value	Value	Quantity	Quantity
Export Restriction (Up)			0.180**	0.181**	0.191**	0.192**
			(0.0755)	(0.0753)	(0.0789)	(0.0788)
Export Restriction (Own)	-0.765***	-0.780***		-0.0243		-0.0158
	(0.209)	(0.205)		(0.0433)		(0.0410)
Unit of observation	ikt	ikt	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	OLS	OLS	OLS	OLS	OLS	OLS
# of Clusters	8,634	8,621	439,251	439,251	438,430	438,430
# of Obs.	154,729	153,319	8,130,302	8,130,302	8,052,989	8,052,989

Notes: This table reports the estimated effects of export restrictions on exports of targeted minerals (Columns 1–2) and their downstream products (Columns 3–6). Dependent variables include export value and quantity (in logs). "Export Restriction (Own)" denotes a restriction on the product itself and "(Up)" a restriction on its upstream mineral input. Country–product pairs are weighted by their 2008 export values. Fixed effects are indexed by country i, product k, and year t. Standard errors are clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A16. Bacon decomposition: OLS estimation

	Targeted Minerals		Downstream Products	
Weight Component	Value	Quantity	Value	Quantity
Timing Groups vs. Never-treated	0.971	0.971	0.940	0.940
Between Timing Groups	0.029	0.029	0.060	0.060

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 for the Two-Sector Model

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

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

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

Differentiating the zero-profit condition (8) for Home (with $p_Y = \tau$ fixed) and substituting labor market clearing (10):

$$d\ln w = -\frac{\alpha\beta L_Y + \gamma L_M}{(1-\alpha)\beta L_Y - \gamma L_M}\, d\ln p_M. \tag{B.2}$$

Differentiating the mining supply curve (7) and mineral output $M = R^{\beta} L_M^{1-\beta}$:

$$d\ln M = \frac{(1-\beta)L_Y}{(1-\alpha)\beta L_Y - \gamma L_M}\, d\ln p_M. \tag{B.3}$$

Differentiating manufacturing output (9) and substituting (B.2):

$$d\ln Y = -\frac{\alpha\beta L_Y + (1+\gamma)L_M}{(1-\alpha)\beta L_Y - \gamma L_M}\, d\ln p_M.$$

Home's mineral demand $D_M = \alpha\tau Y/p_M$ satisfies:

$$d\ln D_M = d\ln Y - d\ln p_M = -\frac{\beta L_Y + L_M}{(1-\alpha)\beta L_Y - \gamma L_M}\, d\ln p_M. \tag{B.4}$$

Analogous expressions hold for Foreign with (L_M^*, L_Y^*) replacing (L_M, L_Y), $d\ln p_M^*$ replacing $d\ln p_M$, and all signs reversed accordingly.

B.1.1 Proof of Proposition 1

Step 1: Home mineral market. Let $s_M \equiv D_M/M$ be the share of Home mineral output consumed domestically. Differentiating (11) and substituting (B.3) and (B.4):

$$\frac{(1-\beta)L_Y}{(1-\alpha)\beta L_Y - \gamma L_M}\, d\ln p_M = -s_M \cdot \frac{\beta L_Y + L_M}{(1-\alpha)\beta L_Y - \gamma L_M}\, d\ln p_M + (1-s_M)\, d\ln X_M.$$

Solving for $d\ln X_M$:

$$d\ln X_M = \varepsilon_M \, d\ln p_M, \quad \varepsilon_M \equiv \frac{(1-\beta)L_Y + s_M(\beta L_Y + L_M)}{(1-s_M)[(1-\alpha)\beta L_Y - \gamma L_M]} > 0, \tag{B.5}$$

where ε_M is Home's mineral export supply elasticity with respect to the domestic mineral price.

Step 2: Foreign mineral market. Let $s_M^* \equiv M^*/(M^* + X_M/\tau)$ be Foreign's mineral self-sufficiency share. Differentiating (12) and applying the Foreign analogues of (B.3) and (B.4), then substituting (B.5):

$$\varepsilon_M \, d\ln p_M = -\varepsilon_M^* \, d\ln p_M^*, \quad \varepsilon_M^* \equiv \frac{\beta L_Y^* + L_M^* + s_M^*(1-\beta)L_Y^*}{(1-s_M^*)[(1-\alpha)\beta L_Y^* - \gamma L_M^*]} > 0,$$

where ε_M^* is the absolute value of Foreign's mineral import demand elasticity with respect to the world mineral price.

Step 3: World price. Substituting (B.1):

$$\varepsilon_M \left(d\ln p_M^* - \frac{dt}{1-t} \right) = -\varepsilon_M^* \, d\ln p_M^*.$$

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

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

Substituting back into (B.1):

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

□

B.1.2 Proof of Proposition 2

Wages. Substituting $d\ln p_M/dt = (\Phi-1)/(1-t)$ from Proposition 1 into (B.2):

$$\frac{d\ln w}{dt} = -\frac{\alpha\beta L_Y + \gamma L_M}{(1-\alpha)\beta L_Y - \gamma L_M} \cdot \frac{\Phi - 1}{1-t} > 0.$$

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

$$\frac{d\ln w^*}{dt} = -\frac{\alpha\beta L_Y^* + \gamma L_M^*}{(1-\alpha)\beta L_Y^* - \gamma L_M^*} \cdot \frac{\Phi}{1-t} < 0.$$

Employment. Differentiating the labor market clearing condition (10), substituting the wage response from (B.2), and using $d\ln p_M/dt = (\Phi-1)/(1-t)$:

$$\frac{d\ln L_Y}{dt} = -\frac{L_M}{(1-\alpha)\beta L_Y - \gamma L_M}\cdot\frac{\Phi-1}{1-t} > 0.$$

The Foreign analogue gives:

$$\frac{d\ln L_Y^*}{dt} = -\frac{L_M^*}{(1-\alpha)\beta L_Y^* - \gamma L_M^*}\cdot\frac{\Phi}{1-t} < 0.$$

Output. Differentiating the manufacturing output equation (9):

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

Substituting the wage and employment responses derived above and $d\ln p_M/dt = (\Phi-1)/(1-t)$, then collecting terms:

$$\frac{d\ln Y}{dt} = -\frac{\alpha\beta L_Y + (1+\gamma)L_M}{(1-\alpha)\beta L_Y - \gamma L_M}\cdot\frac{\Phi-1}{1-t} > 0.$$

The Foreign analogue gives:

$$\frac{d\ln Y^*}{dt} = -\frac{\alpha\beta L_Y^* + (1+\gamma)L_M^*}{(1-\alpha)\beta L_Y^* - \gamma L_M^*}\cdot\frac{\Phi}{1-t} < 0.$$

□

B.1.3 Proof of Proposition 3

Elasticity definitions. Proposition 2 implies that manufacturing output and employment satisfy $d\ln Y = -\varepsilon_Y\, d\ln p_M$ and $d\ln L_Y = -\varepsilon_L\, d\ln p_M$, respectively, where

$$\varepsilon_Y \equiv -\frac{d\ln Y}{d\ln p_M} = \frac{\alpha\beta L_Y + (1+\gamma)L_M}{(1-\alpha)\beta L_Y - \gamma L_M} > 0, \tag{B.6}$$

$$\varepsilon_L \equiv -\frac{d\ln L_Y}{d\ln p_M} = \frac{L_M}{(1-\alpha)\beta L_Y - \gamma L_M} > 0, \tag{B.7}$$

where the sign follows from the stability condition $(1-\alpha)\beta L_Y > \gamma L_M$ and the positivity of the numerator. From (B.5), mineral exports satisfy $d\ln X_M = \varepsilon_M\, d\ln p_M$, where $\varepsilon_M > 0$.

