Effective sanctions

SUMMARY

We build on Baqaee and Farhi (2019, 2021) and derive a theoretically grounded criterion that allows targeting bans on exports to a sanctioned country at the level of ∼5,000 six-digit HS products. The criterion implies that the costs to the sanctioned country are highly convex in the market share of the sanctioning parties. Hence, there are large benefits from coordinating export bans among a broad coalition of countries. Applying our results to Russia reveals that sanctions imposed by the European Union and the United States in response to Russia's invasion of Ukraine are not systematically related to our arguments once we condition on Russia's total imports of a product from participating countries. We discuss drivers of these differences and then provide a quantitative evaluation of the export bans to show that (i) 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 80% with little to no extra cost to the sanctioners; and (iii) there is scope for increasing the cost to Russia further by expanding the set of sanctioned products.

JEL codes: F13, F15, F51

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Economic Policy January 2024 Printed in Great Britain
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On the design of effective sanctions: the case of bans on exports to Russia

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1. INTRODUCTION

In response to the Russian invasion of Ukraine beginning in February 2022, the European Union (EU), the United States 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 six-digit HS products, with substantial heterogeneity both across but also within two-digit HS chapters, as shown in Figure 1. This raises the question about how to design these export restrictions most effectively at a detailed level of disaggregation. In this paper, we seek

* We thank Sophia Henn for excellent research assistance, and the editor, two anonymous referees, Miguel Almunia, Dany Bahar, Sebastian Bustos, Johannes Fritz, James McNerney, Jose Morales-Arilla, David Torun and seminar participants at the Harvard Growth Lab, at the European Central Bank, and at the 77th Economic Policy Panel for valuable comments and suggestions.

The Manging Editor in charge of this paper was Isabelle Mejean.

Economic Policy January 2024 pp. 109–153 Printed in Great Britain

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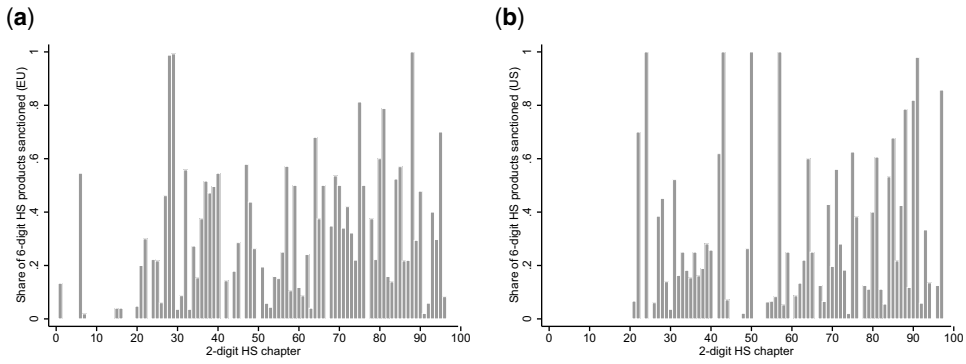

Figure 1. Share of six-digit HS products sanctioned within two-digit HS chapter

Notes: This figure shows for each two-digit HS chapter, the share of six-digit HS products in that chapter that are subject to export restrictions by the EU (a) and the United States (b).

Data: See Section 3.1.

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. Bachmann et al., 2022; Baqaee et al., 2022; Bayer et al., 2022; Berger et al., 2022; Gros, 2022; Hausmann, 2022; Hausmann et al., 2022a,b). 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 was so difficult for the EU to agree on sanctioning Russian energy exports. When it comes to Russian imports, the situation is very different: Pre-crisis, the EU accounted for 40% of Russia's imports, but only less than 2% of EU members' exports went to Russia. This allows the EU to cut Russia off critical supplies with limited impact on the EU's exports, and particularly so when coordinating export restrictions with partnering countries. Indeed, Figure 2 shows that in many six-digit HS products, 'coalition countries' dominate Russian imports, where here and below we consider the EU, the United States, 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 50% of its oil and 75% of its gas 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.

