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On the Design of Effective Sanctions: The Case of Bans on Exports to Russia

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Abstract

We analyze the effects of bans on exports at the level of 5'000 products and show how our results can inform economic sanctions against Russia after its invasion of Ukraine. We begin with characterizing export restrictions imposed by the EU and the US until mid October 2022. We then propose a theoretically-grounded criterion for targeting export bans at the 6-digit HS level. Our results show that the cost to Russia are highly convex in the market share of the sanctioning parties, i.e., there are large benefits from coordinating export bans among a broad coalition of countries. Applying our results to Russia, we find that sanctions imposed by the EU and the US are not systematically related to our arguments once we condition on Russia's total imports of a product from participating countries. Quantitative evaluations of the export bans show (i) that they are very effective with the welfare loss typically ∼100 times larger for Russia than for the sanctioners. (ii) Improved coordination of the sanctions and targeting sanctions based on our criterion allows to increase the costs to Russia by about 60% with little to no extra cost to the sanctioners. (iii) There is scope for increasing the cost to Russia further by expanding the set of sanctioned products.

Keywords Export Ban · Input-Output Linkages · Quantitative Trade Model · Russia · Sanctions · Ukraine
JEL Classification F13 · F51

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1 Introduction

In response to the Russian invasion of Ukraine beginning in February 2022, the EU, the US, and their partners have imposed wide-ranging economic sanctions. An important part of these sanctions are restrictions on exports to Russia. These restrictions were introduced at the level of more than 5'000 6-digit HS products, with substantial heterogeneity both across but also within 2-digit HS chapters, as shown in Figure 1. This raises the question how to design these export restrictions most effectively at a detailed level of dis-aggregation. In this paper, we seek to provide guidance for targeting export restrictions by characterizing the associated economic cost to Russia and its underlying drivers. Our results can readily be applied to other crisis settings to inform economic sanctions.

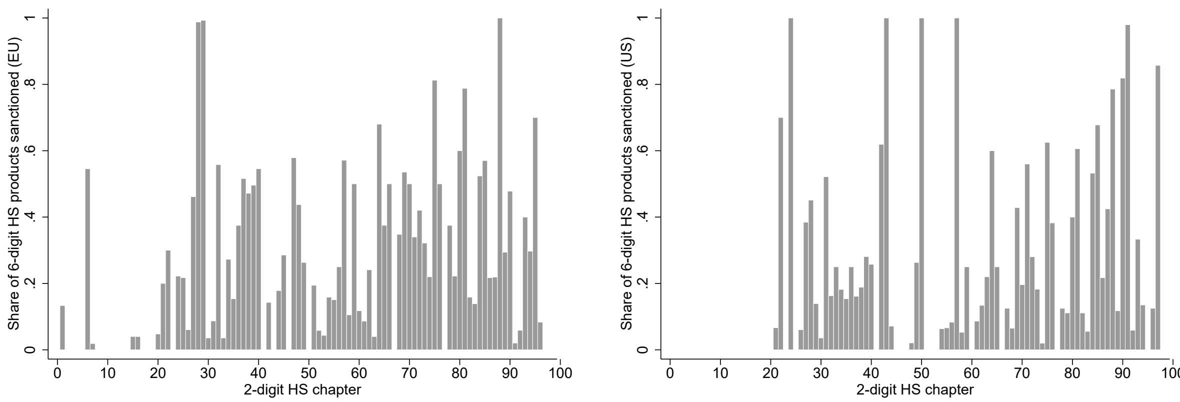
Much of the debates on sanctioning Russia have focused on its energy exports (see e.g., Hausmann 2022; Bachmann et al. 2022; Baqaee et al. 2022; Bayer et al. 2022; Berger et al. 2022; Gros 2022; Hausmann et al. 2022b,a). Russia extracts large rents from its energy exports, and oil and gas are important sources of Russian public revenues. These exports are therefore natural targets for sanctions. When it comes to energy trade, however, before the crisis, the EU was almost as dependent on imports from Russia as Russia was on the EU as a destination for its exports.[1] As a consequence, sanctioning Russia's energy exports may not only inflict large costs on Russia, but interruptions in energy supplies may also inflict significant costs on the EU. This concern is at the heart of why it is so difficult for the EU to agree on sanctioning Russian energy exports. When it comes to Russian imports, the situation is very different: The EU accounts for 40% of Russia's imports, but only less than 2% of EU-members' exports go to Russia. This allows the EU to cut Russia off critical supplies with limited impact on EU's exports, and particularly so when coordinating export restrictions with partnering countries. Indeed, Figure 2 shows that in many 6-digit HS products, 'coalition countries' dominate Russian imports, where here and below we consider the EU, the US, the other G-7 member states, Australia, Korea, and Taiwan to be the *coalition*.[2] In this paper, we argue that export bans are, therefore, an effective instrument for sanctioning Russia and for economic sanctions in general.

[1] Pre-crisis, the EU bought 25% of its oil and 40% of its gas imports from Russia, while Russia sold 75% of its gas exports and 50% of its oil exports to the EU.

[2] The choice of the coalition is motivated by the fact that sanctions against Russia have been coordinated at the G-7, with Australia, Korea, and Taiwan also participating. We did not include e.g. Switzerland in the coalition even though it adopted EU export restrictions against Russia because there is no data on Switzerland in the World Input-Output database, and we will use this data to quantitatively assess sanctions in Section 5.

Figure 1: Share of 6-digit HS Products Sanctioned Within 2-digit HS Chapter

(a) EU (b) US



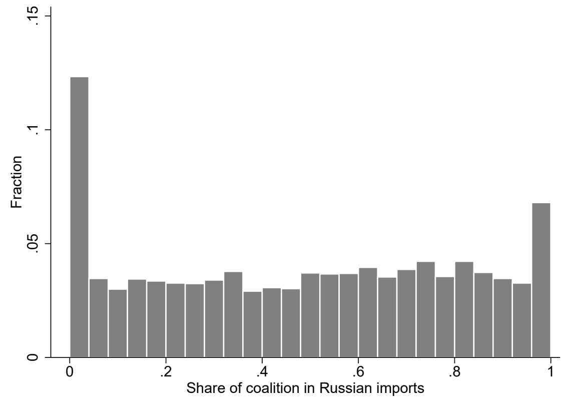
Notes: This figure shows for each 2-digit HS chapter, the share of 6-digit HS products in that chapter that are subject to export restrictions by the EU (left panel) and the US (right panel), respectively.
Data: See Section 4.1.

A key motive underlying the export restrictions by the EU and the US is to target Russia's military and defense sector, but the sanctions were more broadly designed to restrict "*Russia's access to vital technological inputs, atrophying its industrial base [...]*".[3] In our analysis, we focus on the latter and, more specifically, the economic costs of a ban on exports to Russia. Intuitively, restricting Russia's imports of a product from a set of countries should be costly if (i) these imports are large, (ii) the sanctioning countries have a dominant position in the product (i.e., the shock is large in relative terms), and (iii) it is difficult to substitute for the missing imports. Such substitution can happen through imports of the same product from third countries; through the use of alternative products; or—in the case of capital goods or durable consumer goods—inter-temporally by living off pre-existing stocks.

With these considerations in mind, we provide an overview of EU and US restrictions on exports to Russia in Section 2, and compare sanctioned with non-sanctioned products along several dimensions. We show that on average, Russian imports of sanctioned products are higher than of non-sanctioned products, i.e., the export restrictions are biased towards large products in terms of Russian imports. Moreover, the market share of the sanctioning countries in Russia is larger for sanctioned than for non-sanctioned products. This difference is, however, small. Secondly, sanctioned products do not have a systematically lower trade elasticity, which captures the degree to which trade flows within these product categories respond to changes in trade costs and, hence, the ease with which imports of a product from

[3]Source: https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/24/fact-sheet-joined-by-allies-and-partners-the-united-states-imposes-devastating-costs-on-russia/.

Figure 2: Share of Coalition in Russian Imports



Notes: For each 6-digit HS product, we calculate the share of the coalition in Russia's imports. Here, we bin these shares into intervals of 0.04 and show the fraction of products that fall into each bin. Coalition countries are: The EU, the US, the other G-7 members, Australia, Korea, and Taiwan.
Data: See Section 4.1.

one country can be replaced by imports of the same product from other countries. Thirdly, the sanctions are biased towards capital goods, and while the sanctions are well coordinated in general, more than 50% of all products with export restrictions by either the EU or the US are restricted by only one of them. Together, this suggests that it may take time for the cost of the export restrictions inflicted on Russia to materialize. Moreover, there may be scope for increasing the economic impact by stronger coordination among coalition countries and by focusing more systematically on products whose imports are relatively difficult to replace for Russia.

To shed light on the different drivers of the economic cost to Russia from these export restrictions and their appropriate aggregation, we analyze in Section 3 how bans on exports to a sanctioned country impact welfare. To that end, we consider an economy with a production hierarchy and where countries trade varieties of 6-digit HS products. We then build on Baqaee and Farhi (2019, 2021) to characterize the welfare cost to Russia of an export ban in a transparent way, while accounting for non-linear (second-order) effects, which are increasingly important as the shocks get larger. We derive an analytic expression for these costs and show how it confirms the basic intuition from above. We further show that the cost to Russia is highly convex in the market share of the coalition in Russia, suggesting large gains from coordinated sanctions and from focusing sanctions on products with a dominant position of the coalition.

In Section 4, we use our theoretical results to rank products by their implied cost to Russia from an export ban by coalition countries. We show that sanctions in place by the EU and the

US are not systematically related to our ranking once we condition on Russia's total imports of a product from coalition countries. Hence, our arguments suggest that there is scope for sharpening the sanctions, and there are many highly-ranked products that are currently not sanctioned.

Our ranking provides a first step towards an *ex ante* assessment of the economic cost to Russia from a ban on exports of narrowly defined products. It incorporates important dimensions, but it leaves others out of account: It considers sanctioning one product at a time, it is based on simplified input-output linkages, we assume that sanctions are fully enforceable and that there are no parallel imports, and we ignore costs to the sanctioners. In part, these simplifications are driven by data limitation. But even without such limitations, providing ex-ante guidance on export bans at a dis-aggregate level would be difficult in richer environments given the high-dimensionality and the non-linearity of the problem. Nevertheless, an ensuing question is to what extent our analysis can provide valuable guidance in richer settings as well. To shed light on this, we aggregate export bans at the 6-digit HS level to 15 World Input-Output Database (WIOD) manufacturing industries in Section 5. We then assess quantitatively their impact, exploiting the full international input-output (I-O) structure. Three key insights emerge from this analysis: (i) the estimated welfare loss is much larger for Russia than for the sanctioners, typically by a factor of ~ 100 or even higher with the exceptions of the Baltic countries for whom the estimated losses are by a factor ~ 10 lower than the losses for Russia. This is a reflection of the aforementioned asymmetry in the trade relationship between Russia and the sanctioners. (ii) Improved coordination of the sanctions and targeting sanctions based on our criterion allows to increase the costs to Russia by about 60% with little to no extra cost to the sanctioners. (iii) There is scope for tightening the sanctions further by expanding the set of products covered.

We focus on the economic costs to Russia from bans on exports. These are an important motive for the trade sanctions (European Council and Council of the EU, 2022), but there are other important dimensions that are not covered by our analysis. We discuss this in Section 6. For example, we ignore non-economic motives underlying export bans such as ethical considerations or the desire to cut a sanctioned country off critical inputs for its military. The latter motive plays an important role in the sanctions against Russia. More generally, there may be bottlenecks in value chains that have large cascading effects and that are not captured by our quantitative analysis. Similarly, we do not consider the distributional consequences in the sanctioned country, and our analysis is not targeted towards harming 'elites', for example. We are also not taking into account any potential retaliation from Russia, such as gas sanctions to Europe, that might substantially increase the cost to coalition countries, nor the threat of parallel imports that might undermine the cost to Russia. Such considerations are important in their own rights, but they are not readily quantifiable. They therefore need to be considered on a case-by-case basis when designing sanctions. Our analysis is thus best understood not as a blueprint for policy, but as a valuable and easily implementable input into a more comprehensive analytical process.

Relation to the Literature

We build on the literature that uses quantitative trade models to assess the effects of policy changes and shocks, in particular Caliendo and Parro (2015); Costinot and Rodríguez-Clare (2014); Baqaee and Farhi (2019, 2021). Such models have been used to quantify the gains from NAFTA (Caliendo and Parro, 2015), the gains from European integration and the cost of Brexit (Dhingra et al., 2017; Mayer et al., 2019; Felbermayr et al., 2022a), the cost of the US-China trade war (Charbonneau and Landry, 2018; Caliendo and Parro, 2022), and the cost of decoupling global value chains (Eppinger et al., 2021), for example. Closer to our work are Crozet and Hinz (2020) and Hinz and Monastyrenko (2022), who use quantitative trade models to evaluate sanctions that were imposed following the Russian annexation of Crimea in 2014, and Bachmann et al. (2022); Baqaee et al. (2022); Evenett and Muendler (2022b,a); Felbermayr et al. (2022b), who use quantitative trade models to simulate different policy scenarios pertaining to the Russian invasion of Ukraine in 2022. These papers have in common that they evaluate specific (policy) scenarios. As opposed to that, we seek to provide guidance on the design of effective sanctions at a detailed level of disaggregation.

In doing so, we contribute to a large literature on economic sanctions that includes detailed accounts of case studies (Hufbauer et al., 2007), empirical evaluations of the success factors of sanctions (Ang and Peksen, 2007; Escribà-Folch and Wright, 2010), empirical evaluations of the trade effects of sanctions (Haidar, 2017; Felbermayr et al., 2020; Larch et al., 2022; Miromanova, 2022), and game-theoretic analyses of the ability of sanctions—or the threat thereof—to induce change (Eaton and Engers, 1992, 1999; Kaempfer et al., 2004; Hovi et al., 2005; Major and McGann, 2005; Whang et al., 2013; Baliga and Sjöström, 2022)—see Kaempfer and Lowenberg (2007); Peksen (2019); Felbermayr et al. (2021) for surveys. Our work complements this literature in that it builds on trade theory to provide guidance on the design of sanctions, viz. export bans at the product level. Our paper is thus closer to Sturm (2022) who studies economic sanctions as terms-of-trade manipulation in a two-country model. He shows that sanctions as trade taxes optimally target goods that the sanctionee demands and supplies inelastically. While this elasticity also plays an important role in our criterion, our work differs along important dimensions: We simplify by considering export bans rather than general trade taxes, and by considering targeting one product at a time.[4] On the other hand, this allows us to characterize the cost to Russia from an export ban, taking into account the macroeconomic elasticity of substitution in a way that is theoretically grounded, transparent, and easily implementable with readily available data. Moreover, we show that our arguments are quantitatively important, allowing to increase the effectiveness of export bans by $\sim 60\%$.