Welfare decomposition. Differentiating (18) logarithmically and using $s_Y \equiv Y/C$:

$$dW = d\ln C = s_Y\, d\ln Y + (1-s_Y)\left(d\ln p_M^* + d\ln X_M\right).$$

Substituting the elasticity definitions:

$$dW = -s_Y\,\varepsilon_Y\, d\ln p_M + (1-s_Y)\left(d\ln p_M^* + \varepsilon_M\, d\ln p_M\right).$$

Rearranging:

$$dW = (1-s_Y)\, d\ln p_M^* - s_Y\,\varepsilon_Y\, d\ln p_M + (1-s_Y)\,\varepsilon_M\, d\ln p_M.$$

From Proposition 1, $d\ln p_M = (\Phi-1)\,dt/(1-t)$ and $d\ln p_M^* = \Phi\, dt/(1-t)$. Substituting:

$$\begin{aligned}\frac{dW}{dt} &= (1-s_Y)\cdot\frac{\Phi}{1-t} - s_Y\,\varepsilon_Y\cdot\frac{\Phi-1}{1-t} + (1-s_Y)\,\varepsilon_M\cdot\frac{\Phi-1}{1-t}\\ &= \frac{1}{1-t}\left[(1-s_Y)\Phi + s_Y\,\varepsilon_Y\,(1-\Phi) - (1-s_Y)\,\varepsilon_M\,(1-\Phi)\right].\end{aligned}$$

Wedge form. The last two terms can be expressed in terms of the scale externality γ and the export tax t, as reallocations valued at private prices cancel out. From (B.6) and (B.7),

$$\varepsilon_Y - \gamma\,\varepsilon_L = \frac{\alpha\beta L_Y + L_M}{(1-\alpha)\beta L_Y - \gamma L_M}.$$

From (18), $s_Y = Y/C$ and $1-s_Y = p_M^* X_M/(\tau^2 C)$. Combining these with (4) and $p_Y = \tau$ yields

$$(1-t)\frac{1-s_Y}{s_Y} = \frac{p_M X_M}{p_Y Y}.$$

Competitive factor payments imply $wL_M = (1-\beta)p_M M$ and $wL_Y = (1-\alpha)p_Y Y$, giving

$$\frac{p_M M}{p_Y Y} = \frac{(1-\alpha)L_M}{(1-\beta)L_Y}, \qquad s_M = \frac{\alpha(1-\beta)L_Y}{(1-\alpha)L_M}.$$

Using $X_M = (1-s_M)M$ and (B.5),

$$(1-t)\frac{1-s_Y}{s_Y}\varepsilon_M = \frac{p_M M}{p_Y Y}\cdot\frac{(1-\beta)L_Y + s_M(\beta L_Y + L_M)}{(1-\alpha)\beta L_Y - \gamma L_M} = \frac{(1-\alpha)L_M + \alpha(\beta L_Y + L_M)}{(1-\alpha)\beta L_Y - \gamma L_M} = \varepsilon_Y - \gamma\varepsilon_L.$$

Rearranging gives

$$s_Y\,\varepsilon_Y-(1-s_Y)\varepsilon_M=s_Y\,\gamma\,\varepsilon_L-(1-s_Y)t\,\varepsilon_M.$$

Substituting this identity into the preceding expression yields (19). □

B.1.4 Proof of Corollary 1

Setting $dW/dt=0$ in Proposition 3 yields

$$(1-s_Y)\,\Phi+s_Y\,\gamma\,\varepsilon_L\,(1-\Phi)=(1-s_Y)\,t\,\varepsilon_M\,(1-\Phi).$$

Solving for t gives the first expression in (20), with all equilibrium variables evaluated at t^*. To characterize the welfare effect away from the optimum, define

$$T(t)\equiv\frac{(1-s_Y)\,\Phi+s_Y\,\gamma\,\varepsilon_L\,(1-\Phi)}{(1-s_Y)(1-\Phi)\,\varepsilon_M},$$

where the equilibrium variables on the right-hand side are evaluated at tax rate t. Proposition 3 can then be written as

$$\frac{dW}{dt}=\frac{(1-s_Y)(1-\Phi)\,\varepsilon_M}{1-t}\big[T(t)-t\big].$$

Since $(1-s_Y)(1-\Phi)\,\varepsilon_M>0$, the sign of dW/dt is determined by $T(t)-t$. Any interior optimum tax rate t^* must therefore satisfy the fixed-point condition $t^*=T(t^*)$.

At $t=0$, the welfare derivative becomes

$$\left.\frac{dW}{dt}\right|_{t=0}=\left[(1-s_Y)\,\Phi+s_Y\,\gamma\,\varepsilon_L\,(1-\Phi)\right]_{t=0}.$$

Since $\Phi\in(0,1)$ by Proposition 1 and $\gamma\varepsilon_L\geq 0$, the welfare derivative is strictly positive at $t=0$. Hence, a small mineral export tax raises Home welfare.

Rearranging the first expression in (20) gives

$$t^*=\frac{\Phi}{(1-\Phi)\,\varepsilon_M}+\gamma\,\frac{s_Y\,\varepsilon_L}{(1-s_Y)\,\varepsilon_M},$$

with all equilibrium variables evaluated at t^*.

By the definition of Φ in Proposition 1, $\Phi/(1-\Phi)=\varepsilon_M/\varepsilon_M^*$, so the first term reduces to $1/\varepsilon_M^*$, yielding the second expression in (20).

□

B.2 Proofs for the Multi-Stage Model

B.2.1 Proof of Proposition 4

With $\Phi = 0$, Home is small in world markets at every stage, leaving all Foreign prices and quantities unaffected by the policy: $d \ln p_k^* = d \ln Y_k^* = 0$. I denote stage-$k$ employment by $L_{Y,k}$ and use the price pass-throughs ρ_k and employment elasticities $\varepsilon_{L,k}$ defined in the main text. In addition, let $\rho_w \equiv d \ln w / d \ln p_M$ and $\hat{x} \equiv d \ln x / d \ln p_M$ for any other variable x. I normalize $\rho_0 = 1$ and define $Y_0 \equiv M$. Since minerals are homogeneous and exported by Home, first-stage producers purchase them at the domestic price p_M, implying $P_0 = p_M$ and $s_0 = 1$.

Price recursion. Perfect competition with scale economies drives price to unit cost at stage k:

$$p_k = \frac{1}{\alpha^\alpha (1-\alpha)^{1-\alpha}} \cdot \frac{P_{k-1}^\alpha \, w^{1-\alpha}}{A_k \, L_{Y,k}^{\gamma_k}}, \qquad P_{k-1} = \left(p_{k-1}^{1-\sigma} + (\tau p_{k-1}^*)^{1-\sigma} \right)^{\frac{1}{1-\sigma}},$$

where P_{k-1} is the CES price index of the stage-$(k-1)$ composite faced by Home buyers. Log-differentiating with respect to $\ln p_M$:

$$\rho_k = \alpha \, \widehat{P}_{k-1} + (1-\alpha) \, \rho_w + \gamma_k \, \varepsilon_{L,k}. \tag{B.8}$$

The CES index satisfies $\widehat{P}_{k-1} = s_{k-1} \, \rho_{k-1}$, since Foreign prices are fixed. Substituting into (B.8) and reindexing $k \to k+1$ yields (25).

Employment recursion. Cobb–Douglas production with labor share $1-\alpha$ implies $w L_{Y,k} = (1-\alpha) p_k \, Y_k$ (the same log-form holds for mining, with share $1-\beta$), so

$$\hat{Y}_k = \rho_w - \varepsilon_{L,k} - \rho_k. \tag{B.9}$$

Market clearing $Y_k = D_k^H + X_k$, with $\phi_k \equiv X_k / Y_k$, gives in log-derivatives:

$$\hat{Y}_k = (1-\phi_k) \, \widehat{D_k^H} + \phi_k \, \widehat{X_k}. \tag{B.10}$$

Home stage-$(k+1)$ firms' demand for the Home stage-k variety is $D_k^H = (p_k / P_k)^{-\sigma} \, Q_k^H$ with $Q_k^H = \alpha p_{k+1} \, Y_{k+1} / P_k$. Differentiating, using $\widehat{P}_k = s_k \, \rho_k$ and (B.9) at stage $k+1$:

$$\widehat{D_k^H} = -\big[\sigma(1-s_k) + s_k \big] \rho_k + \rho_w - \varepsilon_{L,k+1}. \tag{B.11}$$

Because Home's share in Foreign's composite is negligible, Foreign demand for the Home variety is iso-elastic:

$$\widehat{X_k} = -\sigma\,\rho_k. \tag{B.12}$$

Substituting (B.9), (B.11), and (B.12) into (B.10) and solving for $(1-\phi_k)\varepsilon_{L,k+1}$:

$$(1-\phi_k)\,\varepsilon_{L,k+1} = \varepsilon_{L,k} - \phi_k\,\rho_w + \Big[1-(1-\phi_k)\big(\sigma(1-s_k)+s_k\big) - \phi_k\,\sigma\Big]\rho_k.$$

The bracketed coefficient simplifies to $(1-\sigma)\big[1-s_k(1-\phi_k)\big]$, which gives (26) for $k \geq 1$.