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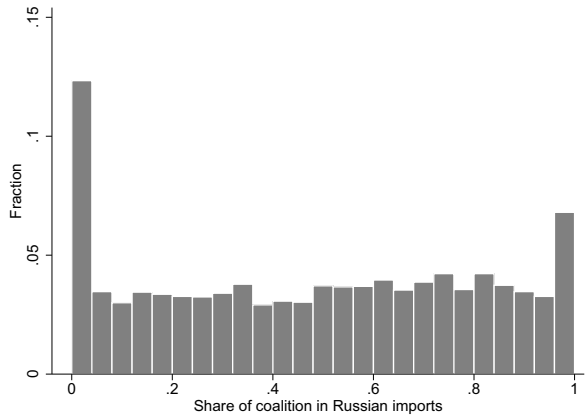

Figure 2. Share of coalition in Russian imports

Notes: For each six-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 United States the other G-7 members, Australia, Korea and Taiwan.

Data: See Section 3.1.

A key motive underlying the export restrictions by the EU and the United States is to target Russia's military and defence 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 – or a sanctioned country in general. To shed light on these costs, we consider in Section 2 an economy with a production hierarchy and where countries trade varieties of six-digit HS products. We then build on Baqaee and Farhi (2019, 2021) to characterize the welfare cost to a sanctioned country of an export ban by a coalition of countries in a transparent way, while accounting for non-linear (second-order) effects. The latter are increasingly important as the shocks get larger. We derive an analytic expression for these costs. This expression is very intuitive: It implies that restricting a country's imports of a product from a set of countries is 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. Our results further imply that the costs to a sanctioned country are highly convex in the

Switzerland in the coalition even though it adopted EU export restrictions against Russia because there are no data on Switzerland in the 2013 version of the WIOD, and we will use these data to quantitatively assess sanctions in Section 5.

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/ (accessed 16 August 2022).

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market share of the coalition, suggesting large gains from coordinated sanctions and from focusing sanctions on products with a dominant position of the coalition.

In Section 3, 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 United States 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. Zooming in on the underlying drivers, we find that (i) the market share of the coalition in Russia is similar for sanctioned and for non-sanctioned products and (ii) that sanctioned products do not have a systematically lower trade elasticity. The latter captures the ease with which imports of a product from one country can be replaced by imports of the same product from other countries. Moreover, sanctions are biased towards capital goods – which suggests that it may take time for the sanctions to become fully effective – and while the sanctions are well coordinated in general, more than 50% of all products with export restrictions by either the EU or the United States are restricted by only one of them.

These findings suggest that there may be scope for sharpening the sanctions against Russia. Differences between our arguments and sanctions in place against Russia may, however, also arise because our analysis leaves out of account other dimensions that are important for the sanctions, as we discuss in Section 4. On the one hand, our analysis ignores factors of the economic costs to Russia, such as the possibility of parallel imports, interaction effects between the sanctions or potential bottlenecks in value chains that can have large cascading effects. On the other hand, our analysis ignores motives for the sanctions other than inflicting economic costs on Russia. The latter is an important motive for the sanctions (European Council and Council of the EU, 2022), but so were ethical considerations or the desire to cut Russia off critical inputs for its military, for example. Similarly, we do not consider the distributional consequences of the sanctions, and our analysis is not targeted towards harming Russian 'elites'. We are also not taking into account any potential retaliation by Russia, that might increase the cost to coalition countries. 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 an easily implementable input into a more comprehensive analytical process.[4]

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: The ranking considers sanctioning one

4 The focus on the economic costs of the sanctions is not exclusive to our work and it applies more broadly to papers that seek to inform sanctions based on (quantitative) trade models. Motives other than economic costs may, however, be particularly important for restrictions on exports to a sanctioned country, which are the focus of our work.