2 Overview of Restrictions on Exports to Russia

In this section, we characterize restrictions on exports to Russia that were imposed by the EU and the US since the Russian annexation of Crimea in 2014 and up to October 14th 2022, the majority of which were imposed—or strengthened—in 2022.[5] Data on the sanctions is from the Global Trade Alert (https://www.globaltradealert.org).[6] Further details on our data are provided in Section 4.1.

Figure 3 provides an overview of the restrictions. As a reference point, panel (a) shows the share of all Russian imports in 2019 that were from the EU, the US, other coalition countries, and China. Prior to the crisis, the coalition accounted for approximately 54% of Russian imports, with the large majority of these imports originating from the EU. Panels (b) and (c) summarize restrictions on exports to Russia. All restrictions by the EU take the form of an export ban, while the US has mostly imposed export controls, but also some export bans. Figure 3 separates these types of sanctions, but we lump together US bans and export controls in the remainder of the paper.[7] Panel (b) shows that $\sim 44\%$ of all product

[4] Export bans correspond to the corner solution with infinite export taxes. Interestingly, this corner solution may be optimal for export taxes, but typically not for import taxes (Sturm, 2022). More generally, export bans may be desirable as a means of disrupting the sanctionee's economy, and for political economy reasons at the sanctioner. In fact, restrictions on exports to Russia by the EU and the US take the form of bans or controls—not taxes—and, hence, our analysis is of evident relevance for policy.

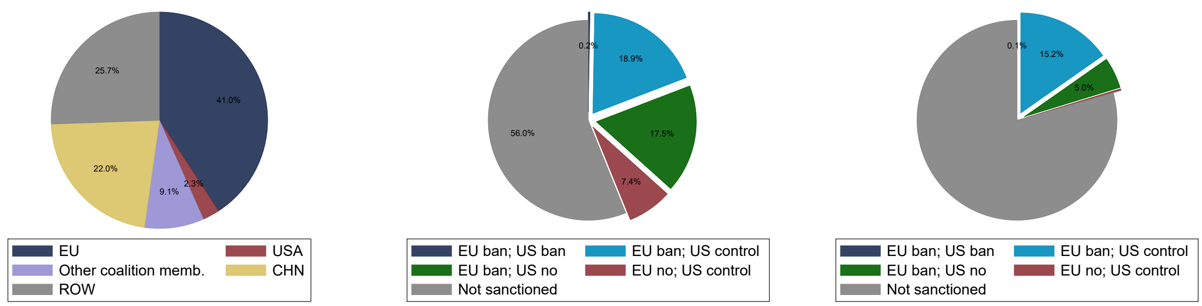
[5] According to data from the Global Trade Alert, only 41 products out of the 1689 products sanctioned by the EU as of October 14th 2022 were sanctioned pre 2022 and not superseded by sanctions since February 2022. All earlier US sanctions were superseded by sanctions in 2022.

[6] We thank Johannes Fritz and the Global Trade Alert for providing us with the data.

[7] When it comes to exports, the US interventions against Russia reported by the Global Trade Alert can be broadly classified into three categories: Export bans, general export controls (licensing requirements), and licensing requirements for exports to certain Russian entities. In what follows, we will treat US export bans and general export controls interchangeably. This is in line with, e.g., US Government (2022), which states that '*Applications for the export, reexport, or transfer (in-country) of any item [...] that requires a license for Russia will be reviewed under a policy of denial [...]*'. Throughout, we do not consider licensing requirements for exports to selected Russian entities because our data does not allow for a detailed account of these sanctions. Moreover, there may be a risk of parallel imports when targeting selected entities. We note

Figure 3: Overview of Export Restrictions by the EU and the US

(a) Shares of Russian Imports by Exporter (b) Share of Product Categories Sanctioned (c) Weighted Share of Product Categories Sanctioned



Notes: Panel (a) shows the share in Russian imports by groups of countries. Panel (b) shows the share of 6-digit HS product categories that were sanctioned by the EU and the US, respectively. Panel (c) shows the share of 6-digit HS product categories that were sanctioned by the EU and the US, respectively, with each product weighted by Russian imports.
Data: See Section 4.1.

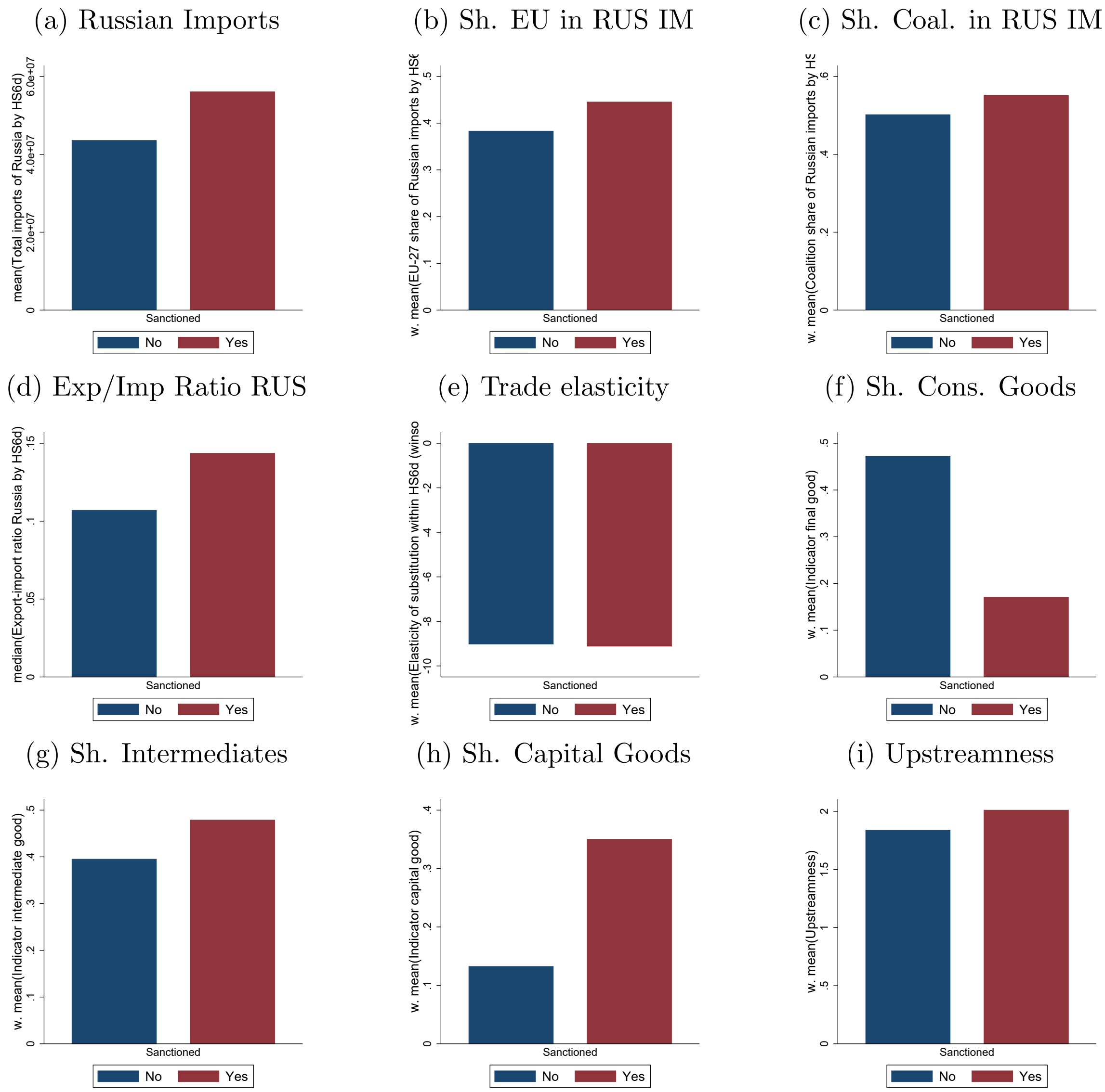
categories have been sanctioned by either the EU, the US, or both. Out of these product categories, ∼ 43% have been sanctioned by both, ∼ 40% by the EU only, and ∼ 17% by the US only. Taken together, the sanctioned exports account for ∼ 20% of Russian imports (panel (c)), and these imports are pre-dominantly in product categories that the EU has also sanctioned, in line with panel (a).

Figure 3 reveals large potential for expanding current sanctions and for stronger coordination between the EU and the US. Figure 4 explores the nature of the sanctioned products and compares them to non-sanctioned products along several dimensions. In each panel, the left (blue) bar indicates the (weighted) average of a characteristic across non-sanctioned products. The right (red) bar indicates the same average across sanctioned products. The figure focuses on sanctions imposed by the EU. An analogous figure for US sanctions is provided in Appendix A.2.

The first row summarizes product characteristics that impact the importance of imports from the EU and coalition countries for Russia. They reveal that sanctioned products are large in terms of Russian total imports (panel (a)). Moreover, the market shares in Russia by the EU and by the coalition are somewhat larger in sanctioned compared to non-sanctioned products (panels (b) and (c)). Intuitively, market shares matter independently of total exports because there are decreasing returns to consumption of a product, implying that large shocks (in

that there is less ambiguity with respect to EU sanctions which—considering the respective market shares in Russia—are also more impactful. Moreover, the classification of US sanctions does not affect our ranking of products by their impact on the Russian economy developed in Sections 3 and 4.2, nor our quantitative assessment of sanctions based on our criteria in Section 5.

Figure 4: Characteristics of Products with vs. without EU Export Restrictions



Notes: The figure compares 6-digit HS products with an EU export ban (blue, left bar) to those without an EU export ban (red, right bar) along the dimensions as specified in the panel titles. Bars refer to weighted means with weights given by Russia's imports, with the exception of panel (a), which considers simple means, and panel (d), which considers the median.
Data: Data on an industry's upstreamness—used in panel (i)—for over 400 NAICS industries is from Antràs et al. (2012). We match NAICS industries to the HS system using the concordance from the BEA (https://www.bea.gov/sites/default/files/2018-04/HSConcord.xls). For all other data, see Section 4.1.

relative terms) are particularly costly. We will get back to this point at the end of Section 3.

Rows 2 and 3 consider different factors that are important for Russia's ability to replace imports of a product from coalition countries. Panels (d) and (e) focus on its ability to source the same product from either within Russia or from third countries. Panel (d) shows that the Russian export to import ratio tends to be higher among sanctioned products—an indication of Russian capabilities, i.e., it suggests potential to source sanctioned products domestically. Panel (e) reveals no differences between sanctioned and non-sanctioned products in terms of how easy it is to switch suppliers of a given product as measured by the trade elasticity, i.e., the response of trade-flows within a 6-digit HS product to trade shocks measured by Fontagné et al. (2022).

Panels (f), (g), and (h)—group products into three categories: consumer goods, intermediates, and capital goods. While this categorization is crude, it captures dimensions that are important for Russia's ability to 'substitute' missing imports of a product by other products or over time. On the one hand, intermediate inputs and capital goods tend to be less substitutable than final consumer goods, which should increase the cost to Russia after a ban on these products. The figure shows that the EU sanctions were strongly concentrated on these goods, and capital goods in particular. On the other hand, capital goods are a stock variable, and flow imports account for only a small share of the stock in the short run. The latter is used for production, suggesting that a stronger focus on intermediate inputs may have a larger impact on the Russian economy in the short run.

Lastly, panel (i) considers the upstreamness of a product's industry in the US input-output tables from Antràs et al. (2012), with a value of 1 representing final goods. Intuitively, this measure summarizes an industry's direct and indirect forward linkages and reflects how sensitive output is to a shock to an industry. As may be seen from panel (i)—and in line with panels (f) to (h)—, sanctioned products are somewhat more upstream, but this difference is small.

In summary, the focus on large products in terms of Russian imports and the alignment of EU and US sanctions suggest sizable effects on the Russian economy. Yet, there may be room for improving the effectiveness of the sanctions in terms of economic costs to Russia by (i) harmonizing them even further between the EU, the US, and their partnering countries, (ii) focusing sanctions on products where coalition countries have a dominant position in Russia, (iii) focusing sanctions on intermediate as opposed to capital goods, and (iv) focusing sanctions on products with a low trade elasticity. We explore this more systematically next and how we can aggregate these different dimensions.

3 Targeting Export Restrictions

In this section, we consider an economy with a production hierarchy. We then build on Baqaee and Farhi (2019, 2021) to derive a theoretically-grounded criterion for targeting bans on exports to Russia. We begin with describing the economic environment.