Mineral stage ($k=0$). Unlike differentiated processed goods, minerals are homogeneous and traded at a fixed world price, so the iso-elastic export demand in (B.12) does not apply. Instead, mineral exports respond with elasticity $\widehat{X_M} = \varepsilon_M$. Since first-stage producers use only domestic minerals, $s_0 = 1$, and (B.11) reduces to $\widehat{D_0^H} = -1 + \rho_w - \varepsilon_{L,1}$. Substituting these expressions and (B.9) at $k=0$, with $\rho_0 = 1$, into (B.10) yields

$$(1-\phi_0)\,\varepsilon_{L,1} = \varepsilon_{L,0} - \phi_0\,\rho_w + \phi_0\,(1+\varepsilon_M),$$

which is the employment recursion with ε_M replacing $-\sigma$, as stated in Proposition 4. □

B.2.2 Proof of Proposition 5

Home welfare is $W = \ln C$, where $C = I/P_C$, so $dW = d\ln I - d\ln P_C$. The derivation allows for arbitrary Φ. In the multi-stage economy, ε_M and ε_M^* denote the general equilibrium elasticities of Home's mineral export supply and Foreign's mineral import demand, rather than the two-sector expressions derived in the proof of Proposition 1. Since the price wedge (4) and mineral market clearing, $\varepsilon_M\,d\ln p_M = d\ln X_M = -\varepsilon_M^*\,d\ln p_M^*$, take the same form as in the two-sector model, Step 3 of that proof applies unchanged: $d\ln p_M/dt = -(1-\Phi)/(1-t)$ and $d\ln p_M^*/dt = \Phi/(1-t)$, with $\Phi \equiv \varepsilon_M/(\varepsilon_M+\varepsilon_M^*)$.

Income and value added. Home's income is $I = wL + \beta p_M M + t\,(p_M^*/\tau)X_M$, as in (5). Mining rents satisfy $\beta p_M M = p_M M - wL_M$, while zero profits at each manufacturing stage imply $p_k Y_k = P_{k-1}Q_{k-1} + wL_{Y,k}$, where Q_{k-1} and P_{k-1} denote the intermediate input composite and its price index. Hence,

$$wL + \beta p_M M = \sum_{k=0}^{N} v_k, \qquad v_0 \equiv p_M M, \quad v_k \equiv p_k Y_k - P_{k-1}Q_{k-1},$$

where v_k denotes value added at stage k, with $Y_0 \equiv M$ and $P_0 = p_M$.

Aggregating production across firms, $Y_k = A_k Q_{k-1}^{\alpha} L_{Y,k}^{1-\alpha+\gamma_k}$. Cost minimization gives $P_{k-1}Q_{k-1} = \alpha p_k Y_k$ and $wL_{Y,k} = (1-\alpha)p_k Y_k$. Differentiating the production function and substituting these conditions:

$$p_k\, dY_k = P_{k-1}\, dQ_{k-1} + w\, dL_{Y,k} + \gamma_k\, p_k\, Y_k\, d\ln L_{Y,k}.$$

For mining, $p_M\, dM = w\, dL_M$. Differentiating value added therefore yields

$$dv_k = Y_k\, dp_k - Q_{k-1}\, dP_{k-1} + w\, dL_{Y,k} + \gamma_k\, p_k\, Y_k\, d\ln L_{Y,k}, \qquad dv_0 = M\, dp_M + w\, dL_M.$$

Welfare decomposition. By Shephard's lemma, $Q_{k-1}\, dP_{k-1} = D_{k-1}^H\, dp_{k-1} + \tau X_{k-1}^*\, dp_{k-1}^*$ for $k \geq 2$, while $Q_0\, dP_0 = D_0^H\, dp_M$. Summing value added across stages, the labor terms cancel by labor market clearing, and the domestic intermediate price terms cancel between consecutive stages. Using $M = D_0^H + X_M$ and $Y_k = D_k^H + X_k$ gives

$$\sum_{k=0}^{N} dv_k = D_N^H\, dp_N + X_M\, dp_M + \sum_{k=1}^{N} X_k\, dp_k - \sum_{k=1}^{N-1} \tau X_k^*\, dp_k^* + \sum_{k=1}^{N} \gamma_k\, p_k\, Y_k\, d\ln L_{Y,k}.$$

From the mineral price wedge (4), $p_M + t\, p_M^*/\tau = p_M^*/\tau$. Combining the mineral price terms with the change in tax revenue:

$$X_M\, dp_M + d\left(t\,\frac{p_M^*}{\tau} X_M\right) = X_M\, d\left(\frac{p_M^*}{\tau}\right) + t\,\frac{p_M^*}{\tau}\, dX_M.$$

By Shephard's lemma, the final consumption price index satisfies $C\, dP_C = D_N^H\, dp_N + \tau X_N^*\, dp_N^*$. Substituting into $dW = (dI - C\, dP_C)/I$ cancels the remaining domestic final-good price term. Using the expenditure shares defined in Proposition 5:

$$dW = \xi_0\, d\ln p_M^* + \sum_{k=1}^{N} \xi_k\, d\ln p_k - \sum_{k=1}^{N} \mu_k\, d\ln p_k^* + \sum_{k=1}^{N} \gamma_k\, \lambda_k\, d\ln L_{Y,k} + \xi_0\, t\, d\ln X_M. \tag{B.13}$$

Elasticity form. Using these price responses and the definitions of the price pass-throughs and employment elasticities, $d\ln p_k = \rho_k\, d\ln p_M$, $d\ln p_k^* = \rho_k^*\, d\ln p_M^*$, $d\ln L_{Y,k} = -\varepsilon_{L,k}\, d\ln p_M$, and $d\ln X_M = \varepsilon_M\, d\ln p_M$. Substituting into (B.13) yields (28). With $N = 1$ and homogeneous manufactures, $\xi_1 = 0$, $\rho_1^* = 0$, and $I = \tau C$. Hence, $\xi_0 = 1 - s_Y$ and $\lambda_1 = s_Y$, so (28) reduces to (19).

□

B.2.3 Proof of Proposition 6

From the labor cost share condition $wL_{Y,k} = (1-\alpha)p_k Y_k$,

$$\lambda_k = \frac{p_k Y_k}{I} = \frac{wL_{Y,k}}{(1-\alpha)I} = \frac{\theta_L n_k}{1-\alpha},$$

where $n_k \equiv L_{Y,k}/L$ and $\theta_L \equiv wL/I$. Substituting into the Pigouvian term of Proposition 5:

$$\sum_k \gamma_k \lambda_k \varepsilon_{L,k} = \frac{\theta_L}{1-\alpha} \sum_k \gamma_k n_k \varepsilon_{L,k}.$$

Adding and subtracting $\bar{\gamma} \sum_k n_k \varepsilon_{L,k}$ gives (29). Since $\bar{\gamma}$ is the employment-weighted average, $\sum_k (\gamma_k - \bar{\gamma}) n_k = 0$, so the second term equals $\sum_k n_k (\gamma_k - \bar{\gamma})(\varepsilon_{L,k} - \bar{\varepsilon}_L)$ for $\bar{\varepsilon}_L \equiv \sum_k n_k \varepsilon_{L,k} / \sum_k n_k$, which is zero when $\varepsilon_{L,k}$ is the same across stages.

If workers are drawn from a sector o with scale elasticity γ_o and the same labor cost share, its contribution to the Pigouvian term is $\theta_L \gamma_o n_o \varepsilon_{L,o}/(1-\alpha)$, where $n_o \equiv L_o/L$ and $\varepsilon_{L,o} \equiv -d \ln L_o / d \ln p_M$. Since the labor force is fixed and all additional manufacturing workers come from sector o, labor market clearing implies

$$n_o \varepsilon_{L,o} = -\sum_k n_k \varepsilon_{L,k}.$$

Combining the source and destination effects gives

$$\frac{\theta_L}{1-\alpha} \sum_k (\gamma_k - \gamma_o) n_k \varepsilon_{L,k},$$

so the relevant scale elasticity is $\gamma_k - \gamma_o$.