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product at a time, it is based on simplified input–output (I–O) linkages, and we ignore costs to the sanctioning countries. In part, these simplifications are driven by data limitations. But even without such limitations, providing *ex ante* guidance on export bans at a disaggregate 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 six-digit HS level to 15 World Input–Output Database (WIOD) manufacturing industries in Section 5. We then assess quantitatively the impact of sanctions, exploiting the full international 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 80% 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.

1.1. 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, Costinot and Rodríguez-Clare (2014), Caliendo and Parro (2015), and Baqaee and Farhi (2019, 2021). Such models have been used to quantify the gains from North American Free Trade Agreement (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., 2022*a*), the cost of the United States–China trade war (Charbonneau and Landry, 2018; Caliendo and Parro, 2022) and the cost of decoupling global value chains (Eppinger et al., 2021; Javorcik et al., 2022), 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 (2022*a*,*b*) and 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;

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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) and 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, namely, export bans at the product level. Our paper is thus closer to contemporaneous work by Chowdhry et al. (2022), Sturm (2022) and Imbs and Pauwels (2023). Chowdhry et al. (2022) provide a comprehensive quantitative analysis of trade sanctions against Iran in 2012 and Russia in 2014 that also highlights the importance of coalitions. This finding echoes our quantitative result on the benefits of coordinating export restrictions. We substantiate these quantitative insights with analytic results that also shed light on the underlying driver: the economic cost to a sanctioned country is highly convex in the market share of the coalition. Imbs and Pauwels (2023) provide a quantitative approximation that allows evaluating trade sanctions. This approximation and our results complement each other insofar as we emphasize differences across products in the ability to substitute for missing imports, while the approximation by Imbs and Pauwels (2023) emphasizes I–O linkages. Moreover, we apply our results to analyse disaggregated sanctions in place against Russia as opposed to hypothetical, aggregated policy scenarios. Last, Sturm (2022) 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.[5] 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: they allow to increase the effectiveness of export bans by $\sim 80\%$.

2. TARGETING EXPORT RESTRICTIONS

In this section, we build on Baqaee and Farhi (2019, 2021) to derive a theoretically grounded criterion for targeting bans on exports to a sanctioned country based on the implied economic costs. We begin with describing the economic environment.

5 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 United States take the form of bans or controls – not taxes – and, hence, our analysis is evidently relevant for policy.

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2.1. Economic environment

We consider an economy with a production hierarchy. There are I countries, indexed by $i,j \in \mathcal{I}$, and G six-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 four-tier production process that uses labour as the only primary factor. At the first stage of the production process, the varieties of six-digit HS products are produced using a constant-returns-to-scale production technology with labour 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 six-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 six-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 labour in a CES production function with constant elasticity of substitution $\theta \leq 1$ (stage 3).[6] Last, 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 3 provides a schematic overview of the economy.[7]

2.2. Impact of an export ban on the sanctioned economy

The economic set-up allows deriving an analytic expression for the impact of a ban on exports of a six-digit HS product by coalition countries on the economy of a sanctioned country. In Section 3, we will apply our theoretical insights to the case of bans on exports to Russia. To simplify the exposition, we will therefore henceforth denote the sanctioned country by 'Russia', but it should be clear that our theoretical results in this section are generic.

An export ban by coalition countries on their varieties of a six-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. $\hat{x} := x'/x$. With this notation, we have

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

6 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.