3.1 Economic Environment

There are I countries, indexed by $i, j \in \mathcal{I}$, and G 6-digit HS products (or goods), denoted by $g \in \mathcal{G}$. Each country produces a distinct variety of each of the G products, analogous to an Armington model (Armington, 1969; Anderson, 1979). Production follows a 4-tier production process that uses labor as the only primary factor. At the first stage of the production process, the varieties of 6-digit HS products are produced using a constant-returns-to-scale production technology with labor as the only input and country-product specific productivity. These varieties are traded with importer-exporter-product specific iceberg trade costs τ. In each country and for every 6-digit HS-product, there is a perfectly competitive producer that combines the domestic and imported varieties in a CES aggregator with product-specific elasticity of substitution $\sigma^g > 1$ (stage 2). We henceforth simply refer to this CES aggregator as the 6-digit HS-product. HS products can be consumer goods or intermediate goods. Intermediate goods are supplied as inputs for domestic downstream production in D downstream sectors—denoted by $d \in \mathcal{D}$—, that combine these inputs and labor in a CES production function with constant elasticity of substitution $\theta \leq 1$ (stage 3).[8] Lastly, downstream sectors are combined with consumer goods in a Cobb-Douglas final-good aggregator, Y. This aggregator is also traded between countries and trade is balanced. Figure 5 provides a schematic overview of the economy.[9]

3.2 Impact of an Export Ban on the Russian Economy

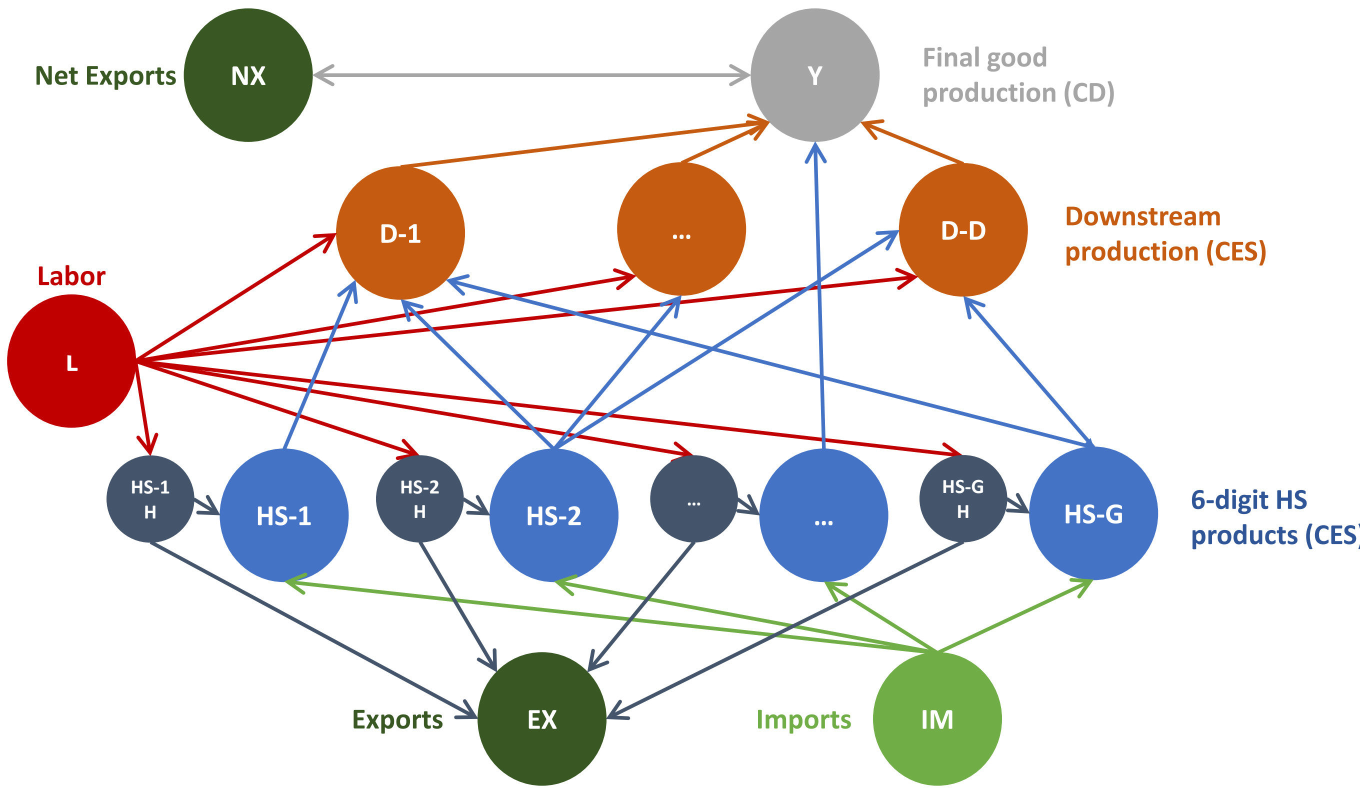
The economic set-up allows to derive an analytic expression for the impact of a ban on exports of a 6-digit HS product by coalition countries on the Russian economy, as we now explain.

An export ban by coalition countries on their varieties of a 6-digit HS product impacts Russia via its effect on the price of the associated CES aggregator. For any variable x, let x' denote its value after the shock and let $\hat{x}$ denote its change in response to the shock, i.e., $\hat{x} := x'/x$.

[8] We are not aware of data that would allow to discipline heterogeneous values of θ across downstream sectors. To simplify the exposition, we therefore assume that θ—the elasticity of substitution of downstream buyers across their inputs—is constant across downstream sectors. It is, however, different for intermediate goods than for final goods, which are directly supplied to final-good production.

[9] While our assumptions simplify input-output linkages in the economy, it is worth noting that the set-up we consider is a generalization of a multi-industry (or product) Armington model (Armington, 1969; Anderson, 1979).

Figure 5: Schematic Overview of Economy



Notes: The figure provides a schematic overview of the economy in Section 3.

With this notation, we have

$$\hat{P}^g = \left(\sum_i \Omega_i^g (\hat{p}_i^g)^{1-\sigma^g} \right)^{\frac{1}{1-\sigma^g}} , \quad \sigma^g > 1$$

where P^g is the price of product g in Russia, p_i^g is the price of variety i of product g, $\Omega_i^g := \frac{p_i^g q_i^g}{P^g Q^g}$ is the pre-shock share of variety i in the total cost of product g, and where here and below we simplify the exposition by omitting the importer-identifier for Russia. For all countries participating in the ban and who exported the product prior to the shock, we have $\hat{p}_i^g = \infty$. Moreover, Russian uptake of product g is a small fraction of global output, implying that $\hat{p}_i^g \approx 1$ for all non-coalition members, including Russia. Hence,

$$\hat{P}^g \approx (1 - \Omega_{CO}^g)^{\frac{1}{1-\sigma^g}} , \tag{1}$$

where Ω_{CO}^g is the pre-shock market share of coalition members in Russia. That is, $\Omega_{CO}^g := \sum_{i \in \mathcal{I}_{CO}} \Omega_i^g$ with $\mathcal{I}_{CO}$ denoting the set of countries in the coalition. Intuitively, the shock is bigger if coalition members have a larger market share in Russia (Ω_{CO}^g larger) and if it is harder to substitute for the missing varieties (σ^g smaller).

How does such a shock on Russian imports of a product impact aggregate output in Russia? Baqaee and Farhi (2021, section 6) show how this can be analyzed by considering a 'dual' closed economy where the price change $\hat{P}^g$ is induced by a change in the sector-specific productivity, $\hat{\check{A}}^g$. In such an economy, Hulten's theorem implies that—to a first order—the impact on aggregate output would be given by (Hulten, 1978; Baqaee and Farhi, 2019)

$$\Delta \ln(\check{Y}) \approx \check{\lambda}^g \Delta \ln(\check{A}^g), \tag{2}$$

where $\check{\lambda}^g := \frac{\check{P}^g \check{Q}^g}{\check{Y}\check{P}}$ is the sales share—or Domar-weight—of product g in the dual closed economy.[10] Intuitively, the allocation is efficient, and any re-allocations do not have first-order effects. Hence, all that matters is the direct cost effect on the buyers of product g, and the network structure is irrelevant conditional on $\check{\lambda}^g$.

For large shocks, however, re-allocations may matter. We can conceive of such shocks as a chain of small shocks, each governed by Equation (2). Hence, the change in λ^g is important for the economy's response to large shocks. In turn, this change depends on the macroeconomic elasticity of substitution, i.e., on the economy's overall ability to substitute away from g.[11] In Appendix B.1, we build on Baqaee and Farhi (2019, 2021) to show that in our economy, this can be reduced to the following expression for the impact of the shock:

Proposition 1

Consider a ban on exports to Russia of product g by coalition countries. The impact on the Russian economy of this ban is

$$\Delta \ln(Y) \approx \lambda^g \left[\frac{1}{\sigma^g - 1} \ln\left(1 - \Omega^g_{CO}\right) + (\theta^g - 1) \left[\frac{1}{\sigma^g - 1} \ln\left(1 - \Omega^g_{CO}\right) \right]^2 \right], \tag{3}$$

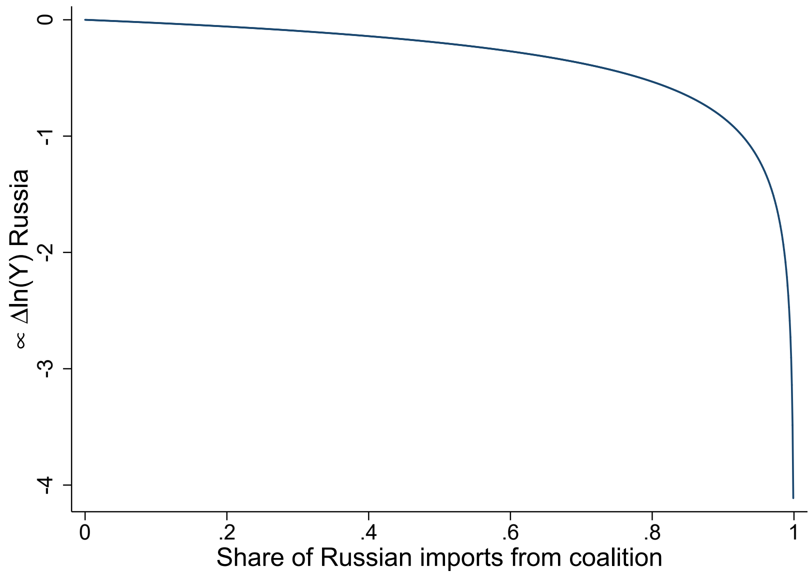
where θ^g is the elasticity of substitution across inputs of the downstream buyers of g, i.e., $\theta^g = 1$ for consumer goods and $\theta^g = \theta \leq 1$ otherwise.

Intuitively, the export ban has a larger effect if (i) g is an important input for the Russian economy as summarized by λ^g, (ii) imports from coalition-members account for a large share of total Russian expenditure on g (Ω^g_{CO} large), (iii) these missing imports cannot easily be substituted by varieties from non-participating countries (σ^g is small), (iv) downstream buyers cannot easily substitute the now costlier input g by other inputs (θ^g small). The

[10] As noted in Baqaee and Farhi (2021), this sales share need not be equal to the one in the original open economy. In the economy considered here, this is nevertheless the case—see Appendix B.1

[11] In general, this depends on microeconomic elasticities of substitution in production and consumption, and on the input-output structure. Intuitively, the macro-elasticity depends on the ability of g's buyers to substitute away from buying g, the ability of the buyer's buyer to substitute away, and so on.

Figure 6: Market Share of Coalition and Change in Russian GDP



Notes: The figure illustrates the convexity of $\Delta \ln(Y)$ in Equation (3) with respect to the share of coalition countries in Russian imports, Ω^g_{CO}, for $\sigma^g = 5$ and $\theta^g = 0.2$.

latter implies that in response to a positive price shock on g, its buyers will increase their expenditure on g, and λ^g increases.

Equation (3) shows how the different forces discussed in Section 2 can be aggregated into a single statistics in this economy. This aggregation has an interesting implication: Ceteris paribus, the cost of an export restriction on g to the Russian economy becomes higher as the share of coalition countries in Russian imports, Ω^g_{CO}, gets larger. More importantly, this relationship is highly convex, implying large gains from coordinating sanctions among a broad coalition of countries and from sanctioning products with a dominant market position of the coalition:

Corollary 1

There are large gains from coordinating sanctions among a broad coalition of countries and from sanctioning products with a large market share of the coalition in Russia.

We show the convexity of $\Delta \ln(Y)$ with respect to Ω^g_{CO} in Appendix B.2 and illustrate this point in Figure 6 for $\sigma^g = 5$ and $\theta^g = 0.2$.

4 Application to Russia

In this section, we use Equation (3) to rank products by their economic cost to Russia from an export ban by coalition countries. We then compare this ranking to current sanctions in place and use it to identify potential targets for additional restrictions on exports to Russia. We begin with describing the underlying data.

4.1 Data

To take Equation (3) to the data, we need 4 sets of variables: (1) Total expenditure over GDP on product g (λ^g). (2) The market share of the coalition in Russia (Ω^g_{CO}). (3) The elasticity of substitution at the 6-digit HS level σ^g. (4) And the elasticity of substitution across inputs of downstream buyers (θ^g).

To measure λ^g and Ω^g_{CO}, we start from trade data for 2019 from the Atlas of Economic Complexity.[12] This data provides us with trade at the exporter-importer-product level for 6-digit HS products. It does not, however, provide us with Russia's home share in a 6-digit HS product. To estimate this, we complement the trade data with data from the ITPD-E, which provides us with Russian home shares in year 2013 for 37 industries.[13] We use this data to compute the ratio of Russian home sales to exports by industry. We then assume that this ratio is constant for all products within an industry to impute Russia's home sales for 6-digit HS products. We finally combine this estimate with the trade data to get λ^g and Ω^g_{CO}.

Elasticities of substitution across varieties of 6-digit HS products, σ^g, are from Fontagné et al. (2022). To reduce noise, we winsorize these elasticities at the 10th and the 90th percentile. To classify products into consumer goods, intermediates, and capital goods, we use the classification of broad economic categories (BEC), rev. 4. Consumer goods are directly used in final good production. In combination with our assumption of a Cobb-Douglas final-good aggregator this implies $\theta^g = 1$ for all consumer goods. As opposed to that, intermediates are combined in downstream CES aggregators, and we assume an elasticity of substitution across intermediate inputs of $\theta^g = 0.2$.[14]

[12] The data was downloaded in March 2022 from https://atlas.cid.harvard.edu/.

[13] The data was downloaded from https://www.usitc.gov/data/gravity/itpde_guide/construction/#construction-of-the-international-trade-data in March 2022.

[14] As noted in Baqaee and Farhi (2021), this is broadly in line with Atalay (2017), Boehm et al. (2019), and Herrendorf et al. (2013). When compared to Baqaee and Farhi (2021), we simplify by assuming Cobb-Douglas final consumption instead of a CES demand with elasticity of substitution of 0.9.

In what follows, we use this data to identify potential targets for bans on exports to Russia, and to compare these with export restrictions by the EU and the US. The data on the latter is from the Global Trade Alert.

4.2 Ranking

Table 1 lists the top-20 products according to Equation (3). Not surprisingly, these products are relatively large in terms of Russian imports, with each of them belonging to the top 10% of all products, and the top 5 products all having imports of over 1 billion USD. Yet, the table also illustrates the importance of the other factors. For example, 843680 (germination, bee-keeping plant) is ranked below 903289 (transmission for motor vehicles) even though Russian imports are larger and it imports a larger share from coalition countries. This is because 843680 has a relatively high trade elasticity. On the other hand, 940190 (parts of seats) is ranked below 843680, because the coalition has a lower share in this product in the Russian market.

The last two columns of Table 1 indicate whether the EU and the US have imposed an export ban (1) or an export control (2) on the specific product. In case of the EU, the share of the top 20 products that have been sanctioned is about the same as the average share across all products (7 out of the list of 20 products). In case of the US, the former share is larger (14 out of 20). Yet, there are many unsanctioned products that might be viable targets for additional sanctions.