□

C Measuring Relative Downstreamness in AIPNET

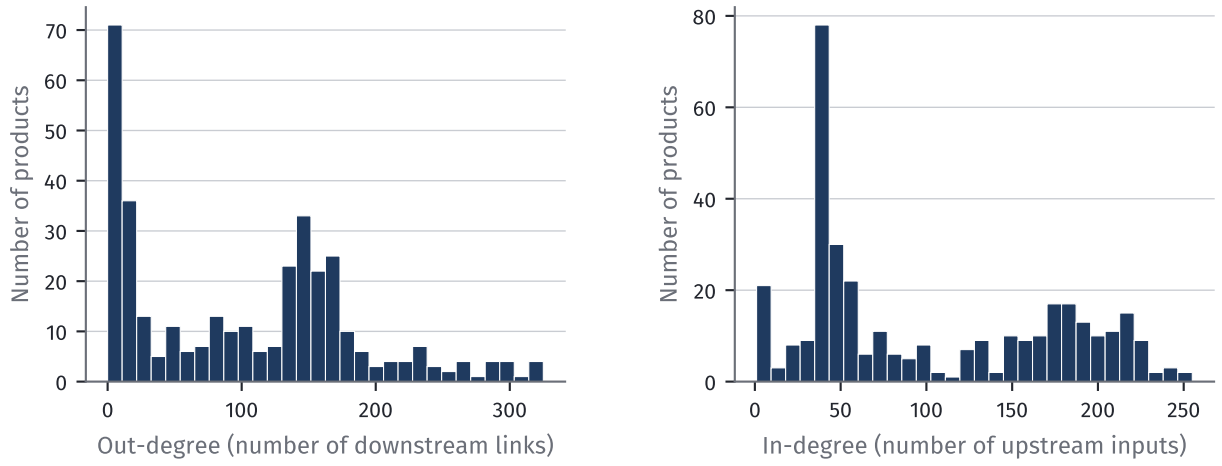
This appendix details the construction of the relative downstreamness measure used in the empirical analysis. The objective is to characterize the internal structure of production stages among mineral-related downstream products associated with a given upstream mineral input, and to establish a well-defined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

Setup. 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 starting from each upstream mineral u. 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 C1. 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 C1 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 Tarjan's 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. Tarjan's 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.

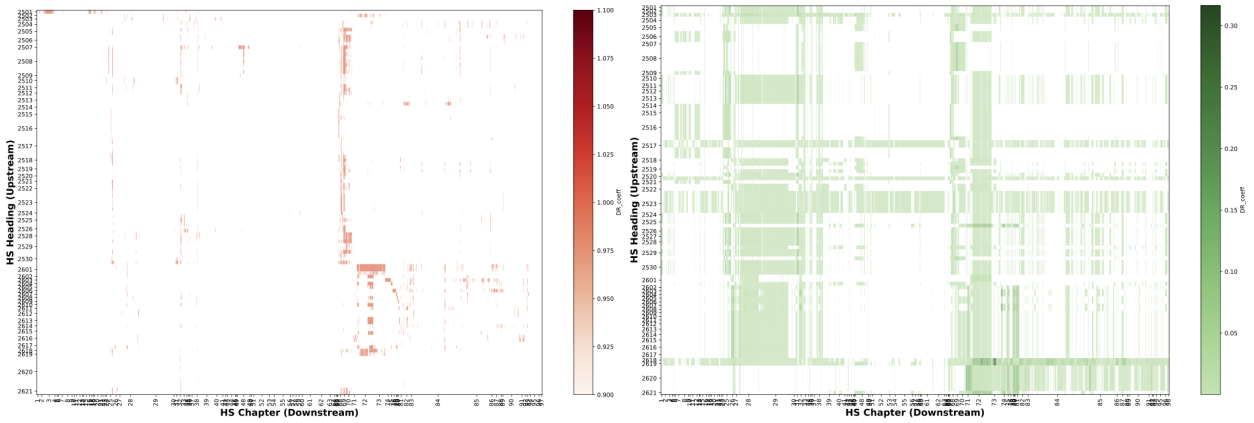
Second, across countries, the same downstream product may face different minimum exposure distances, reflecting cross-country variation in the set of upstream minerals subject to export restrictions. At the same time, downstream products in the never-treated group must also be assigned an exposure level 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 observed in the sample, taking the larger value in case of ties. 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 taking the smaller value or excluding these products altogether.

D 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).

D.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 D1. Full downstream linkages of raw minerals

Figure D1 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 HS6 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 D1. Predicting AIPNET linkages using BEA coefficients

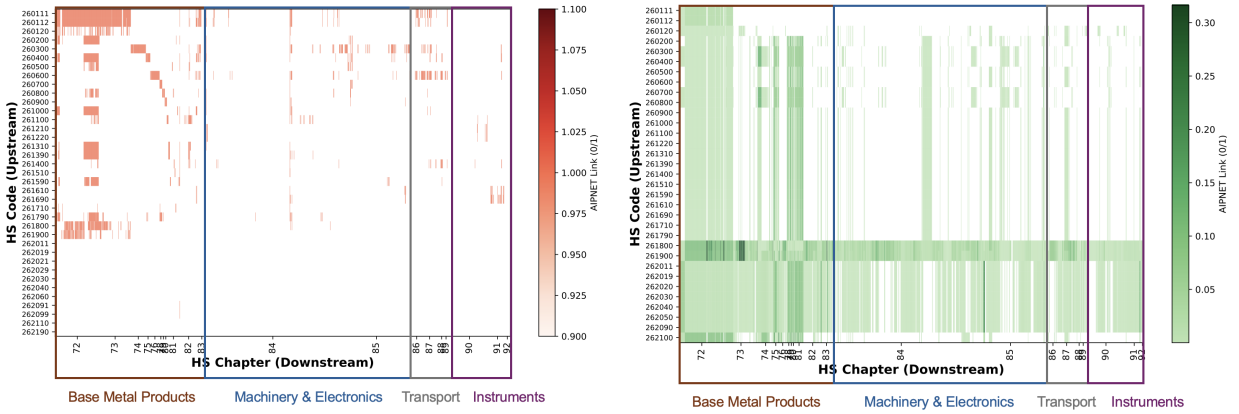
	$Link_{ij}$	$Link_{ij}$	$Link_{ij}$	$Link_{ij}$	$Link_{ij}$
DR_{ij}	14.902***	0.753***	0.740***	0.723***	0.738***
	(1.541)	(0.154)	(0.141)	(0.180)	(0.158)
Input FE			✓		✓
Output FE				✓	✓
Estimator	Logit	OLS	OLS	OLS	OLS
(Pseudo-)R^2	0.0375	0.0152	0.0969	0.194	0.256
# of Obs.	123,089	123,089	123,089	123,082	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 D1, the two datasets exhibit a significant positive association at the HS6 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.

D.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.

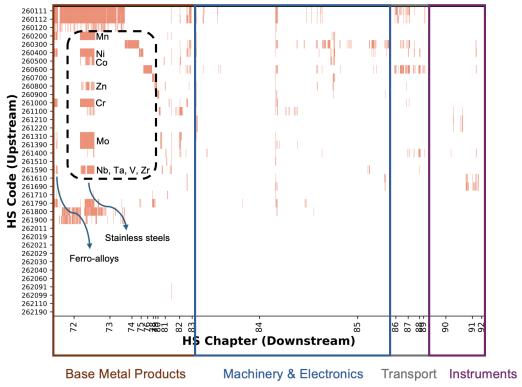


(a) AIPNET (b) BEA IO Table

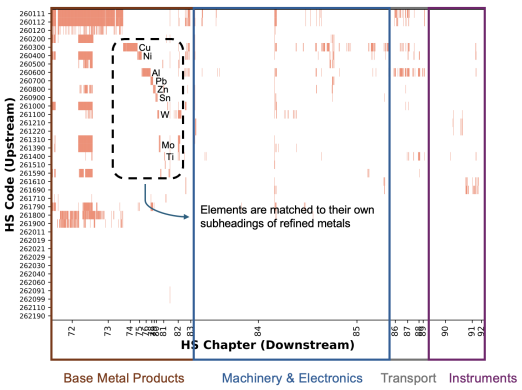
Figure D2. Downstream linkages of metal ores in selected industries

Figure D2 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.

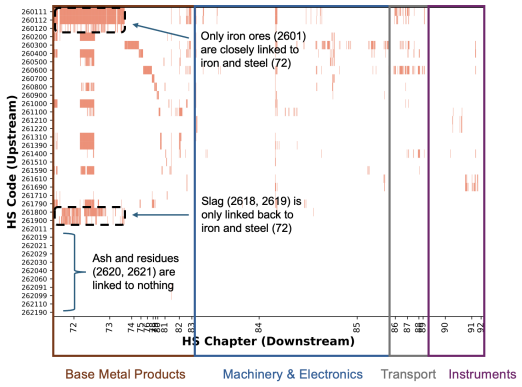
AIPNET continues to provide substantially more disaggregated product-level linkage information than the BEA input–output table, even within this targeted subset of downstream industries. In particular, it outperforms along four key dimensions:



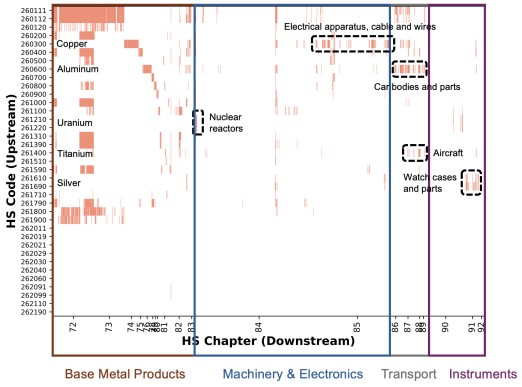
1. Identifying ferro-alloy elements.
Ferro-alloys and stainless steels constitute a substantial share of base metal products. Consequently, elements that form commercially viable alloys with iron exhibit distinct downstream linkages compared to those that do not. AIPNET clearly identifies such elements 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.