7 While our assumptions simplify I–O 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).

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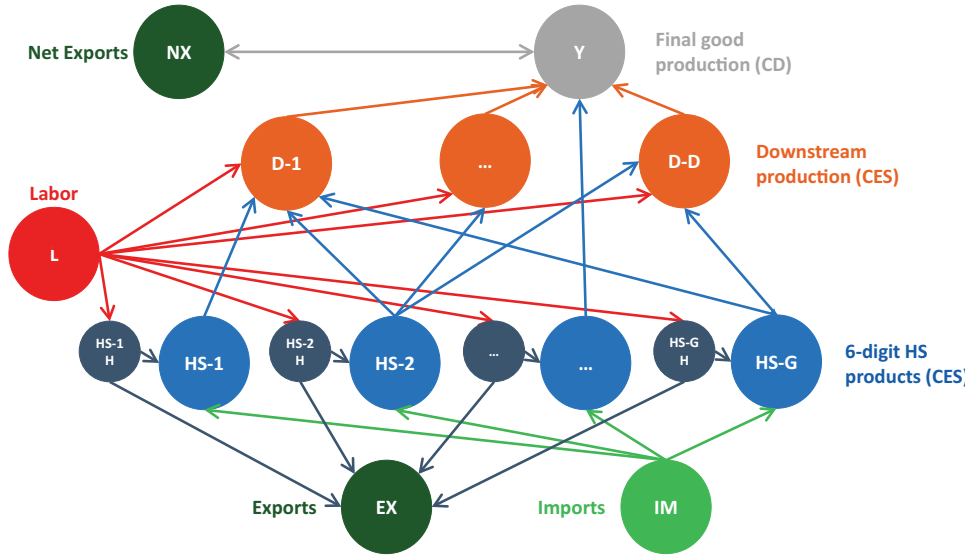

Figure 3. Schematic overview of economy

Notes: The figure provides a schematic overview of the economy in Section 2.

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.[8] 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 analysed by considering a 'dual' closed economy where the price change $\hat{P}^g$ is induced by a change in the sector-specific productivity, $\check{A}^g$, where here and below $\check{x}$ indicates variable x in the dual

8 In fact, in our set-up prices p_i^g for non-coalition members could change only due to general equilibrium effects. We consider a ban on exports of one six-digit HS product to one destination and, hence, these effects are small. See also the discussion following Proposition 1.

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closed economy. 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.[9] 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.[10] The following proposition characterizes the economic costs to Russia from an export ban on product g by coalition countries, taking into account non-linear, second-order effects.

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*

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

In the above, 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. The derivation of Expression (3) is provided in section 'Derivation of Equation (3)' in Appendix 2. To show the result, we build on the duality result in Baqaee and Farhi (2021, Section 6.2), which in turn allows using the second-order approximations in Baqaee and Farhi (2019). Pinning down the dual productivity shock requires knowledge of the change in the domestic input share in response to the trade-cost shock in the original open economy. In general, this change cannot be readily determined analytically.[11] We make progress by considering one export ban at a time at the level of ~5,000 six-digit HS products. This results in shocks that are large at the Russian product level, but small in aggregate terms. In turn, this allows deriving a second-order approximation for the welfare implications of

9 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 section 'Derivation of Equation (3)' in Appendix 2.

10 In general, this depends on microeconomic elasticities of substitution in production and consumption, and on the I–O structure. Intuitively, the macro-elasticity depends on the ability of g's buyers to substitute away from buying g, the ability of the buyers' buyers to substitute away, and so on.

11 This is akin to the welfare effect of a trade shock in gravity models, which depends on the change in a country's home share (Arkolakis et al., 2012). This change in the home share is readily quantifiable when moving to autarky – i.e. when moving to a situation with home share equal to one – but for general trade shocks it requires solving the model quantitatively in changes.

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an export ban. It implies, however, that the approximation in Proposition 1 ignores interaction effects between the sanctions and that it does not consider the cost to the sanctioning coalition. We will get back to this point in Section 5, where we present a quantitative evaluation of sanctions based on the result in Proposition 1, considering simultaneous bans on many products – i.e. shocks that are large in aggregate – and taking into account international I–O linkages.

Proposition 1 implies that, quite intuitively, an 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), and (iv) downstream buyers cannot easily substitute the now costlier input g by other inputs (θ^g small). The 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) has an interesting immediate implication: Ceteris paribus, the cost of an export restriction on g to the Russian economy increases 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 section 'Convexity of cost to Russia' in Appendix 2 and illustrate this point in Figure 4 for $\sigma^g = 5$ and $\theta^g = 0.2$.