Figures 7 to 9 evaluate the relationship between our rankings and sanctions in place more systematically. These figures rank products in decreasing order of the economic cost to Russia from an export ban by all coalition countries. Figure 7 then compares this ranking to the sanctions in place by the EU (left panel) and the US (right panel). In both panels, the gray histogram in the back shows the uniform distribution of ranks, i.e., a benchmark allocation of sanctions to products that is unrelated to the arguments developed here. The red histogram compares this benchmark to the actual sanctions in place by the EU and the US, respectively, considering US export bans and controls combined.[15] Figure 7 shows that the export restrictions to Russia in place by both the EU and the US are biased towards highly ranked products. This, however, is entirely driven by the fact that export restrictions are biased towards products that are large in terms of Russian expenditure on these products

[15] To derive the ranking, we assume that the entire coalition adopts the sanctions. Hence, strictly speaking, the red histograms consider the desirability of EU and US sanctions, respectively, if the entire coalition were to adopt them.

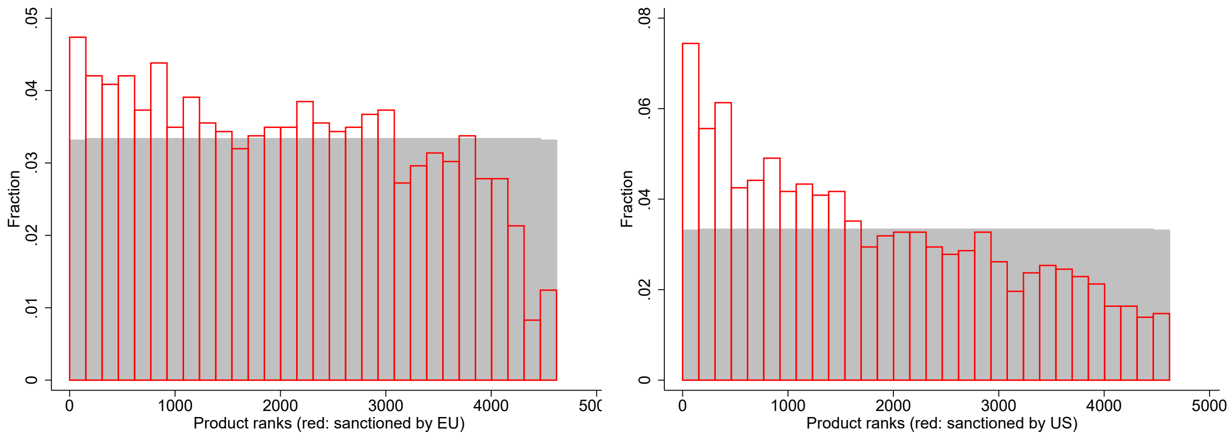
Table 1: Top 20 Products

Rank	HS-6	Description	Russian Imports	Coalition Share	Durables	Intermediate Good	Capital Good	Elasticity	Sanction EU	Sanction US
1	870323	Automobiles, spark ignition, 1500-3000cc	$5.30 B	0.18	1	0	0	-9.37	0	2
2	300490	Medicaments, doses, nes	$7.33 B	0.54	0	0	0	-20.1	0	0
3	870829	Parts of motor vehicle bodies	$1.47 B	0.43	0	1	0	-4.78	0	0
4	848180	Taps, cocks, valves, appliances, nes	$1.58 B	0.31	0	1	0	-3.48	1	2
5	847989	Machines & mechanical appliances nes	$1.18 B	0.48	0	0	1	-4.47	1	2
6	901890	Instruments for medical science, nes	$691 M	0.68	0	0	1	-3.86	1	2
7	870333	Automobiles, diesel, >2500cc	$1.51 B	0.48	1	0	0	-7.27	0	2
8	870899	Motor vehicle parts nes	$1.77 B	0.28	0	1	0	-6.47	0	2
9	330210	Mixed odors, food & drink	$354 M	0.79	0	1	0	-3.48	0	0
10	880240	Fixed wing aircraft, >15,000kg	$2.70 B	0.16	0	0	1	-13.8	1	2
11	903289	Automatic controlling equipment nes	$394 M	0.68	0	0	1	-3.48	0	2
12	870840	Transmissions for motor vehicles	$1.15 B	0.49	0	1	0	-6.99	0	0
13	870324	Automobiles, spark ignition, >3000cc	$1.17 B	0.39	1	0	0	-7.40	0	2
14	841989	Machinery for temperature change	$670 M	0.59	0	0	1	-5.05	1	2
15	271000	Oils petroleum, bituminous, distillates	$1.23 B	0.010	0	0	0	-4.31	1	2
16	853710	Electrical control & distribution boards, <1kV	$851 M	0.19	0	1	0	-4.72	1	2
17	870332	Automobiles, diesel, 1500-2500cc	$1.15 B	0.28	1	0	0	-7.55	0	2
18	843680	Germination, bee-keeping plant	$417 M	0.92	0	0	1	-8.57	0	0
19	901819	Electro-diagnostic apparatus	$371 M	0.74	0	0	1	-4.45	0	2
20	940190	Parts of seats	$403 M	0.51	0	1	0	-3.72	0	0

Notes This table shows the top 20 products according to Equation (3). The last two columns indicate whether the product has been sanctioned by the EU and the US, respectively. A 1 indicates an export ban and a 2 an export control.
Data: See Section 4.1.

Figure 7: EU and US Export Restrictions vs Ranking by Equation (3)

(a) EU (b) US



Notes: This figure compares the export restrictions by the EU (left) and the US (right), respectively, to a ranking of products by Equation (3). The gray box in the back shows a uniform distribution over these ranks, i.e., a distribution of products that is unrelated to Equation (3). The red histogram in the front shows the distribution of EU and US export restrictions, respectively, considering US export bans and controls combined.
Data: See Section 4.1.

as summarized in λ^g in Equation (3). It is known since Hulten (1978) that λ^g is an important factor of the cost to Russia from an export ban, and this is also the case here. At the same time, however, the foregone exports by the coalition also scale with λ^g and, hence, potential costs to the sanctioners. We will consider these costs in our quantitative exercise in Section 5. For now, we note that an alternative criterion for prioritizing bans on exports to Russia would therefore be to focus on products where the economic cost to Russia per foregone dollar of coalition exports are highest. Proposition 1 readily lends itself to such an analysis: Dividing Equation (3) by total coalition exports yields

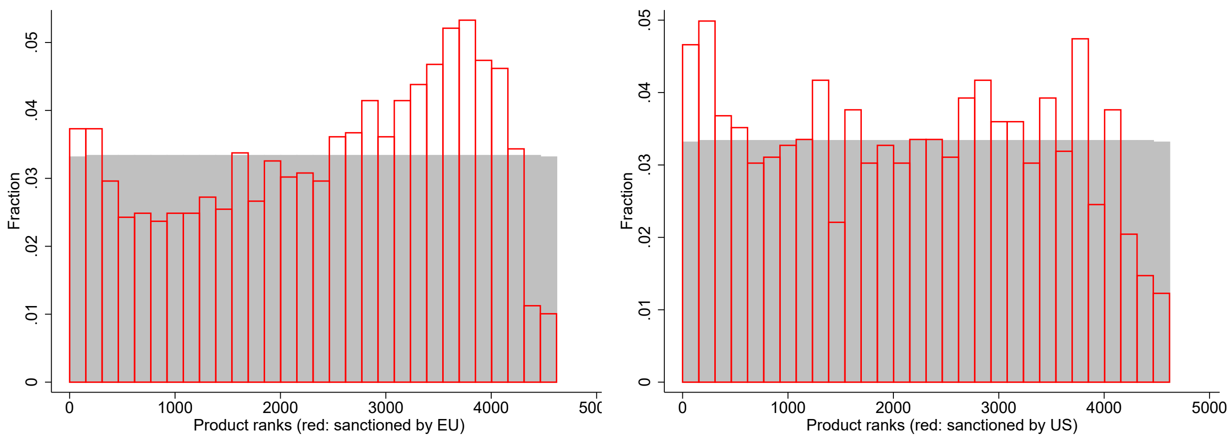
$$\frac{\Delta \ln(Y)}{\Omega_{CO}^g P^g Q^g} \underset{\sim}{\propto} \frac{1}{\Omega_{CO}^g} \left[\frac{1}{\sigma^g - 1} \ln\left(1 - \Omega_{CO}^g\right) + \left(\theta^g - 1\right) \left[\frac{1}{\sigma^g - 1} \ln\left(1 - \Omega_{CO}^g\right) \right]^2 \right]. \tag{4}$$

Figure 8 compares this alternative criterion to the sanctions in place by the EU and the US to find no systematic relationship. That is, EU and US sanctions are concentrated on large products in terms of Russian expenditure, but less so on products with low elasticities of substitution or a large market share of the coalition in Russia, in line with our discussions of Section 2. This suggests that there is potential for improving the effectiveness of bans on exports to Russia. We will get back to this point in Section 5.

Moreover, even when accounting for λ^g, there are many highly ranked products that are not

Figure 8: EU and US Export Restrictions vs Ranking by Equation (4)

(a) EU (b) US



Notes: This figure compares the export restrictions by the EU (left) and the US (right), respectively to a ranking of products by Equation (4). The gray box in the back shows a uniform distribution over these ranks, i.e., a distribution of products that is unrelated to Equation (4). The red histogram in the front shows the distribution of EU and US export restrictions, respectively, considering US export bans and controls combined.
Data: See Section 4.1.

subject to export restrictions. This may be seen from Figure 9, which shows the frequency distribution of non-sanctioned products by the EU and the US, respectively, over ranks based on our baseline criterion from Equation (3). In other words, there is ample room for identifying target products for impactful additional sanctions. The arguments developed here may help identify such products.

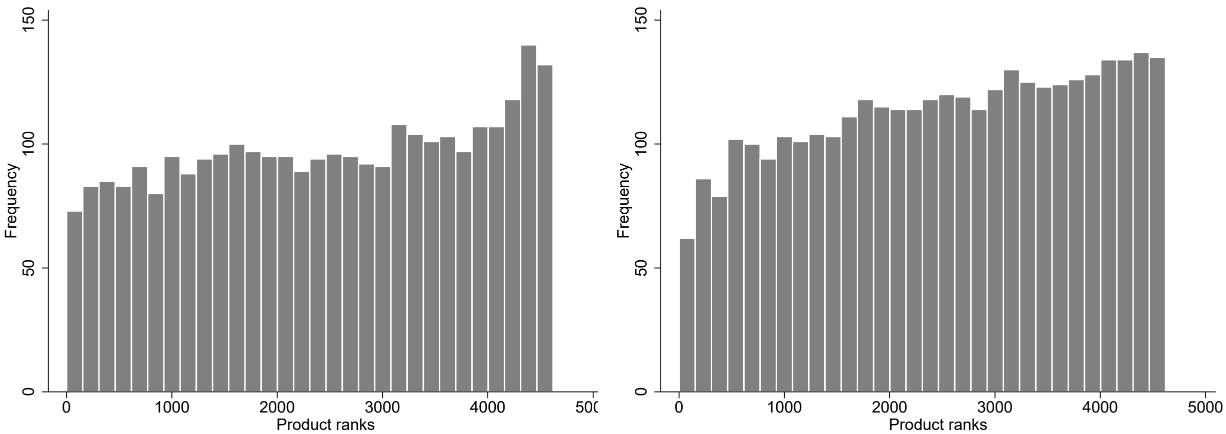
Equations (3) and (4) provide theoretically grounded, transparent, and easily implementable *ex ante* guidance on the cost from a ban on exports of a product by coalition countries to Russia.[16] To derive this equation, we assumed an input-output structure with a production hierarchy, and then considered sanctioning one product at a time. That is, Equation (3) and (4) ignore potential interaction effects between the sanctions. Introducing such interactions would allow to refine targeting the sanctions. In particular, there should be gains from jointly banning exports of products that are close substitutes to each other. While it is difficult to get data on elasticities at such a detailed level, one way forward might be to group products into industries and then postulate that pairs of products in the same industry are closer substitutes than pairs of products in different industries. In such case, there would be additional gains

[16]To take Equations (3) and (4) to the data, we rely on imputations of the Russian home share in a product, i.e., the Russian market share in its domestic market, and on trade elasticities that are estimated with uncertainty. Appendix A.1 shows that the ranking is robust to alternative choices for these parameters, and particularly so at the tails, i.e., among the highest and the lowest ranked products.

Figure 9: Products not Subject to an Export Restriction by the EU and the US

(a) EU

(b) US



Notes: This figure shows the frequency distribution of products without export restrictions by the EU (left) and the US (right), respectively, over product ranks according to Equation (3).
Data: See Section 4.1.

from concentrating bans at the industry level.

Our simplifying assumptions are in part driven by data limitations and in particular, at the level of disaggregation considered here, there is no data on input-output linkages. Yet, these simplifications are also needed to increase the tractability of the problem. Even with better data, identifying an optimal combination of export restrictions with rich input-output linkages would be difficult due to the high dimensionality of the problem and the non-linearities involved. Equation (3) and (4) therefore represent a reasonable compromise that can provide valuable guidance on this issue in richer environments as well. To show this and shed light on the costs involved for the sanctioners, we consider a quantitative analysis next.

5 Quantitative Evaluation of Export Bans

In this section, we present a quantitative assessment of the bans on exports to Russia in an environment with rich I-O linkages. A key challenge in doing so is that export restrictions by the EU and the US were imposed at the level of 6-digit HS products, and there is no data on input-output (I-O) linkages at this level of disaggregation. We therefore aggregate 6-digit HS export bans to 15 goods industries present in the World Input-Output Database (WIOD) (Timmer et al., 2015). We then assess the impact of these bans using a trade framework with international production networks analogous to Caliendo and Parro (2015); Costinot and Rodríguez-Clare (2014); Baqaee and Farhi (2021); Çakmaklı et al. (2021). We begin with outlining the economic environment.

5.1 Economic Environment

To stay as close as possible to our set-up of Section 3, we again consider an 'Armington'-type model with I countries, indexed by $i, j \in \mathcal{I}$, D industries, indexed by $d, e \in \mathcal{D}$, and perfect competition in all markets. As opposed to Section 3, however, there are no HS products. Instead, we assume that every country is equipped with a distinct variety in every industry, which are traded with an exporter-importer-industry specific iceberg trade-cost $\tau_{ij}^d \geq 1$. This provides a tractable set-up that allows calibrating our (pre-shock) model to exactly match the WIOD data. In this section, we describe our model. Technical details are relegated to Appendix B.3.