E Domestic Production

This appendix examines the effects of mineral export restrictions on domestic production. Because direct product-level data on downstream output are not available, I rely on two indirect tests. First, building on the finding that export restrictions reduce raw mineral exports while increasing downstream exports, I test whether domestic mining output remains stable. If so, this would suggest that minerals are being diverted from export markets to domestic processing. Second, I test whether imports of downstream products fall, which would provide complementary evidence of expanding domestic manufacturing.

E.1 Domestic Mineral Production

Virtually all countries that impose mineral export restrictions are producers of the targeted minerals, and most raw minerals require processing before they can be used. These two features let mine production serve as an indirect window onto domestic processing. Since exports of the targeted mineral fall after a restriction, mine production that holds steady implies that a growing share of output is retained at home; and because most of these minerals have little direct end use, this retained output must feed domestic processing. This inference assumes that inventories do not accumulate substantially, so that the gap between production and exports reflects increased demand from domestic processing rather than stockpiling. For the minerals considered here, this assumption is plausible because their low value-to-weight ratios make storage costly, while uncertainty regarding the duration of export restrictions discourages speculative accumulation.

Mine production data come from the British Geological Survey's *World Mineral Statistics*, which report annual production quantities by country and mineral commodity. I use data from 2002 to 2023, consistent with the main analysis period, and match 47 mineral production series to products classified under HS Chapters 25 and 26.[1] For each country–mineral pair, treatment begins with the first export restriction imposed on any of its matched HS codes. The resulting panel covers 168 countries, of which 22 impose export restrictions on at least one of 41 minerals, yielding 108 treated country–mineral pairs. As a robustness check, Table E2 replicates the analysis using the U.S. Geological Survey's *Mineral Commodity Summaries*.

Table E1 reports the estimated effects of mineral export restrictions on domestic mineral production. The baseline estimate is small and statistically insignificant, and the results remain

[1] Production series are matched to the corresponding six-digit HS codes of raw minerals. For example, iron ore is matched to HS 2601.11–2601.12 and bauxite to HS 2606.00. Cement and cement clinker are also included because they fall under HS Chapter 25 (HS 2523); Column (3) of Table E1 excludes these products.

Table E1. Effects of mineral export restrictions on domestic mine production

	Baseline	Log OLS	Excl. Cement
Export Restriction	-0.0944	0.148	-0.0818
	(0.102)	(0.114)	(0.112)
Unit of observation	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	PPML	OLS	PPML
# of Clusters	1,678	1,661	1,615
# of Obs.	30,800	29,443	29,568

Notes: This table reports estimates of the effects of mineral export restrictions on domestic mine production of targeted minerals, using the British Geological Survey's *World Mineral Statistics* for 2002–2023. The dependent variable is mine production quantity in levels (Columns 1 and 3) or in logs (Column 2). Fixed effects are indexed by country i, mineral k, and year t. Standard errors are clustered at the country–mineral level. World Mineral Statistics contributed by permission of the British Geological Survey. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table E2. Effects of mineral export restrictions on domestic mine production: USGS data

	Baseline	Balanced Panel		Interpolated Panel	
		All Countries	Excl. Residual	All Countries	Excl. Residual
Export Restriction	-0.0272	-0.0673	0.0399	-0.0284	0.0720
	(0.349)	(0.357)	(0.409)	(0.345)	(0.376)
Unit of observation	ikt	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
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, using the U.S. Geological Survey *Mineral Commodity Summaries*. The dependent variable is mine production quantity in levels. Fixed effects are indexed by country i, mineral k, and year t. Standard errors are clustered at the country–mineral level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

similar when excluding cement or using log-linear OLS, with the coefficient turning positive under the latter specification. The 95 percent confidence interval rules out average declines in production exceeding approximately 25 percent, substantially smaller than the 56 percent reduction in export quantities of targeted minerals (Table 1). The event study in Figure E1 shows no evidence of differential pre-trends. Although the estimates turn negative and are statistically significant three to four years after the restriction, they subsequently move back toward zero. Taken together, these findings suggest that the sharp decline in mineral exports was not accompanied by a comparable contraction in domestic production, consistent with a larger share of mineral output being retained for domestic processing.

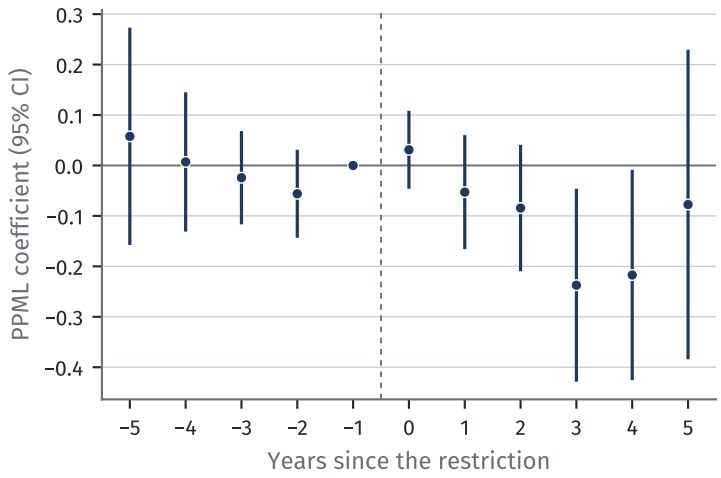


Figure E1. Domestic mine production: event study

Notes: This figure plots the dynamic effects of mineral export restrictions on domestic mine production of the targeted minerals, based on a PPML event-study regression on the sample of Table E1 (BGS *World Mineral Statistics*, 2002–2023). Bars represent 95% confidence intervals, with standard errors clustered at the country–mineral level. World Mineral Statistics contributed by permission of the British Geological Survey.

E.2 Downstream Imports

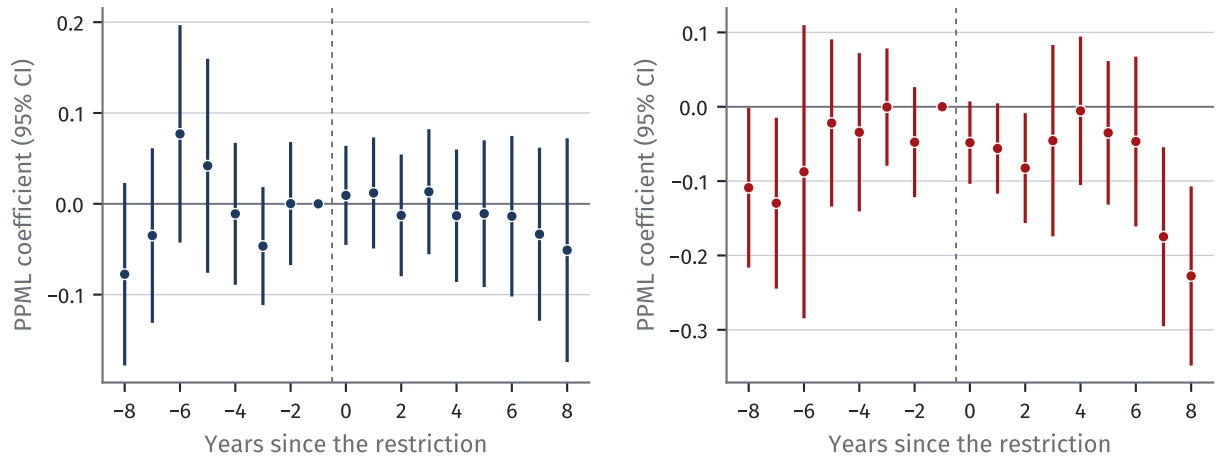
Table E3. Effects of mineral export restrictions on downstream imports

	Import Value		Import Quantity		Unit Value
Export Restriction (Up)	-0.00897	-0.00903	-0.0656	-0.0627	-0.00172
	(0.0356)	(0.0356)	(0.0616)	(0.0607)	(0.00685)
Export Restriction (Own)		0.00568		-0.0769	
		(0.0308)		(0.0649)	
Unit of observation	ikt	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	PPML	PPML	PPML	PPML	OLS
# of Obs.	18,370,288	18,370,288	18,164,770	18,164,770	14,482,727

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

I now examine how mineral export restrictions affect downstream imports, an indirect indicator of domestic production. The analysis mirrors the baseline but substitutes import data for export data, using otherwise identical datasets and specifications. As Table E3 shows, mineral export restrictions have no statistically significant effect on downstream imports. The estimated

coefficients are close to zero for import value and modestly negative for import quantity, while the event study in Figure E2 shows no systematic response following the restrictions. These findings provide little evidence of widespread import substitution in downstream products. At the same time, the absence of a comparable decline in imports, alongside the increase in downstream exports documented in Section 6, is consistent with an expansion of domestic production, although changes in domestic absorption cannot be ruled out. Figure E3 further examines heterogeneity by technological complexity and input complexity. The largest import decline occurs among products with the least complex inputs, for which import value falls by 36 percent. This is also the group exhibiting the strongest export response, indicating that import substitution may accompany export expansion in relatively simple processing activities. Across complexity terciles, however, import responses are small and statistically insignificant. Overall, these findings suggest that downstream export gains are not generally accompanied by import substitution, except potentially in products with relatively simple inputs.