3. APPLICATION TO RUSSIA

In this section, we use Equation (3) to analyse the current sanctions in place on exports to Russia and to identify target products for additional restrictions. We begin by discussing our data and its sources.

3.1. Data

To take Equation (3) to the data, we need four sets of variables: (i) total expenditure over GDP on product g (λ^g); (ii) the market share of the coalition in Russia (Ω^g_{CO}); (iii) the elasticity of substitution at the six-digit HS level σ^g; (iv) 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] These data provide us with trade at the exporter–importer–product level for six-digit HS products. It does not, however, provide us with Russia's

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

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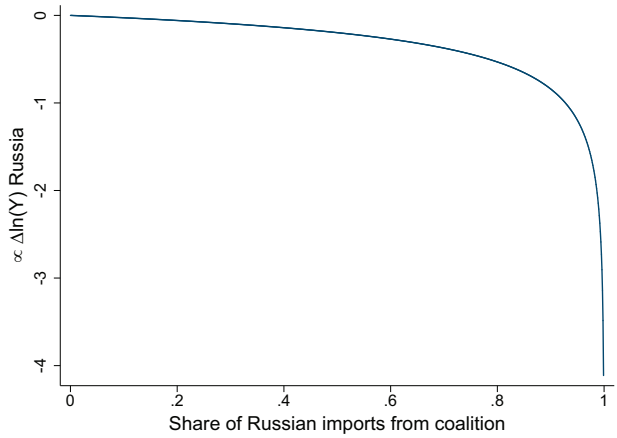

Figure 4. Market share of coalition and change in Russian GDP

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 $\theta^g = 0.2$.

home share in a six-digit HS product. To estimate this, we complement the trade data with data from the ITPD-E, which provide us with Russian home shares in the year 2013 for 41 industries.[13] We use these 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 six-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 six-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 specify θ^g, we classify products into consumer goods, intermediates and capital goods, using the classification of broad economic categories (BECs), 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. Intermediates and capital goods, on the other hand, are combined in downstream CES aggregators, and we assume an elasticity of substitution across intermediate inputs of $\theta^g = 0.2$.[14]

In what follows, we use these data to identify potential targets for bans on exports to Russia, and to compare these with export restrictions by the EU and the United States. The data on the latter are from the Global Trade Alert and cover restrictions that were imposed by the EU and the United States since the Russian annexation of Crimea in

13 The data were 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) and Çakmakli et al. (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.

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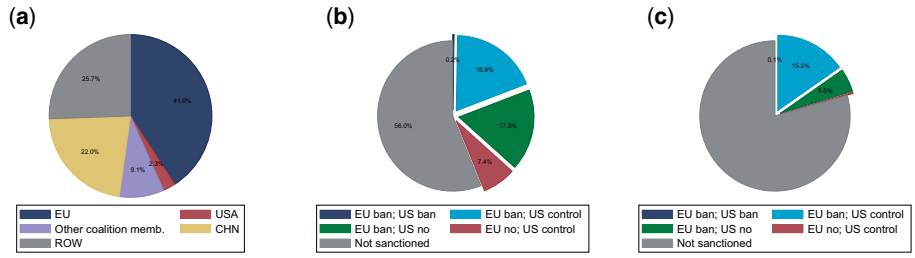

Figure 5. Overview of export restrictions by the EU and the United States

Panel (a) shows the share in Russian imports by groups of countries. Panel (b) shows the share of six-digit HS product categories that were sanctioned by the EU and the United States. Panel (c) shows the share of six-digit HS product categories that were sanctioned by the EU and the United States, with each product weighted by Russian imports.

Data: See Section 3.1.