To capture the richness of the international input-output structure in the data, we assume that varieties are produced combining industry-specific labor with industry-specific intermediate input bundles in a CES production function with constant elasticity of substitution $\phi \leq 1$. $\phi \leq 1$ implies that labor and intermediate inputs are complements in production.[17] Intermediate input bundles in turn are two-tier CES-aggregators: The lower-tier combines the origin-specific varieties of, say, metals into a 'metal' bundle with constant elasticity of substitution ξ^d. The upper-tier combines input bundles from different industries into aggregate intermediate input bundles with constant elasticity of substitution ϵ. These aggregate bundles are then used in production. They are destination-country and buying-industry specific. That is, the US transport equipment industry, for example, sources a different input mix when compared to other industries in the US or the transport equipment industry in Japan. Likewise, it buys its 'metal' inputs from a range of countries, and this source country mix for metals is different from the one of other industries in the US or the transport equipment industry in other countries. We calibrate our model such that these input shares within and across industries match the data.[18]

Analogous to the intermediate inputs, final consumption is based on a two-tier CES aggregator of the varieties. These aggregators also have destination-country and final-consumption specific weights that we calibrate to match the consumption shares in the data. The lower-tier

[17] We use sector-specific factors to capture the short-run effects, following Baqaee and Farhi (2021) and Çakmaklı et al. (2021).

[18] In the WIOD data, source-country mixes for a given input typically differ across buying industries in a given destination because the home shares differ. To capture these differences in our model, we nevertheless need to allow the source-country mix of a given input to be destination and buying-industry specific.

elasticities of substitution are the same as for the intermediate-input bundles, the upper-tier elasticity ϵ^f is assumed to be larger than for the intermediate input bundles to reflect the fact that goods tend to be more substitutable in consumption than in production.

5.2 Aggregation of Export Bans

To quantitatively analyze export restrictions in place by the EU and the US and compare them to export restrictions based on our analysis of Sections 3 and 4, we feed industry-specific iceberg trade-cost shocks for exports from coalition countries to Russia into this model. We choose these trade shocks such that they have the same overall direct effect on Russian industry-level price indices as export bans have in a 'disaggregated' economy analogous to Section 3.[19] That is, an 'Armington' economy, where origin-specific varieties are combined in 6-digit HS products using CES aggregators with constant elasticity of substitution σ^g, and these products are then combined in D WIOD industries using CES aggregators with elasticity of substitution θ^d. As we show in Appendix B.4 this is the case if

$$\tau^d = \left(\frac{\left[\sum_{g \in \mathcal{G}^d \setminus \mathcal{B}^d} \Omega^{gd} + \sum_{g \in \mathcal{B}^d} \Omega^{gd} (1 - \Omega^g_{CO})^{\frac{1-\theta^d}{1-\sigma^g}} \right]^{\frac{1-\xi^d}{1-\theta^d}} - (1 - \Omega^d_{CO})}{\Omega^d_{CO}} \right)^{\frac{1}{1-\xi^d}} . \tag{5}$$

Ω^g_{CO} and Ω^d_{CO} are the market share of the coalition for product g and industry d, respectively, in Russia, Ω^{gd} is the share of Russian expenditure in industry d that is on product g, $\mathcal{G}^d$ is the set of products that belong to industry d, and $\mathcal{B}^d \subseteq \mathcal{G}^d$ the subset of these products with an export ban.[20]

[19] An alternative would be to consider a more granular economy as e.g. in di Giovanni et al. (2022). In their model, however, varieties are aggregated into country-output bundles at the WIOD-industry level that are then used as inputs into production. That is, if the 'transport equipment' industry, for example, consists of, say, cars and airplanes, then they aggregate Japanese cars and airplanes into a Japanese transport bundle which is then used for production. We are interested in analyzing trade restrictions at the 6-digit HS level and important inputs for our analysis are the coalition market share in Russia and the elasticity of substitution at the level of 6-digit HS products—see Proposition 1. We therefore opt for computing shocks to Russia at the 6-digit HS product level first, and then aggregating them to the WIOD level in a way that preserves the direct effect on Russian industry-level prices. See Appendix B.4 for further details.

[20] In the economy of Section 5.1, input shares are buying-industry specific. That is, the coalition share in industry d in Russia depends on which Russian industry is buying d. In principle, it would be possible to account for this heterogeneity by introducing iceberg trade-cost shocks from coalition countries to Russia that are industry-pair specific, i.e., specific to the selling and the Russian buying industry (or final consumer). We simplify matters by considering a single trade shock per export industry from coalition countries.

5.3 Data and Parameter Choices

To take the model of Section 5.1 to the data and quantitatively assess the export bans, we need information on international input-output linkages, coalition shares in Russia, and elasticities of substitution as introduced in the previous sections.

We take industry-level trade data with international input-output linkages from the World Input-Output Database (WIOD), which provides us with information for 41 countries and 30 industries.[21] To decrease the computational burden, we aggregate countries into 18 country groups.[22] Further, we aggregate industries into 16 by collapsing all service industries. A list of countries and industries can be found in Table A.1 of the Appendix. We combine the WIOD data with the product level trade data as discussed in Section 4.1, from which we observe the coalition shares in Russia at the 6-digit HS-level (Ω^g_{CO}) and the share of 6-digit HS products in the total Russian expenditure on a WIOD industry (Ω^{gd}).

This leaves us with 6 sets of elasticities that need to be specified: $\{\xi^d\}_{d\in\mathcal{D}}$, ϵ, ϕ, ϵ^f, $\{\sigma^g\}_{g\in\mathcal{G}}$, and $\{\theta^d\}_{d\in\mathcal{D}}$. We obtain the elasticities of substitution across varieties in WIOD industries in the 'aggregated' economy, ξ^d, from Caliendo and Parro (2015).[23] For the upper-tier elasticities across input bundles from different industries, we follow Baqaee and Farhi (2021) and Çakmaklı et al. (2021) and select $\epsilon = 0.2$, which is broadly in line with Atalay (2017), Boehm et al. (2019), and Herrendorf et al. (2013). For the elasticity between labor and intermediate inputs in production, we choose $\phi = 0.6$ (Baqaee and Farhi, 2021; Çakmaklı et al., 2021; Di Giovanni et al., 2022). On the consumption side, we assume that there is greater scope to substitute across industries and choose a Cobb-Douglas function with $\epsilon^f = 1$. To take Equation (5) to the data, we further need elasticities from the 'disaggregated' economy. We take the elasticities across varieties of 6-digit HS products from Fontagné et al. (2022), as discussed in Section 4.1. Lastly, we need to choose the elasticity of substitution across intermediate inputs in the disaggregated economy, θ^d. Note that this elasticity is different from ξ^d: The former refers to the elasticity of substitution across different 6-digit HS products within a WIOD industry. The latter refers to substitution across different source countries at the level of 15 industries and, hence, also reflects substitution taking place within narrowly defined underlying 6-digit HS product categories. This suggests that $\theta^d \leq \xi^d$. To err on the

[21] We use the WIOD data processed by Baqaee and Farhi (2021).

[22] We aggregate countries by geographic proximity. Specifically, we aggregate the Baltic countries, EU members other than DEU, FIN, FRA, ITA, and the Baltic countries, as well as Australia & Taiwan and Mexico & Brazil, respectively.

[23] Caliendo and Parro (2015) provide trade elasticities at the WIOD industry level. These trade elasticities correspond to $\xi^d - 1$ in our model. Table A.1 lists ξ^d for the industries in our sample.

Table 2: Elasticities

Parameter	Value	Description
σ^g	Fontagné et al. (2022)	Elasticity of substitution across HS-6 level varieties
θ^d	Caliendo and Parro (2015)	Elasticity of substitution across HS-6 level products in the aggregation to WIOD industries
ξ^d	Caliendo and Parro (2015)	Elasticity of substitution across WIOD varieties
ϵ	0.2	Elasticity of substitution across intermediate inputs
ϕ	0.6	Elasticity of substitution between labor and intermediates
ϵ^f	1 (Cobb-Douglas)	Elasticity of substitution between sectors in consumption

Notes: This table provides an overview of the different elasticities used for our quantitative analysis.

side of caution and for lack of data, we choose $\theta^d = \xi^d$, i.e, we use the sector-specific values from Caliendo and Parro (2015) as well. Table 2 shows the summary of all elasticities we used in our empirical analysis. In Section B.5 of the Appendix, we use different values for these elasticities as a robustness exercise.

5.4 Quantitative Results

To assess the impact of the sanctions on the Russian economy, we run six different scenarios. In the first scenario, we take the EU and US sanctions as is.[24] In the second scenario, we evaluate the economic impact of the sanctions if all coalition countries were to adopt EU sanctions. In the third scenario, we do the same but with the US sanctions instead of EU sanctions. In the fourth scenario, we consider the case where the EU & the US sanctions remain in place, but in addition all coalition countries (i.e., including the EU & the US) adopt optimal sanctions according to Equation (4) in Section 4. That is, we add the top products according to the ranking in Figure 8. We choose the number of banned products such that the total banned exports from coalition countries to Russia are the same as if all coalition countries were to adopt the EU sanctions (scenario 2). In scenario 5, we consider the case where all coalition countries impose bans on exports to Russia following the ranking in Figure 8, again choosing the number of banned products such that the total banned exports from coalition countries to Russia are the same as in scenario 2. Lastly, in scenario 6 we consider again optimal sanctions, but choosing the number of banned products such that the total pre-crisis exports of coalition countries to Russia that are subject to the ban are 1.5

[24]This scenario underestimates the total effect of export restrictions by *all* coalition countries. This is because—due to data constraints—we consider restrictions imposed by the EU and the US only, and do not account for sanctions imposed by other coalition members.

times those of scenario 2.[25]

Figure 10a shows the economic impact of the sanctions on the coalition (left, blue bar) and Russia (right, red bar), respectively, under the six different scenarios.[26] In all scenarios, the economic cost of the export bans are much larger for Russia than for the coalition. This is true when comparing absolute costs as indicated by the heights of the bars in the figure: These costs are by at least a factor 2 larger for Russia and, in case of sanctions based on our criterion—scenario 5—even a factor of more than 5—we will get back to this point momentarily. Differences are even more dramatic when considering proportionate welfare losses instead as indicated by the percentages on top of the bars: These proportionate losses are by a factor of ~ 100 smaller for the coalition than for Russia.

Not surprisingly, the quantifications also suggest that the cost to Russia would increase vis-à-vis scenario 1 if all coalition countries were to adopt the EU and / or the US sanctions (scenarios 2 and 3). This is because in such case the total amount of banned exports increases, and the sanctions are getting perfectly coordinated, which implies that the share of Russian imports of a product that is banned tends to increase. Scenario 4 sheds light on the respective importance of these two forces. In this scenario, we keep the total banned exports the same as in scenario 2, but with less coordination among the coalition. The results suggest that the extra costs to Russia from an improved coordination (scenario 2 vs. scenario 4) are as big or even bigger than the extra cost from an expansion of the sanctions (scenario 4 vs. scenario 1), in line with our theoretical reasoning of Section 3.[27]

Interestingly, even with perfect coordination and for a given amount of total banned exports, there is large scope for improving the effectiveness of the sanctions. This is shown in scenario 5, where we assume that all coalition countries adopt sanctions following our criterion from Section 4. In such case, the cost to Russia increase by an additional $\sim 30\%$ compared to scenario 2 at very little extra cost to the coalition. Combined, this implies that our arguments developed here—i.e., improved coordination and targeting sanctions based on our

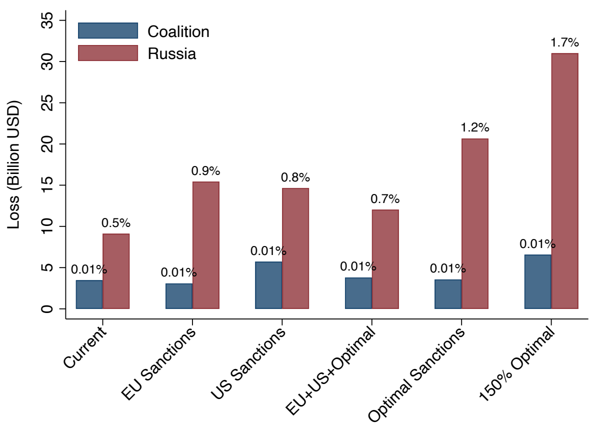
[25] We note that in scenarios 1 and 4 the iceberg shocks differ across coalition members. This is to reflect the heterogeneity of sanctions in these scenarios. To compute these heterogeneous shocks within industries, we proceed in two steps: We first compute shocks according to Equation (5), considering one coalition member at a time. We then scale these shocks proportionally to ensure that Equation (5) is satisfied with all shocks combined.

[26] In Section B.5 of the Appendix, we run this exercise with different parameter choices for the elasticities of substitution, to find patterns consistent with Figure 10.

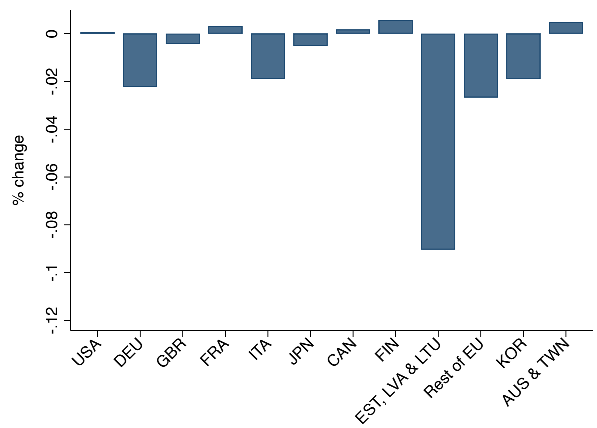
[27] We note that this comparison likely underestimates the gains from coordination for two reasons: First, sanctions in scenario 4 are more coordinated when compared to scenario 1 because we assume that the entire coalition adopts the additional sanctions that are needed to get to the same total banned exports as in scenario 2. Second, these additional sanctions are chosen following our ranking from Section 4, which should also increase their effectiveness as shown in scenario 5.

Figure 10: Different Sanction Scenarios

(a) Losses for the coalition and Russia



(b) Impact of optimal sanctions on coalition



Notes: This figure shows the results of our quantitative exercise using the elasticities of substitution shown in Table 2. The left panel shows the cost to the coalition (blue, left bar) and to Russia (red, right bar), respectively for different scenarios. The right panel shows the cost by coalition country from scenario 5 ("Optimal Sanctions").

criterion—allow to increase the cost to Russia by $\sim 60\%$ with little to no extra cost to the coalition (scenario 5 vs. scenario 4).