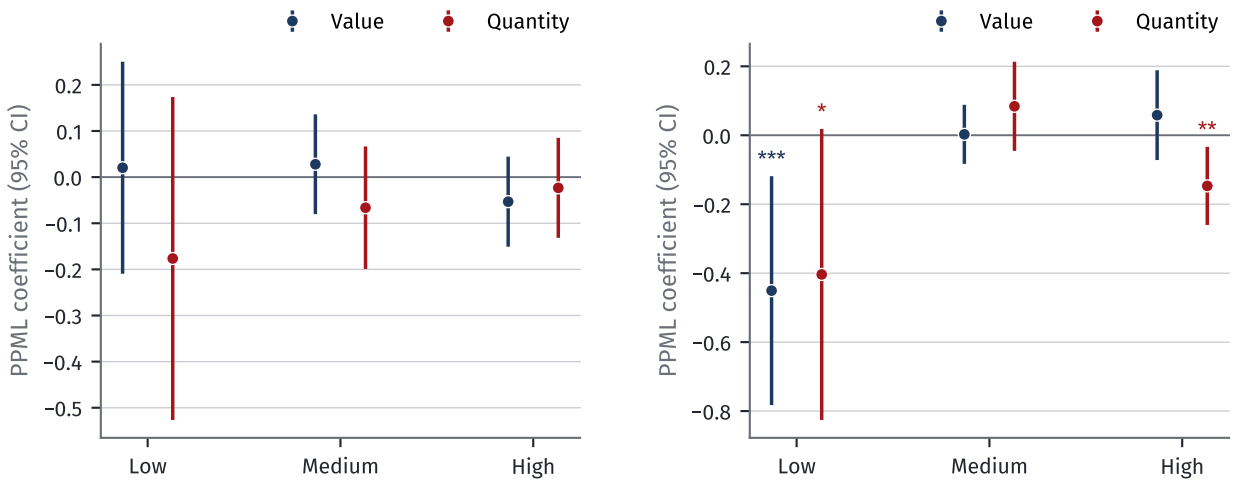


(a) Import Value

(b) Import Quantity

Figure E2. Downstream imports: event study

Notes: This figure plots the dynamic effects of upstream mineral export restrictions on imports 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 complexity

Figure E3. Downstream imports: product and input complexity

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 complexity (the average complexity of upstream inputs), and treatment effects are estimated separately for each group. Bars denote 95% confidence intervals, with standard errors clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

F 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.

F.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 A2 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 Equations (30) and (31). 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.

F.2 Direct Effects

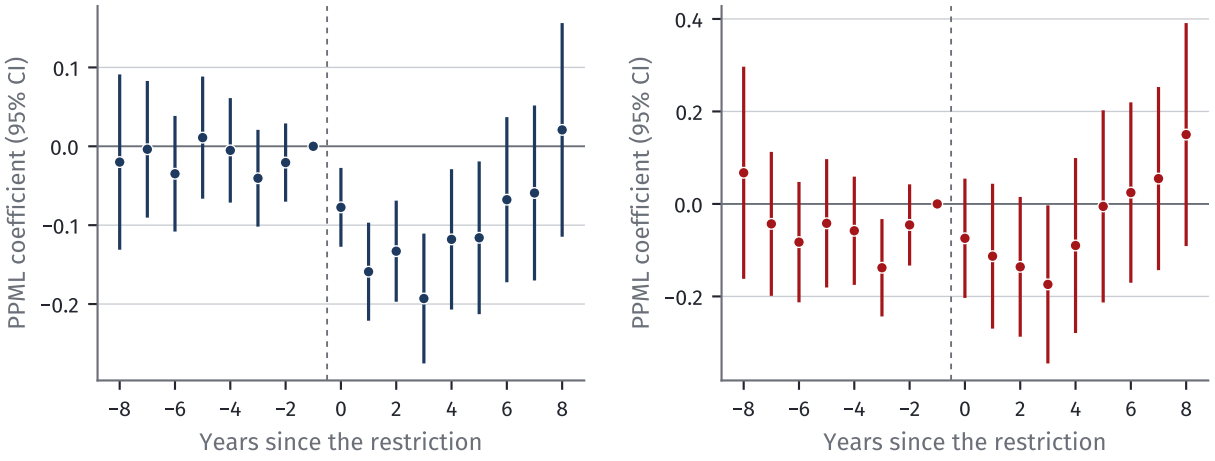
Table F1 reports the direct effects of export restrictions on the targeted agricultural products. While the restrictions do lead to a reduction in exports, the estimated effects are smaller in magnitude and less statistically significant compared to those reported in Table 1.

[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 F1. Direct effects of agricultural export restrictions

	Export Value	Export Quantity	Unit Value
Export Restriction	-0.0988***	-0.0312	-0.00560
	(0.0376)	(0.0854)	(0.0127)
Unit of observation	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	PPML	PPML	OLS
# of Clusters	122,516	121,955	109,424
# of Obs.	2,669,699	2,648,227	1,578,042

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). Fixed effects are indexed by country i, product k, and year t. 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 F1. 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 F1 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.

F.3 Downstream Effects

I then examine whether export restrictions on agricultural products generate export-stimulating effects for downstream products. The estimates reported in Table F2 provide a clear negative answer: all coefficients on upstream restrictions are statistically insignificant, and those for export values are even negative. In short, export restrictions on agricultural products do not give rise to any measurable downstream export effects.

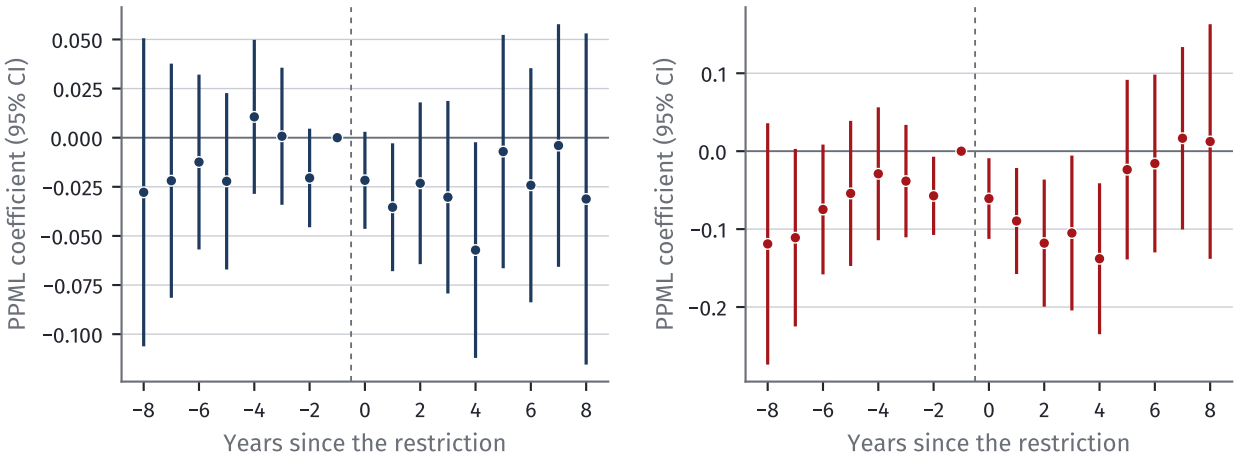
Table F2. Downstream effects of agricultural export restrictions

	Export Value		Export Quantity		Unit Value	
Export Restriction (Up)	-0.0162	-0.00496	-0.00909	-0.00399	0.00751	0.00775
	(0.0295)	(0.0295)	(0.0588)	(0.0593)	(0.00672)	(0.00674)
Export Restriction (Own)		-0.0980**		-0.0305		-0.00682
		(0.0383)		(0.0866)		(0.0127)
Unit of observation	ikt	ikt	ikt	ikt	ikt	ikt
Fixed Effects	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt	ik, it, kt
Estimator	PPML	PPML	PPML	PPML	OLS	OLS
# of Clusters	122,516	122,516	121,955	121,955	109,424	109,424
# of Obs.	2,669,699	2,669,699	2,648,227	2,648,227	1,578,042	1,578,042

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). Fixed effects are indexed by country i, product k, and year t. Standard errors are clustered at the country–product level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

The event-study estimates presented in Figure F2 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



(a) Export Value

(b) Export Quantity

Figure F2. 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 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.