2014 and up to 14 October 2022 (https://www.globaltradealert.org).[15] The majority of the sanctions were imposed – or strengthened – in 2022.[16]

Figure 5 provides an overview of the EU and US restrictions on exports to Russia. As a reference point, panel (a) shows the share of all Russian imports in 2019 that were from the EU, the United States, other coalition countries and China. Prior to the crisis, the coalition accounted for ∼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 United States has mostly imposed export controls, but also some export bans. Figure 5 separates these types of sanctions, but we lump together US bans and export controls in the remainder of the paper.[17] Panel (b) shows that ∼ 44% of all product categories have been sanctioned by either the EU, the United States or both. Out of these product categories, ∼ 43% have been sanctioned by both, ∼ 40% by the EU only, and ∼ 17% by the United States only. Taken together, the sanctioned exports account for ∼ 20% of

15 We thank Johannes Fritz and the Global Trade Alert for providing us with the data.

16 According to the data from the Global Trade Alert, only 41 products out of the 1,689 products sanctioned by the EU as of 14 October 2022 were sanctioned pre-2022 and not superseded by sanctions since February 2022. All earlier US sanctions were superseded by sanctions in 2022.

17 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 do not allow for a detailed account of these sanctions. Moreover, there may be a risk of parallel imports when targeting selected entities. We note 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 2 and 3.2, nor our quantitative assessment of sanctions based on our criteria in Section 5.

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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 5(b) immediately reveals a lack of coordination of the sanctions between the EU and the United States. From Corollary 1, we know that this undermines the effectiveness of the sanctions. Intuitively, in the absence of better coordination, Russia can substitute missing imports of a product from one coalition country by sourcing more of that same product from other coalition countries. We will get back to this point in Section 5, where we show the quantitative importance of a lack of coordination, and turn to analysing the design of the sanctions next, i.e. to analysing the set of products that were subjected to export bans.

3.2. Analysis of bans on exports to Russia

In this section, we use Equation (3) to rank products by their economic cost to Russia from an export ban. These costs depend on the product under consideration (σ^g, θ^g, λ^g), but also on the sanctioning coalition (Ω^g_{CO}). To rank products, we, therefore, consider the case where all coalition countries adopt the export ban. We then compare the ensuing ranking to current sanctions in place by the EU and the United States, and use it to identify potential targets for additional restrictions on exports to Russia.

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. Yet, the table also illustrates the importance of the other factors. For example, HS-843680 (germination, bee-keeping plant) is ranked below HS-903289 (transmission for motor vehicles) even though Russian imports are larger and it imports a larger share from coalition countries. This is because HS-843680 has a relatively high trade elasticity. On the other hand, HS-940190 (parts of seats) is ranked below HS-843680, because the coalition has a lower share of this product in the Russian market.

The last two columns of Table 1 indicate whether the EU and the United States have imposed an export ban (1) or an export control (2) on the specific product. In the 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 the case of the United States, the former share is larger (14 out of 20). Yet, there are many unsanctioned products that might be viable targets for additional sanctions.

Figures 6–8 evaluate the relationship between our ranking 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 6 then compares this ranking to the sanctions in place by the EU (left panel) and the United States (right panel). In both panels, the grey 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