In scenarios 2, 4, and 5, $\sim 45\%$ of all coalition exports to Russia are banned. This suggests scope for tightening the sanctions even further, as shown in scenario 6. In this scenario, we again consider sanctions following our criterion of Section 4, but expanding the sanctions such that 50% more exports are banned when compared to scenario 2. As the figure shows, this has a further sizable effect on the cost to Russia.

Figure 10b shows the impact of the export restrictions from scenario 5 on coalition countries separately. The largest losses are observed in the Baltic countries (Estonia, Latvia and Lithuania). This is consistent with the proximity and historical ties that these countries have with Russia and, hence, the relatively large importance of Russia for these countries as a trading partner. But even for these countries, the welfare losses are by a factor of more than 10 smaller when compared to Russia—see Figure 10a. All other countries face much smaller losses or they even gain.

While the cost to Russia are much larger than the cost to coalition countries, the welfare loss of 1.1% in scenario 5 is nevertheless moderate. This loss is in the same magnitude as similar numbers in related work, e.g., Bachmann et al. (2022); Evenett and Muendler (2022b). More importantly, our main interest is less in the point estimates but more in the relative sizes of the cost to Russia across the different scenarios, and the cost to Russia vis-à-vis the coalition. To the extent that our quantification is not biased in favor of specific countries or scenarios, these insights are robust. Nevertheless, two remarks are in order regarding the estimated costs: First, we consider only restrictions on exports to Russia, and do not account for sanctions on imports from Russia or financial sanctions, for example. The overall cost to Russia from the sanctions may therefore be much higher.[28] Second, some of the elasticities that we use are estimated from small shocks, while we consider large shocks in our analysis. Our quantification may thus over-estimate Russia's ability to substitute for its missing inputs. Indeed, Russian officials warn that the lack of critical imports from coalition countries and the lack of good alternatives are a significant threat for the Russian economy (Bloomberg, 2022).

In sum, these quantifications strongly suggest that export restrictions inflict higher costs on Russia than on the coalition, a key guiding principle for the sanctions. While this is true for all six scenarios considered, there is great potential for improving the effectiveness of the sanctions by re-designing them based on the arguments developed here. Our quantifications suggest that improved coordination and targeting sanctions based on the ranking in Section 4 could increase the economic cost to Russia by $\sim 60\%$ at little to no extra cost to the coalition.

6 Discussion and Conclusion

Economic sanctions are among the swiftest policy measures taken by countries at the onset of international crisis. In today's globalized economy, such sanctions allow to exert pressure on aggressors without direct engagement in an armed conflict, and particularly so if the leading economies of the world participate in the sanctions. A case in point are the international sanctions against Russia in response to its invasion of Ukraine starting in February 2022, which are the main focus of our analysis. We show that restrictions on exports to a sanctioned country are an effective policy instrument in this regard, and propose an intuitive, theoretically grounded, and easily-implementable criterion that provides guidance on which products to sanction. A quantitative analysis suggests that following this criterion could significantly increase the effectiveness of restrictions on exports to Russia.

Our analysis captures important drivers of the cost to Russia from an export ban, but it leaves out of account other dimensions that are important for designing sanctions. In our

[28] Evenett and Muendler (2022a) show that the cost to Russia could be increased further by sanctioning transportation and increasing shipping costs to and from Russia.

analysis, we assume that sanctions are fully effective, while in practice, sanctions may be undermined through parallel imports. Miromanova (2022), for example, discusses anecdotal evidence suggesting that smuggling might have partially undermined the Russian ban on imports from the 'West' that it imposed as a retaliation to sanctions that it was confronted with following its annexation of Crimea in 2014. She does, however, not find systematic evidence in official trade statistics. When it comes to the sanctions imposed against Russia in 2022, parallel imports are hindered by the fact that many sanctions were also imposed on Belarus. More generally, to the extent that there are no systematic biases across products in terms of how easy parallel imports are, such leakages will lower the overall effectiveness of sanctions, but not our arguments for prioritizing sanctions at a disaggregated product level.

In Section 3, we have shown that the cost to Russia of a ban on exports by coalition countries are highly convex in the market share of the coalition. Hence, there are large gains from coordinating sanctions among a broad coalition of countries. Such coordination may be challenging. In Section 4.2, we have ignored this and ranked products, holding the set of countries in the coalition constant. An alternative exercise would be to identify products where exports to Russia are concentrated in a small set of countries, i.e., where only a small coalition of countries is required to cut Russia off its supplies of these products. Our framework readily lends itself to such an analysis as well.

Russia might retaliate by imposing sanctions on its own. For example, in response to sanctions imposed in 2014, Russia retaliated by banning imports of agricultural products from Western countries (Crozet and Hinz, 2020; Hinz and Monastyrenko, 2022; Miromanova, 2022). Such retaliations might significantly increase the costs to coalition countries and, in fact, they were a major concern in the debates on sanctioning Russia following its invasion of Ukraine in 2022, in particular considering Europe's reliance on Russian energy. In our analysis we do not account for potential strategic interactions in the 'sanctions game'. Importantly, however, to the extent to which Russian retaliation does not depend on the detailed design of the sanctions that it faces but only on their overall impact, our arguments remain again intact.

In times of crisis it is desirable to impose sanctions with immediate impact. Figures 4 and A.2 suggest room for sharpening sanctions against Russia along this dimension as well. These figures show that the export restrictions imposed by the EU and the US are heavily biased towards capital goods. This may limit the short-run impact of the sanctions, as Russia can live off pre-existing stocks.[29] A detailed account of capital goods is beyond the scope of

[29] In line with these arguments, internal Russian documents as summarized by Bloomberg (2022) raise the concern that, e.g., lack of access to foreign-made planes or spare parts could lead the aviation '*fleet to shrink*

our paper. Nevertheless, the main point can be illustrated by means of a stylized example. Suppose, for simplicity, that flow services of a capital good are a Cobb-Douglas aggregator of the pre-existing stock with the flow investment, and where the flow investment has a weight of δ^g. In such case, ceteris paribus, a shock Δ to the price of the flow investment translates into a shock Δ^{δ^g} to the price of the flow service of the capital good. Hence, the direct effect of the shock is

$$\hat{P}^g \approx (1 - \Omega^g_{CO})^{\frac{\delta^g}{1-\sigma^g}} , \tag{6}$$

and the short-term impact of an export ban on capital goods is attenuated by a factor $\sim \delta^g$ vis-à-vis a ban on intermediate goods.[30]

There may be motives for the focus on, e.g., capital goods not captured by our theoretical framework. At a general level, the sanctions were intended to undermine Russia's ability to project power. An important means to this end is to limit Russia's ability to finance its war and to undermine its economic strength. Indeed, the trade restrictions were '*designed to maximise the negative impact of the sanctions for the Russian economy while limiting the consequences for EU businesses and citizens*' (European Council and Council of the EU, 2022). Our analysis suggests that export bans might be effective in this regard and they can be designed to maximize impact. Yet, Russia's economy heavily relies on energy exports, and revenues from related taxes accounted for 45% of Russia's federal budget pre-crisis.[31] Targeting Russia's energy sector directly may therefore be very effective. In the short run, this boils down to reducing Russian rents from its direct energy exports to the sanctioners. Indeed, this goal has featured prominently in academic and policy debates (see, e.g., Hausmann 2022; Bachmann et al. 2022; Baqaee et al. 2022; Bayer et al. 2022; Berger et al. 2022; Gros 2022; Hausmann et al. 2022b,a), and the EU has made impressive progress on that front, reducing its natural gas imports from Russia by 80% vis-à-vis 2021, for example.[32] Over a longer time horizon, however, Russia may redirect its energy exports, and a complementary policy instrument is therefore to deprive Russia of critical inputs for its energy industry, which was an important motive underlying the export restrictions.[33] Similarly, the export restrictions were designed to undermine Russia's military capacity.[34] Analyzing the effectiveness of the

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as they go out of service'.

[30]We note that relying too heavily on pre-existing stocks without proper replacement for defect components may increase the depreciation rate and, hence, have costs not captured by our previous arguments.

[31]https://www.iea.org/articles/frequently-asked-questions-on-energy-security, accessed on 11 Jan 2023.

[32]Source: https://www.bruegel.org/dataset/european-natural-gas-imports, accessed on 10 Jan 2023.

[33]See e.g. https://www.consilium.europa.eu/en/press/press-releases/2022/02/25/russia-s-military-aggression-against-ukraine-eu-imposes-sanctions-against-president-putin-and-foreign-minister-lavrov-and-adopts-wide-ranging-individual-and-economic-sanctions/, accessed on 11 Jan 2023.

[34]Andrew Griffith, Ecocnomic Secretary to the UK Treasury, for example, said *'We have imposed the*

sanctions in terms of undermining the Russian war and energy capabilities would require a detailed account of the input requirements of these Russian sectors and the identification of potential bottlenecks. Such an in-depth analysis of the energy and military sectors would be a promising avenue for future research.[35]

A war economy like Russia is also prone to distortions. In principle, the framework by Baqaee and Farhi (2021) allows for rich distortions. We are, however, not aware of good data that would allow disciplining these at the granular level at which we rank products or for the purpose of our quantitative analysis, and we therefore ignore them throughout. Analyzing distortions would be a promising avenue for future research. This might also allow shedding light on relevant interactions between financial sanctions and export restrictions, for example.

Lastly, our analysis does not take into consideration ethical and distributional consequences of the sanctions. For example, coalition countries directly targeted individuals with political power, executive positions in the defense industry, or who were directly engaged in war crimes. On the contrary, export and import restrictions '*exclude products primarily intended for consumption and products related to health, pharma, food and agriculture, in order not to harm the Russian population*' (European Council and Council of the EU, 2022). Such motives are important in their own rights, but they are not readily quantifiable. They therefore need to be considered on a case-by-case basis when designing sanctions.

In sum, designing economic sanctions is an intricate task. There are a multitude of instruments available, sanctions are particularly effective when coordinated among a broad coalition of countries, their effects are difficult to predict, and they also impact the sanctioners themselves. The latter concern features prominently in the debates on sanctioning Russia, and it is widely agreed that, at the least, sanctions should '*damage Russia more than the sanctioners*' (Olaf Scholz, chancellor of Germany, on 19 May 2022).[36] We show that

most severe sanctions ever on Russia and it is crippling their war machine.' Source: https://www.gov.uk/government/news/uk-sanctions-on-russia-top-18-billion-for-the-first-time, accessed on 9 Jan 2023; cf European Council and Council of the EU (2022) and https://www.defensenews.com/industry/2022/11/14/us-announces-sanctions-targeting-russian-military-suppliers/ for similar statements from the EU and the US, respectively.

[35] The WIOD data covers I-O linkages for the energy sector as well, but at an aggregated level. This or similar data has been used to evaluate the effect of energy supply or price shocks on the overall economy, e.g., Baqaee and Farhi 2019; Bachmann et al. 2022. Our main interest when it comes to understanding the implications of sanctions on the Russian energy and defense sectors is the reverse, and it would therefore ideally be rooted in a more granular account of the relevant supply chains. More generally, there may be bottlenecks in value chains that have large cascading effects and that are not captured by our quantitative analysis.

[36] Source: https://www.bundesregierung.de/breg-de/service/bulletin/regierungserklaerung-von-bundeskanzler-olaf-scholz-2041828, accessed on 31 August 2022. The original German quote is: '*Alles, was wir tun, muss Russland mehr schaden als uns selbst und unseren Partnern.*'

restrictions on exports to a sanctioned country are an effective policy instrument in this regard, and develop a theoretically grounded, transparent, and easily implementable criterion that allows to prioritize export restrictions based on their economic impact on the targeted country. This is an important motive for sanctions, and we believe that our analysis can thus provide valuable inputs for the design of effective sanctions. When designing policy, however, other motives have to be taken into account as well. Our analysis is thus best understood not as a blueprint for policy, but as a valuable and easily implementable input into a more comprehensive analytical process.

Appendix

A Empirical Appendix

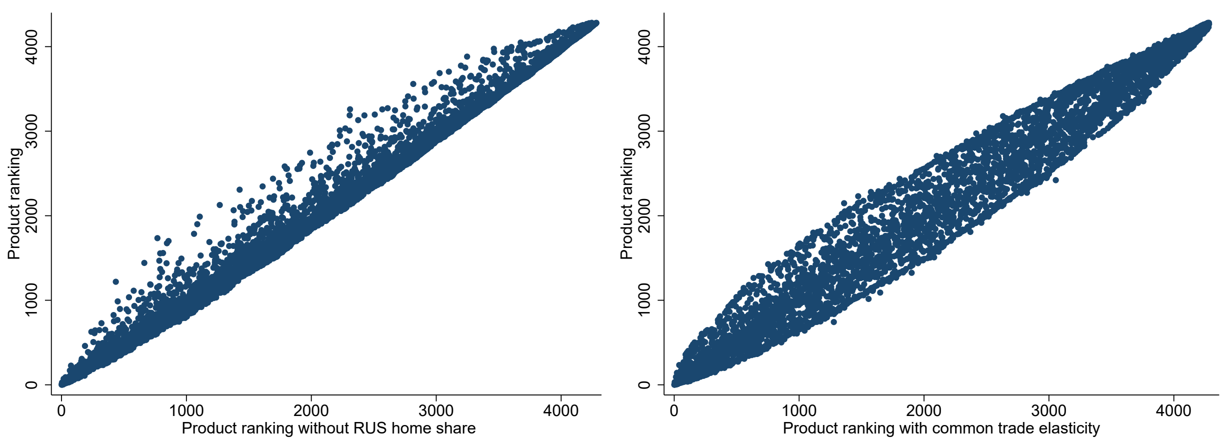
A.1 Robustness of Product Ranking

Figure A.1 shows the robustness of the product ranking according to Equation (3). Each panel presents a scatter plot with the baseline product ranking on the vertical axis and a robustness check on the horizontal axis.