G Quantification Details

This section provides details for the quantification in Section 8. It describes the data, infers the tariff equivalent from the estimated price responses, expresses the welfare effect in terms of the estimated trade responses, and reports sensitivity analyses. Throughout the section, BCDR denotes Bartelme et al. (2025) and LL denotes Lashkaripour and Lugovskyy (2023).

G.1 Data

The unit of analysis is the restricted country–mineral pair. Of the 200 restricted pairs, 197 record exports in the three years before the restriction was first announced; they are imposed by 27 countries. For each pair, mineral exports and the world market share q_i are averages over those three years in CEPII-BACI, or over 2005–2007 for pairs first restricted in 2008.

The downstream products of a restricted pair are the products linked to its mineral in AIPNET. A product linked to several minerals restricted by the same country is assigned to the production stage of its closest link, and its exports and output are divided equally among the restricted minerals at that link, so that each product is counted once. Exports are 2005–2007 averages in CEPII-BACI. Because product-level output is not observed, I measure it as exports divided by the export share of output in the corresponding two-digit ISIC sector, using the UNIDO INDSTAT database. Sector-level scale elasticities are taken from Table 1 of BCDR and Table 3 of LL and assigned to products through their two-digit ISIC sector. The manufacturing average weights these estimates by each country's manufacturing employment in INDSTAT.[1]

G.2 Tariff Equivalent

Proposition 1 implies that a restriction with tariff equivalent t changes the world and domestic mineral prices by

$$\Delta \ln p_M^* = -\Phi \ln(1-t), \qquad \Delta \ln p_M = (1-\Phi)\ln(1-t). \tag{G.1}$$

The first response is the estimated effect on the restricting country's export price in Table 2. The second is not observed. Abstracting from wage and scale feedback, Equation (25) implies that the first-stage price moves by α times the domestic mineral price, so I recover the second response as the estimated effect on first-stage export prices in Table 4 divided by the mineral cost

[1] Table G5 reports the sector composition of these downstream exports, together with their estimated export responses and scale elasticities.

share α. The two responses give t and Φ. Together with the estimated decline in mineral export quantities in Table 1, they also give Foreign's import demand elasticity, $\varepsilon_M^* = |\Delta \ln X_M| / \Delta \ln p_M^*$, and Home's export supply elasticity, $\varepsilon_M = \Delta \ln X_M / \Delta \ln p_M$.

Table G1 reports these objects for three values of α. The baseline value of 0.25 is informed by the World Input–Output Database for 2005–2007 (Timmer et al., 2015), in which purchases from mining and quarrying per dollar of basic-metals output are 0.13 worldwide, 0.17 in China, 0.26 in Brazil, and 0.28 in Indonesia. These figures are sector averages that include later processing steps, so the share at the first processing stage is higher.

Table G1. Model objects implied by the estimated price and quantity responses

	Mineral Cost Share α		
	0.15	0.25	0.50
World mineral price, $\Delta \ln p_M^*$	0.133	0.133	0.133
Domestic mineral price, $\Delta \ln p_M$	-0.147	-0.088	-0.044
Tariff equivalent, t	0.24	0.20	0.16
Pass-through coefficient, Φ	0.48	0.60	0.75
Home export supply elasticity, ε_M	5.7	9.4	18.9
Foreign import demand elasticity, ε_M^*	6.2	6.2	6.2
Terms-of-trade optimal tax, $1/\varepsilon_M^*$	0.16	0.16	0.16

Notes: This table reports the model objects implied by the empirical estimates for three values of the mineral cost share of first-stage output. The world price response is the estimated effect on the restricting country's export price (Table 2). The domestic price response is the estimated effect on first-stage export prices (Table 4) divided by α. The tariff equivalent and the pass-through coefficient follow from Equation (G.1). The elasticities use the estimated decline in mineral export quantities of 0.831 log points (Table 1).

G.3 Welfare Effect of a Restriction

By Proposition 5, the terms-of-trade and Pigouvian effects of a marginal increase in the tax do not depend on its level, while the Harberger loss is proportional to it. Integrating Equation (28) from zero to t, holding shares and elasticities constant, gives the welfare effect of a restriction to a second-order approximation:

$$\Delta W = -\ln(1-t)\Big[\Phi\Big(\xi_0 - \sum_k \mu_k \rho_k^*\Big) - (1-\Phi)\sum_k \xi_k \rho_k + (1-\Phi)\sum_k \gamma_k \lambda_k \varepsilon_{L,k} - \tfrac{1}{2}(1-\Phi)\,\xi_0\, t\, \varepsilon_M\Big]. \tag{G.2}$$

Using Equation (G.1) and the definitions of ρ_k, ρ_k^*, $\varepsilon_{L,k}$, and ε_M, each elasticity can be replaced by the change it produces under the restriction:

$$\Delta W = \xi_0 \,\Delta \ln p_M^* - \sum_k \mu_k \,\Delta \ln p_k^* + \sum_k \xi_k \,\Delta \ln p_k + \sum_k \gamma_k \,\lambda_k \,\Delta \ln L_{Y,k} + \tfrac{1}{2}\,\xi_0 \,t \,\Delta \ln X_M. \quad \text{(G.3)}$$

The five terms are the gain from the higher world mineral price, the loss from higher prices of imported processed goods, the loss from lower prices of processed exports, the Pigouvian gain, and the Harberger loss. Since ξ_0, ξ_k, μ_k, and λ_k are expressed relative to national income, multiplying by national income restates each term in values. Let X_M, X_k, and Y_k denote the values of mineral exports, stage-k exports, and stage-k output. I drop the import-price term, which is estimated to be zero (Appendix Table E3), and use $\Delta \ln p_M^* = |\Delta \ln X_M|/\varepsilon_M^*$. The restriction then raises welfare if

$$\sum_k \gamma_k \,Y_k \,\Delta \ln L_{Y,k} > \left(\frac{t}{2} - \frac{1}{\varepsilon_M^*}\right) X_M \,|\Delta \ln X_M| + \sum_k X_k \,|\Delta \ln p_k|. \quad \text{(G.4)}$$

Without downstream externalities and processed exports, this condition reduces to $t < 2/\varepsilon_M^*$, the criterion used in Table 7. Dividing both sides by the downstream expansion, the restriction raises welfare if the average of γ_k, weighted by the expansion of each stage, exceeds

$$\gamma^{\text{implied}} = \frac{\left(\frac{t}{2} - \frac{1}{\varepsilon_M^*}\right) X_M \,|\Delta \ln X_M| + \sum_k X_k \,|\Delta \ln p_k|}{\sum_k Y_k \,\Delta \ln L_{Y,k}}. \quad \text{(G.5)}$$

The numerator is the cost of the restriction net of its terms-of-trade gain, and the denominator is the downstream expansion. When the sector from which workers are drawn has scale elasticity γ_o, the Pigouvian term depends on $\gamma_k - \gamma_o$ (Proposition 6), and γ^{implied} is the required value of this difference. The first-order condition for the optimal tax is Equation (G.4) with equality and with t in place of $t/2$. With a single stage and no processed exports, its second term vanishes, $X_M/Y = (1 - s_Y)/s_Y$, and $|\Delta \ln X_M|/\Delta \ln L_Y = \varepsilon_M/\varepsilon_L$, so that it coincides with Equation (21).