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Table 1. Top-20 products

Rank	HS-6	Description	Russian Imports	Coalition Share	Durables	Intermediate Good	Capital Good	Elasticity	Sanction EU	Sanction United States
1	870323	Automobiles, spark ignition, 1,500–3,000cc	$5.30 billion	0.18	1	0	0	−9.37	0	2
2	300490	Medicaments, doses, nes	$7.33 billion	0.54	0	0	0	−20.1	0	0
3	870829	Parts of motor vehicle bodies	$1.47 billion	0.43	0	1	0	−4.78	0	0
4	848180	Taps, cocks, valves, appliances, nes	$1.58 billion	0.31	0	1	0	−3.48	1	2
5	847989	Machines & mechanical appliances nes	$1.18 billion	0.48	0	0	1	−4.47	1	2
6	901890	Instruments for medical science, nes	$691 million	0.68	0	0	1	−3.86	1	2
7	870333	Automobiles, diesel, >2500cc	$1.51 billion	0.48	1	0	0	−7.27	0	2
8	870899	Motor vehicle parts nes	$1.77 billion	0.28	0	1	0	−6.47	0	2
9	330210	Mixed odors, food and drink	$354 million	0.79	0	1	0	−3.48	0	0
10	880240	Fixed wing aircraft, >15,000 kg	$2.70 billion	0.16	0	0	1	−13.8	1	2
11	903289	Automatic controlling equipment nes	$394 million	0.68	0	0	1	−3.48	0	2
12	870840	Transmissions for motor vehicles	$1.15 billion	0.49	0	1	0	−6.99	0	0
13	870324	Automobiles, spark ignition, >3,000cc	$1.17 billion	0.39	1	0	0	−7.40	0	2
14	841989	Machinery for temperature change	$670 million	0.59	0	0	1	−5.05	1	2
15	271000	Oils petroleum, bituminous, distillates	$1.23 billion	0.01	0	0	0	−4.31	1	2
16	853710	Electrical control & distribution boards, <1kV	$851 million	0.19	0	1	0	−4.72	1	2
17	870332	Automobiles, diesel, 1,500–2,500cc	$1.15 billion	0.28	1	0	0	−7.55	0	2
18	843680	Germination, bee-keeping plant	$417 million	0.92	0	0	1	−8.57	0	0
19	901819	Electro-diagnostic apparatus	$371 million	0.74	0	0	1	−4.45	0	2
20	940190	Parts of seats	$403 million	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 United States, respectively. A 1 indicates an export ban and a 2 an export control.
Data: See Section 3.1.

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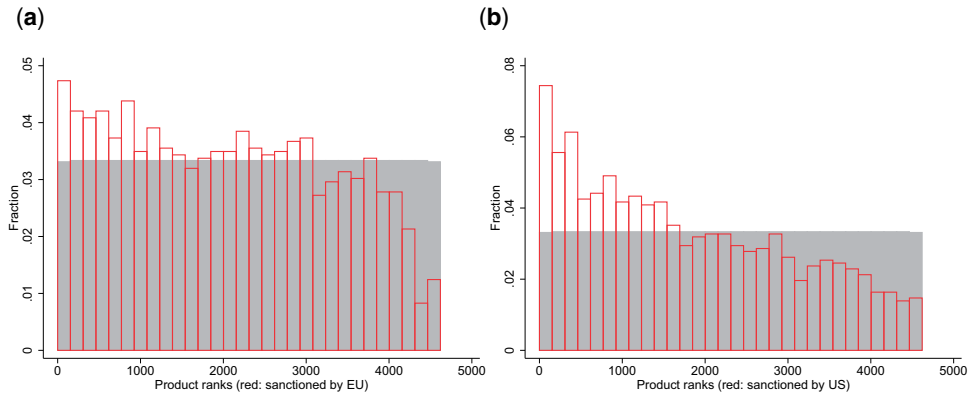

Figure 6. EU and US export restrictions versus ranking by Equation (3)

Notes: This figure compares the export restrictions by the EU (a) and the United States (b), respectively, to a ranking of products by Equation (3). The grey 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 the EU and US export restrictions, considering US export bans and controls combined.

Data: See Section 3.1.