Figure A.1: Robustness of Product Ranking

(a) No Home Share Russia

(b) Common Trade Elasticity



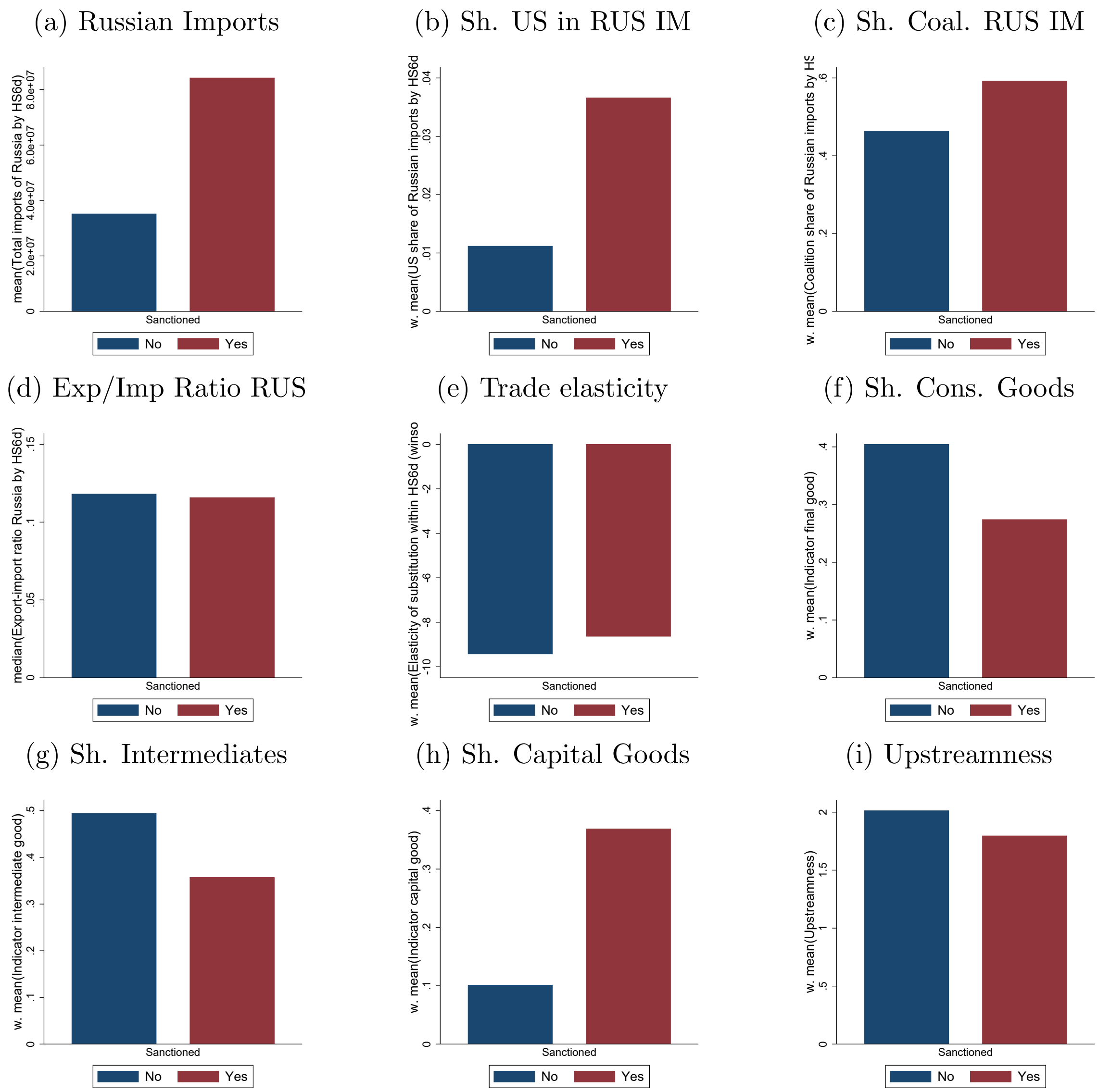
Notes: This figure shows robustness checks for a product ranking according to Equation (3). Panel (a) locates each product in a a scatter plot with its baseline ranking on the vertical axis and a ranking without Russian homeshares on the horizontal axis. Panel (b) shows an analogous scatter plot, but where the ranking on the horizontal axis has been computed assuming a common trade elasticity of -8.2, which is the median trade elasticity at the 6-digit HS level in Fontagné et al. (2022).
Data: See Section 4.1.

To measure the total expenditure over GDP on product g (λ^g) and the share of the coalition in Russian expenditure (Ω^g_{CO}), we rely on an imputation of the Russian home share in a product—see Section 4.1. Panel (a) shows a robustness check where we ignore the Russian home share. Panel (b) shows a ranking assuming that σ^g is constant across products and equal to 1 + the median trade elasticity in our data. As may be seen from the figures, the ranking is quite robust and particularly so in the tail of the ranking. The rank correlation is .99 for panel (a) and .98 for panel (b), and out of the top 1'000 products according to the main ranking, 934 (panel (a)) and 880 (b) are also among the top-1'000 products in the respective robustness check.

A.2 Additional Figures

Figure A.2 replicates Figure 4 from the main text, but considering export restrictions imposed by the US instead of the EU.

Figure A.2: Characteristics of Products with vs. without US Export Restrictions



Notes: The figure compares 6-digit HS products with a US export ban or control (blue, left bar) to those without a US export ban or control (red, right bar) along the dimensions as specified in the panel titles. Bars refer to weighted means with weights given by Russia's imports, with the exception of panel (a), which considers simple means, and panel (d), which considers the median.
Data: Data on an industry's upstreamness (panel (i)) for over 400 NAICS industries is from Antràs et al. (2012). We match NAICS industries to the HS system using the concordance from the BEA (https://www.bea.gov/sites/default/files/2018-04/HSConcord.xls). For all other data, see Section 4.1.

A.3 Overview of Countries and Industries in Section 5

Table A.1 provides an overview of the countries and industries included in our quantitative analysis, along with the industry-level elasticities from Caliendo and Parro (2015).

Table A.1: List of countries and industries

	Countries	**Industries**	ξ^d
1	USA	Agriculture, Hunting, Forestry & Fishing	9.11
2	Germany	Mining & Quarrying	16.72
3	United Kingdom	Food, Beverages & Tobacco	3.55
4	France	Textiles & Textile Products	6.56
5	Italy	Leather, Leather & Footwear	6.56
6	Japan	Wood & Products of Wood & Cork	11.83
7	Canada	Pulp, Paper, Printing & Publishing	10.07
8	Finland	Coke, Refined Petroleum & Nuclear Fuel	52.08
9	Estonia, Latvia & Lithuania	Chemicals & Chemical Products	5.75
10	Rest of European Union	Rubber & Plastics	5.75
11	Republic of Korea	Other Non-Metallic Mineral	3.76
12	Australia & Taiwan	Basic Metals & Fabricated Metal	8.99
13	China	Electrical & Optical Equipment	11.6
14	India	Machinery, NEC	2.52
15	Turkey	Transport Equipment	1.37
16	Mexico & Brazil	Services	6
17	Russia		
18	Rest of the World		

Notes: This table provides an overview of the countries and industries included in our quantitative analysis of Section 5. The last column shows the industry-level elasticities from Caliendo and Parro (2015).

B Mathematical Appendix

B.1 Derivation of Equation (3)

In this appendix, we derive Equation (3). To do so, we build on the second-order duality (Corollary 4) in Baqaee and Farhi (2021).

Baqaee and Farhi (2021, Theorem 7) show that a trade shock in an open economy has the same impact on welfare as a matching productivity shock in a 'dual' closed economy has on GDP. In our economy, the dual shock to an export ban on g by coalition countries is given by

$$\Delta \ln \breve{A}^g = \Delta \ln(P^g),$$

where here an below $\breve{x}$ indicates variable x in the dual closed economy. Combining this with the results in Baqaee and Farhi (2019) allows deriving a second-order approximation for the impact of the original shock in the open economy (Baqaee and Farhi 2021, Corollary 4). To simplify notation, let the 6-digit HS producer both produce the domestic variety from labor and combine this variety with imported varieties in the CES aggregator. Let $\mathcal{G}$ be the set of all such 6-digit HS producers, $\mathcal{D}$ be the set of downstream producers, and $\mathcal{H} := \mathcal{G} \bigcup \mathcal{D} \bigcup L \bigcup Y$, i.e., $\mathcal{H}$ is the union of the sets of all producers including the primary factor. Consider a shock to one HS-producer $g \in \mathcal{G}$ only. The impact of this shock is then approximately given by

$$\Delta \ln \check{Y} \approx \check{\lambda}^g \Delta \ln \check{A}^g + \frac{1}{2} \sum_{k \in \mathcal{H}} \epsilon^k \check{\lambda}^k \left[\check{\sum}_{l \in \mathcal{H}} \check{\Omega}^{kl} \left(\check{\Psi}^{lg} \Delta \ln \check{A}^g \right)^2 - \left(\sum_{l \in \mathcal{H}} \check{\Omega}^{kl} \check{\Psi}^{lg} \Delta \ln \check{A}^g \right)^2 \right], \quad (7)$$

where ϵ^k is -1 plus the elasticity of substitution across k's inputs, $\check{\Omega}^{kl}$ is k's expenditure on l's input as a fraction of k's revenues, and $\check{\Psi}^{lg}$ is element lg of the Leontief inverse of matrix $\check{\boldsymbol{\Omega}}$, i.e.,

$$\check{\boldsymbol{\Psi}} := \boldsymbol{I} + \check{\boldsymbol{\Omega}} + \check{\boldsymbol{\Omega}}^{\mathbf{2}} + \ldots .$$

$\check{\boldsymbol{\Psi}}$ measures the direct and indirect dependence of l on g. Intutively, the second order term aggregates across all buyers k of g their ability to substitute away from g. The latter is governed by the elasticity of substitution across k's inputs, ϵ^k, and the differential exposure of all of k's suppliers to the shock to g.

Now, $\check{\boldsymbol{\Omega}}$ is a matrix of expenditure shares in the dual closed economy, i.e., a matrix of expenditure shares on domestic inputs scaled to sum to 1. In our economy, $\check{\boldsymbol{\Omega}}$ therefore has the following structure

$$\check{\boldsymbol{\Omega}} = \begin{array}{cc} & \begin{array}{cccccccc} L & & G & & & D & & Y \end{array} \\ \begin{array}{c} L \\ \\ G \\ \\ \\ D \\ \\ Y \end{array} & \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\ \check{\Omega}^{d_1 L} & \check{\Omega}^{d_1 g_1} & . & \check{\Omega}^{d_1 g_G} & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \check{\Omega}^{d_D L} & \check{\Omega}^{d_D g_1} & . & \check{\Omega}^{d_D g_G} & 0 & \cdots & 0 & 0 \\ 0 & 0 & \cdots & 0 & \alpha^{d_1} & \cdots & \alpha^{d_D} & 0 \end{bmatrix} \end{array},$$

where α^d is the Cobb-Douglas expenditure share of the final good producer on downstream sector d. We can write this matrix in block form as

$$\check{\boldsymbol{\Omega}} = \begin{array}{r} \\ L\ (1)\,\{ \\ G\ (\mathrm{G})\,\{ \\ D\ (\mathrm{D})\,\{ \\ Y\ (1)\,\{ \end{array} \begin{array}{c} \begin{array}{cccc} \overbrace{\ }^{L} & \overbrace{\ }^{G} & \overbrace{\ }^{D} & \overbrace{\ }^{Y} \end{array} \\ \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \check{\boldsymbol{\Omega}}^{\boldsymbol{L}} & \check{\boldsymbol{\Omega}}^{\boldsymbol{G}} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \boldsymbol{\alpha} & \mathbf{0} \end{bmatrix} \end{array}.$$

The terms in brackets next to the row labels indicate the dimensionality of rows and corresponding columns. It is a matter of simple algebra to show that

$$\check{\boldsymbol{\Omega}}^2 = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \check{\boldsymbol{\Omega}}^{\boldsymbol{G}}\mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{\alpha}\check{\boldsymbol{\Omega}}^{\boldsymbol{L}} & \boldsymbol{\alpha}\check{\boldsymbol{\Omega}}^{\boldsymbol{G}} & \mathbf{0} & \mathbf{0} \end{bmatrix} \qquad \check{\boldsymbol{\Omega}}^3 = \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \boldsymbol{\alpha}\check{\boldsymbol{\Omega}}^{\boldsymbol{G}}\mathbf{1} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \qquad \check{\boldsymbol{\Omega}}^n = 0,\ \forall\ n > 3.$$

Hence,

$$\check{\boldsymbol{\Psi}} = \boldsymbol{I} + \check{\boldsymbol{\Omega}} + \check{\boldsymbol{\Omega}}^2 + \check{\boldsymbol{\Omega}}^3$$

and

$$\check{\Omega}^{kl}\check{\Psi}^{lg}\Delta\ln\check{A}^g = \begin{cases} \check{\Omega}^{kl}\Delta\ln\check{A}^g & \text{if } k \in \mathcal{D} \text{ and } l = g \\ \alpha^l\check{\Omega}^{lg}\Delta\ln\check{A}^g & \text{if } k = Y \text{ and } l \in \mathcal{D} \\ 0 & \text{otherwise} \end{cases}. \tag{8}$$

Using Equation (8) in Equation (7) and the fact that $\epsilon^k = 0$ for the final-good producer yields

$$\begin{aligned} \Delta\ln\check{Y} &\approx \check{\lambda}^g\Delta\ln\check{A}^g + \frac{1}{2}\sum_{k\in\mathcal{D}}\epsilon^k\check{\lambda}^k\left[\check{\Omega}^{kg}\left(\Delta\ln\check{A}^g\right)^2 - \left(\check{\Omega}^{kg}\Delta\ln\check{A}^g\right)^2\right] \\ &= \check{\lambda}^g\Delta\ln\check{A}^g + \frac{\left(\Delta\ln\check{A}^g\right)^2}{2}\sum_{k\in\mathcal{D}}\epsilon^k\check{\lambda}^k\left[\check{\Omega}^{kg}\left(1-\check{\Omega}^{kg}\right)\right]. \end{aligned}$$

If g is a consumer good, it is sourced by a single downstream producer who just passes it on to final-good production, implying that $\check{\Omega}^{kg} \in \{0, 1\}$. All other downstream producers source from over 4000 6-digit HS products that Russia imports, and we assume that expenditure shares of individual HS products are small, which implies

$$\check{\Omega}^{kg}\left(1-\check{\Omega}^{kg}\right) \approx \check{\Omega}^{kg}$$

for all $k \in \mathcal{D}$ and intermediate or capital goods g. Using that $\epsilon^k = \theta^g - 1$ for all downstream producers and noting that $\sum_{k\in\mathcal{D}}\check{\lambda}^k\check{\Omega}^{kg} = \check{\lambda}^g$, we get

$$\Delta\ln\check{Y} \approx \check{\lambda}^g\left[\Delta\ln\check{A}^g + \frac{\left(\Delta\ln\check{A}^g\right)^2}{2}(\theta^g - 1)\right].$$

Let $\Omega^g_{CO} := \sum_{i \in \mathcal{I}_{CO}} \Omega^g_i$ denote the total share of coalition members. Equation (3) then follows from (i) noting that

$$\Delta \ln \check{A}^g = -\Delta \ln P^g \approx \frac{1}{1-\sigma^g} \ln(1-\Omega^g_{CO}), \tag{9}$$

by Equation (6), and (ii) the fact that $\lambda^g = \check{\lambda}^g$.[37]

B.2 Convexity of Cost to Russia

In this appendix, we show that the cost to Russia of a ban on exports of a product are convex in the share of coalition countries in Russia.