I evaluate Equation (G.5) for each restricted pair, with $t = 0.20$, the pair-specific $1/\varepsilon_M^*$ from Equation (32), the estimated $\Delta \ln X_M$ and $\Delta \ln p_k$, and the export quantity responses by production stage as $\Delta \ln L_{Y,k}$. Table G2 counts the pairs for which the scale elasticity of the expansion, less that of the sector releasing the workers, exceeds γ^{implied}, under alternative sources of downstream workers.[2] The case without scale economies in the releasing sector corresponds

[2] Table G4 repeats this count under alternative inputs.

to the model, in which workers leave mining, and is an upper bound. Figure G1 traces the count as the scale elasticity of the releasing sector varies from 0 to 0.30. Table G3 reports the underlying distribution by world market share. The terms of trade suffice when γ^{implied} is negative, and no externality suffices when it exceeds the scale elasticity of the expansion itself. For the pairs in between, the table reports the median of γ^{implied} and the median ceiling on γ_o, the largest scale elasticity of the releasing sector at which the restriction raises welfare.

Table G2. Restricted pairs that raise welfare, by source of downstream workers

	Scale Elasticity of the Source	Pairs	Share of Exports
No externality (terms of trade only)		17	0.50
Downstream workers drawn from:			
No scale economies (upper bound)	0	136 / 136	0.85 / 0.85
Agriculture and mining	0.14	83 / 97	0.56 / 0.74
Other manufacturing	0.22 / 0.26	20 / 21	0.20 / 0.34
All restricted pairs		197	1.00

Notes: This table reports the number of restricted country–mineral pairs for which the welfare effect implied by Proposition 5 is positive, and their share of restricted mineral exports. The welfare effect is evaluated to a second-order approximation at a tariff equivalent of 0.20 and the empirical estimates. The first row sets the Pigouvian term to zero. The remaining rows value the downstream expansion at the scale elasticity of the expanding activities less that of the sector from which workers are drawn: zero, as assumed outside manufacturing by BCDR; the estimate for agriculture and mining in LL; or the country's manufacturing average, whose mean across pairs is shown. Entries separated by a slash use the sector-level scale elasticities of BCDR and LL, respectively.

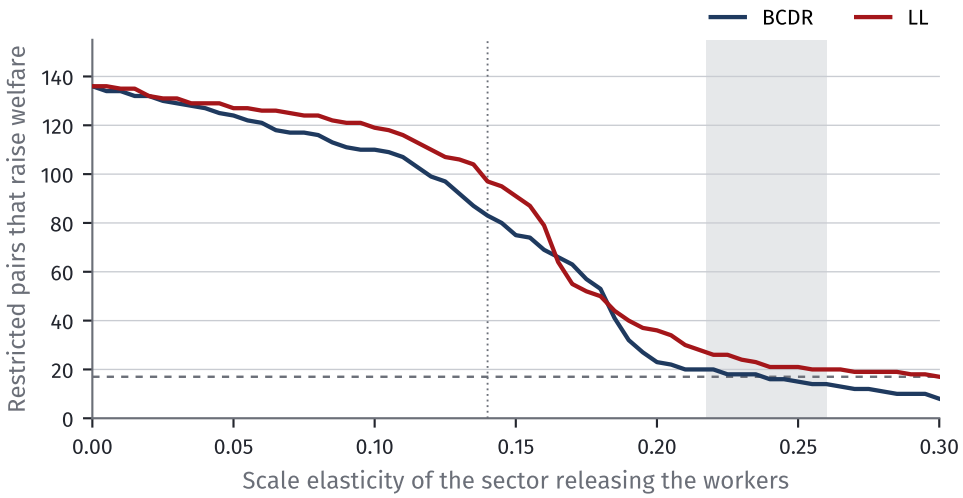


Figure G1. Restricted pairs that raise welfare and scale economies of the releasing sector

Notes: This figure plots the number of restricted country–mineral pairs, out of 197, for which the welfare effect implied by Proposition 5 is positive, against the scale elasticity of the sector from which downstream workers are drawn. The two lines use the scale elasticities of BCDR and LL for the expanding activities. The dashed line marks the number of pairs that raise welfare without any externality, the dotted line the estimate for agriculture and mining in LL, and the shaded area the manufacturing average under the two sets of estimates.

Table G3. Externality required for restrictions to raise welfare, by world market share

World Market Share	Pairs	Share of Pairs			Implied Externality	Ceiling on γ_o
		ToT Suffices	Externality Required	No Externality Suffices		
Below 1%	97	0.00	0.72	0.28	0.03	0.15 / 0.16
1% to 10%	78	0.00	0.58	0.42	0.03	0.15 / 0.15
10% to 30%	13	0.77	0.15	0.08	0.06	0.14 / 0.23
Above 30%	9	0.78	0.22	0.00	0.00	0.15 / 0.18
All	197	0.09	0.60	0.31	0.03	0.15 / 0.16
Share of Exports		0.50	0.34	0.15		

Notes: This table reports the distribution of the implied externality in Equation (G.5) across restricted country–mineral pairs, grouped by world market share. The terms of trade (ToT) suffice when the implied externality is negative. No externality suffices when it exceeds the scale elasticity of the pair's downstream expansion, or when the pair has no downstream expansion. For the pairs that require an externality, the last two columns report the median implied externality and the median ceiling on γ_o, the scale elasticity of the expansion less the implied externality. Entries separated by a slash use the scale elasticities of BCDR and LL, respectively.

Table G4. Restricted pairs that raise welfare under alternative inputs

	t	No Externality	Downstream Workers Drawn From: No Scale Economies	Agriculture and Mining	Other Manufacturing
Baseline	0.20	17	136 / 136	83 / 97	20 / 21
Mineral cost share $\alpha = 0.15$	0.24	14	126 / 128	75 / 93	20 / 19
Mineral cost share $\alpha = 0.50$	0.16	21	144 / 144	94 / 108	24 / 23
Tariff equivalent of 0.10	0.10	36	159 / 160	111 / 132	36 / 32
Tariff equivalent of 0.30	0.30	12	122 / 123	73 / 89	19 / 16
Country–product export price	0.18	19	139 / 137	87 / 103	21 / 21
Fally–Sayre elasticities	0.20	21	141 / 139	89 / 102	24 / 24
Export value responses	0.20	17	140 / 142	87 / 107	20 / 19
First-stage response only	0.20	17	99 / 98	52 / 72	16 / 14
Only exports expand	0.20	17	100 / 102	41 / 51	18 / 19
Shared products not divided	0.20	16	163 / 161	111 / 130	15 / 11
No processed-export price term	0.20	19	137 / 137	97 / 104	20 / 21
Optimal-tax criterion	0.20	8	115 / 117	62 / 77	15 / 13

Notes: This table reports the number of restricted country–mineral pairs, out of 197, that raise welfare under alternative inputs. Each row repeats Table G2 after changing one input. "Country–product export price" recovers the tariff equivalent from the unit value response in Table 1 instead of the bilateral price response in Table 2. "Fally–Sayre elasticities" sets $\varepsilon_D = 0.4$ and $\varepsilon_S = 0.6$ in Equation (32) without rescaling them. "Export value responses" replaces the export quantity responses by stage with the value responses in Appendix Table A11. "First-stage response only" sets the response at stages 2 and beyond to zero. "Only exports expand" applies the responses to downstream exports instead of output. "Shared products not divided" attributes the full expansion of a downstream product to every restricted pair linked to it. "Optimal-tax criterion" counts the pairs whose restriction is no tighter than the optimal tax, replacing $t/2$ with t in Equation (G.5). Entries separated by a slash use the scale elasticities of BCDR and LL, respectively.

Table G5. Downstream exports linked to restricted minerals by sector

	Share of	Estimated Response		Scale Elasticity	
Sector	Exports	Value	Quantity	BCDR	LL
Base Metals	0.31	0.279***	0.397***	0.13	0.21
Stone & Glass	0.11	0.0505	0.159	0.19	0.17
Jewelry & Gems	0.03	0.101	0.179	0.17	0.18
Chemicals	0.05	-0.263***	0.326*	0.21	0.23
Machinery & Electronics	0.34	-0.0107	-0.0412	0.26	0.48
Transport Equipment	0.14	0.147	0.0277	0.19	0.13
Precision Instruments	0.01	-0.272*	-0.135	0.27	0.55
Others	0.02	0.0645	0.0712	0.30	0.31
Downstream expansion				0.17	0.19
Manufacturing average				0.22	0.26

Notes: This table reports the sector composition of the downstream exports linked to restricted minerals in 2005–2007, together with the estimated export responses from Appendix Table A12, where standard errors are reported. Sectors are ordered as in Figure 10. Scale elasticities are export-weighted averages of the two-digit ISIC estimates of BCDR and LL. "Downstream expansion" weights the scale elasticities of the linked downstream products by the expansion of their output implied by the stage-specific quantity responses, as in the welfare calculation. The manufacturing average weights the same estimates by manufacturing employment in each restricting country, and countries by the same expansion. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.