Differentiating Equation (3) with respect to Ω^g_{CO} yields

$$\frac{d\Delta Y}{d\Omega^g_{CO}} = \lambda^g \left[-\frac{1}{\sigma^g - 1} \frac{1}{1-\Omega^g_{CO}} - 2(\theta^g - 1) \left(\frac{1}{\sigma^g - 1} \right)^2 \frac{\ln(1-\Omega^g_{CO})}{1-\Omega^g_{CO}} \right] < 0$$

$$\frac{d^2\Delta Y}{d^2\Omega^g_{CO}} = \lambda^g \left(\frac{1}{1-\Omega^g_{CO}} \right)^2 \left[-\frac{1}{\sigma^g - 1} + 2(\theta^g - 1) \left(\frac{1}{\sigma^g - 1} \right)^2 [1 - \ln(1-\Omega^g_{CO})] \right] < 0.$$

The inequalities follow from $\sigma^g > 1$, $\theta^g \leq 1$ and $\Omega^g_{CO} \in [0, 1]$. The concavity of ΔY implies that the cost to Russia, $-\Delta Y$, are convex in Ω^g_{CO}.

B.3 Details on Economic Environment of Section 5

In this appendix, we provide details on the model of Section 5. The environment is similar to Baqaee and Farhi (2021) and Çakmaklı et al. (2021).

Production We consider an 'Armington'-type model with I countries, D industries, rich international input-output linkages, and perfect competition in all markets. Countries are indexed by $i, j \in \mathcal{I}$, where j denotes an exporter when applicable. Industries are indexed by $d, e \in \mathcal{D}$, where e denotes a selling industry when applicable. Each country is equipped with a distinct variety in every industry. Varieties are produced by combining a country-sector specific intermediate input bundle with sector specific labor using the following calibrated CES aggregator

$$Y^d_i = \left[\gamma^d (L^d_i)^{\frac{\phi-1}{\phi}} + (1-\gamma^d_i)(M^d_i)^{\frac{\phi-1}{\phi}} \right]^{\frac{\phi}{\phi-1}},$$

where Y^d_i is total output of country i's variety in industry d, L^d_i is its endowment with sector-specific labor, and γ^d_i is country i's value-added share in industry d, which we calibrate to

[37] This is because g and its downstream sectors other than the final-good sector are non-traded.

match the data. $\phi < 1$ captures the elasticity of substitution between the intermediate input and labor, which we take as complementary. We denote the country-industry specific intermediate input bundle with M_i^d. These bundles are formed using two-tier CES aggregators: The lower-tier combines country-varieties to industry bundles with constant elasticity of substitution ξ^d

$$M_i^{de} = \left[\sum_j \Omega_{ij}^{de} (X_{ij}^{de})^{\frac{\xi^e - 1}{\xi^e}} \right]^{\frac{\xi^e}{\xi^e - 1}}.$$

M_i^{de} denotes the industry-e CES bundle that is used for production in industry d and country i, X_{ij}^{de} is the input of the country-j variety into this bundle, and Ω_{ij}^{de} is the baseline share of country j in country i's absorption of industry e by industry d. We calibrate Ω_{ij}^{de} to match the data and take the industry-specific elasticity of substitution parameters, ξ^e, from Caliendo and Parro (2015). The upper-tier combines these industry bundles into aggregate intermediate input bundles with constant elasticity of substitution ϵ

$$M_i^d = \left[\sum_e \Omega_i^{de} (M_i^{de})^{\frac{\epsilon - 1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon - 1}},$$

where Ω_i^{de} captures the share of industry e in industry d's intermediate inputs. The elasticity of substitution between intermediate inputs from different industries, ϵ, is taken to be smaller than 1 to model the complementary nature of these inputs.

In the WIOD, we observe the values of inputs between country-industry pairs. Suppose that the input of industry e from country j by industry d in country i is given by X_{ij}^{de} and its price is given by P_{ij}^{de} (here, we take this price as the purchaser's price, which includes all trade costs). Let P_i^d be the producer price of industry d in country i. We can then define the input share as

$$\tilde{\Omega}_{ij}^{de} = \frac{P_{ij}^{de} X_{ij}^{de}}{P_i^d Y_i^d}.$$

From this, we can calibrate the share parameters that we use in the production side, namely γ_i^d, Ω_{ij}^{de}, and Ω_i^{de} as follows. The value-added share can be calculated as

$$\gamma_i^d = 1 - \sum_j \sum_e \tilde{\Omega}_{ij}^{de}.$$

Sector shares in the intermediate bundle are obtained by

$$\Omega_i^{de} = \frac{\sum_j \tilde{\Omega}_{ij}^{de}}{1 - \gamma_i^d}.$$

And finally, the share of country j in the absorption of industry e by industry d in country i is calculated as

$$\Omega_{ij}^{de} = \frac{\tilde{\Omega}_{ij}^{de}}{\sum_j \tilde{\Omega}_{ij}^{de}}.$$

Consumption On the consumption side, we also employ a nested CES-structure. The final consumption good, which we denote as sector 0, is an aggregate of industry-bundles

$$C_i = \left[\sum_e \Omega_i^{0e} (C_i^{0e})^{\frac{\epsilon^f - 1}{\epsilon^f}} \right]^{\frac{\epsilon^f}{\epsilon^f - 1}}.$$

Here, Ω_i^{0e} is the final consumption share of industry e in country i and C_i^{0e} captures the consumption bundle of industry e in country i. The elasticity of substitution, ϵ^f, dictates the inter-industry substitutability in consumption. We assume this elasticity to be equal to 1. Analogous to production, the industry consumption bundles are generated by aggregating over country varieties

$$C_i^{0e} = \left[\sum_j \Omega_{ij}^{0e} (C_{ij}^{0e})^{\frac{\xi^e - 1}{\xi^e}} \right]^{\frac{\xi^e}{\xi^e - 1}}.$$

Ω_{ij}^{0e} is the share of variety j in consumption of industry e in country i. C_{ij}^{0e} is the amount of variety j in industry e that country i buys for consumption. ξ^e are the same elasticities as on the production side.

Similar to the production side, we only observe the consumption value of industry e from country j in destination country i, $P_{ij}^{0e} C_{ij}^{0e}$. From this we can derive consumption shares in terms of the total expenditure of country i, which we denote by E_i, as

$$\tilde{\Omega}_{ij}^{0e} = \frac{P_{ij}^{0e} C_{ij}^{0e}}{E_i}.$$

The industry shares are then

$$\Omega_i^{0e} = \sum_j \tilde{\Omega}_{ij}^{0e},$$

and the variety shares

$$\Omega_{ij}^{0e} = \frac{\tilde{\Omega}_{ij}^{0e}}{\Omega_i^{0e}}.$$

Equilibrium The economy is in equilibrium if all sector specific factors are employed and the good markets clear

$$Y_j^e = \sum_i \sum_d X_{ij}^{de} + \sum_i C_{ij}^{0e},$$

subject to production functions and consumption preferences setting the prices of goods and the different types of labor.

Solving the model We are interested in the impact of the bans on exports by coalition countries to Russia. To that end, we introduce iceberg trade shocks from coalition countries to Russia that mimic the sanctions introduced at the 6-digit product level. Details on these shocks are given in Section B.4. We then solve the model in changes following the approach in Baqaee and Farhi (2021), and modifying their Matlab code to accommodate sector-specific factors.

B.4 Derivation of Equation (5)

In this appendix, we derive Equation (5)

Consider an 'aggregated' economy with 15-WIOD industries and rich I-O linkages. Let $\tilde{P}^d$ be the effect (in changes) on the Russian price index for industry d of a shock τ^d to iceberg trade costs from coalition countries to Russia in this economy. Analogous to Section 3, this effect is given by

$$\tilde{P}^d = \left(1 + \Omega^d_{CO}\left[{\tau^d}^{1-\xi^d} - 1\right]\right)^{\frac{1}{1-\xi^d}}, \tag{10}$$

where Ω^d_{CO} is the market share of the coalition in industry d in Russia.

Consider a 'disaggregated' economy analogous to Section 3 instead. In this economy, origin-specific varieties of 6-digit HS products are combined in a CES aggregator with product-g specific constant elasticity of substitution σ^g and these products are then combined in D industries using CES aggregators with elasticity of substitution θ^d. The direct effect of a ban on exports of good g by coalition countries on the price for good g in Russia is then given by

$$\hat{P}^g = (1 - \Omega^g_{CO})^{\frac{1}{1-\sigma^g}}.$$

Let $\mathcal{G}^d$ be the set of products that belong to industry d and $\mathcal{B}^d \subseteq \mathcal{G}^d$ be the subset of these products that are subject to the ban. Aggregating over all products $g \in \mathcal{G}^d$, we then get for the direct effect of the export bans on the industry-d price index

$$\hat{P}^d = \left(\sum_{g\in\mathcal{B}^d} \Omega^{gd}(1 - \Omega^g_{CO})^{\frac{1-\theta^d}{1-\sigma^g}} + \sum_{g\in\mathcal{G}^d\setminus\mathcal{B}^d} \Omega^{gd}\right)^{\frac{1}{1-\theta^d}}, \tag{11}$$

where Ω^{gd} is the share of product g in industry d in Russia. Equation (5) then follows from equating (10) and (11) and solving for τ^d.

Table B.1: Elasticities in Robustness Exercises

Parameter	**Robustness 1**	**Robustness 2**
σ^g	Fontagné et al. (2022)	Fontagné et al. (2022)
θ^d	0.05	Caliendo and Parro (2015)
ξ^d	0.05	Caliendo and Parro (2015)
ϵ	0.2	0.1
ϕ	0.6	0.1
ϵ^f	1	0.5

Notes: This table summarizes the elasticity choices for the two robustness checks of our quantitative results from Section 5.

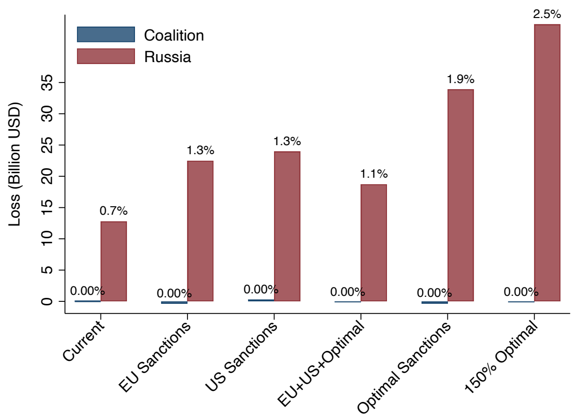
B.5 Robustness

In our baseline specification, we follow Baqaee and Farhi (2021) and Çakmaklı et al. (2021) and calibrate ϵ, ϕ, and ϵ^f, based on estimates from the literature as discussed in Section 5.3. Elasticities between varieties at the 6-digit HS-level and WIOD industry level are taken from Fontagné et al. (2022) and Caliendo and Parro (2015), respectively—see Table 2 for a summary of these elasticities. In this appendix, we present robustness checks with regards to these elasticities. In the first robustness exercise, we choose $\theta^d = \xi^d = 0.05$ to mimic a situation where at the level of WIOD industries there is a very little possibility to substitute different inputs in the short run. In the second robustness check, we decrease all other elasticities. Table B.1 shows a summary of our elasticity choices in the two robustness exercises.

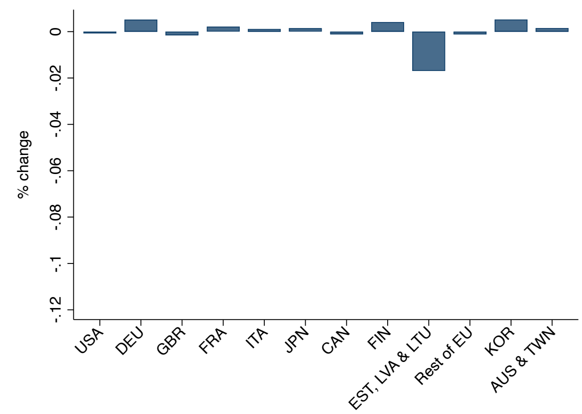
As shown in Figure B.1, regardless of these elasticities, our main results remain the same, with the Russian economy carrying the highest burden when the optimal sanctions are employed, and Baltic countries being affected the most among the coalition. The main difference is that with a strong level of complementarity at the WIOD industry level, the coalition may even get net gains from imposing the export bans.

Figure B.1: Sanction Scenarios

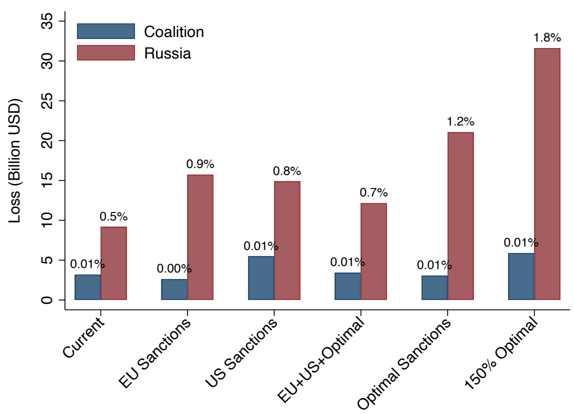
(a) Robustness 1 - Coalition vs Russia



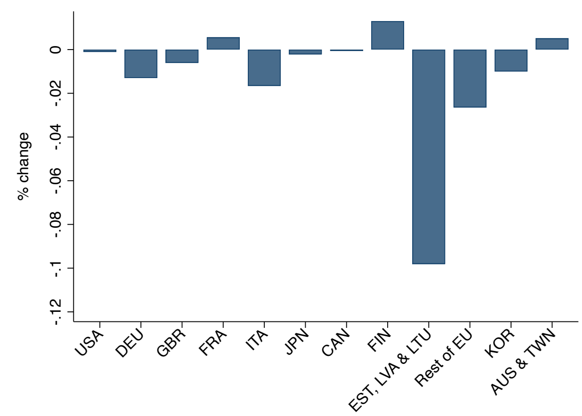
(b) Robustness 1 - Coalition countries



(c) Robustness 2 - Coalition vs Russia



(d) Robustness 2 - Coalition countries



Notes: This figure replicates Figure 10 for the elasticity choices as summarized in Table B.1.

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