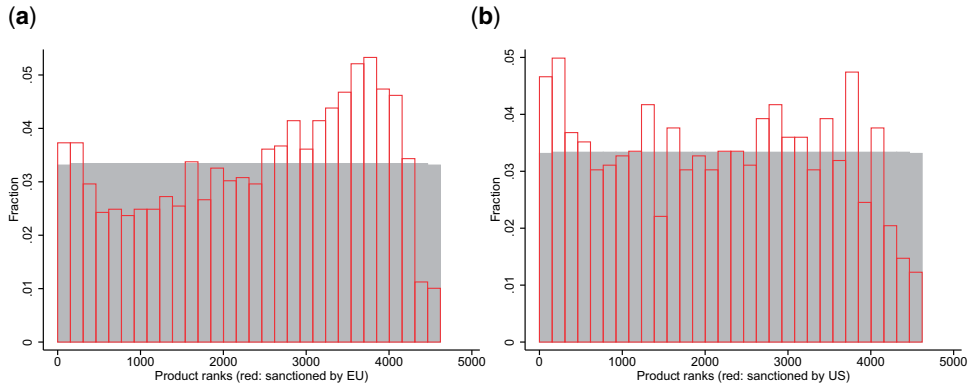

Figure 7. EU and US export restrictions versus ranking by Equation (4)

Notes: This figure compares the export restrictions by the EU (a) and the United States (b) 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, considering US export bans and controls combined.

Data: See Section 3.1.

sanctions in place by the EU and the United States, respectively, considering US export bans and controls combined.

Figure 6 shows that the restrictions on exports to Russia in place by both the EU and the United States are biased towards highly ranked products. Interestingly, this suggests that our analysis is useful not only as a benchmark but also to analyse actual sanctions. The tight connection is, however, entirely driven by the fact that export restrictions are biased towards products that are large in terms of Russian expenditure on these products as summarized in λ^g in Equation (3). It is known since Hulten (1978) that λ^g is an

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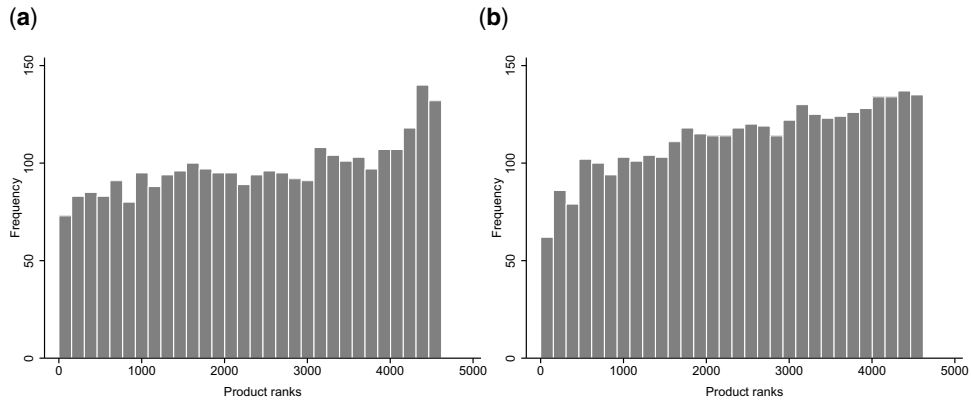

Figure 8. Products not subject to an export restriction by the EU and the United States

Notes: This figure shows the frequency distribution of products without export restrictions by the EU (a) and the United States (b), over product ranks according to Equation (3).

Data: See Section 3.1.

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 is highest. Proposition 1 readily lends itself to such an analysis: dividing Equation (3) by total coalition exports yields

$$\frac{\Delta \ln(\Upsilon)}{\Omega^g_{CO} P^g \underset{\sim}{Q}^g} \overset{\propto}{\sim} \frac{1}{\Omega^g_{CO}} \left[\frac{1}{\sigma^g - 1} \ln(1 - \Omega^g_{CO}) + (\theta^g - 1)\left[\frac{1}{\sigma^g - 1} \ln(1 - \Omega^g_{CO})\right]^2\right]. \quad (4)$$

Figure 7 compares this alternative criterion to the sanctions in place by the EU and the United States to find no systematic relationship. That is, the 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, as we will discuss further in Section 4. This suggests that there might be 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 subject to export restrictions. This may be seen from Figure 8(a) and (b), which shows the frequency distribution of non-sanctioned products by the EU and the United States, respectively, over ranks based on our baseline criterion from Equation (3). In other words, there might be room for identifying target products

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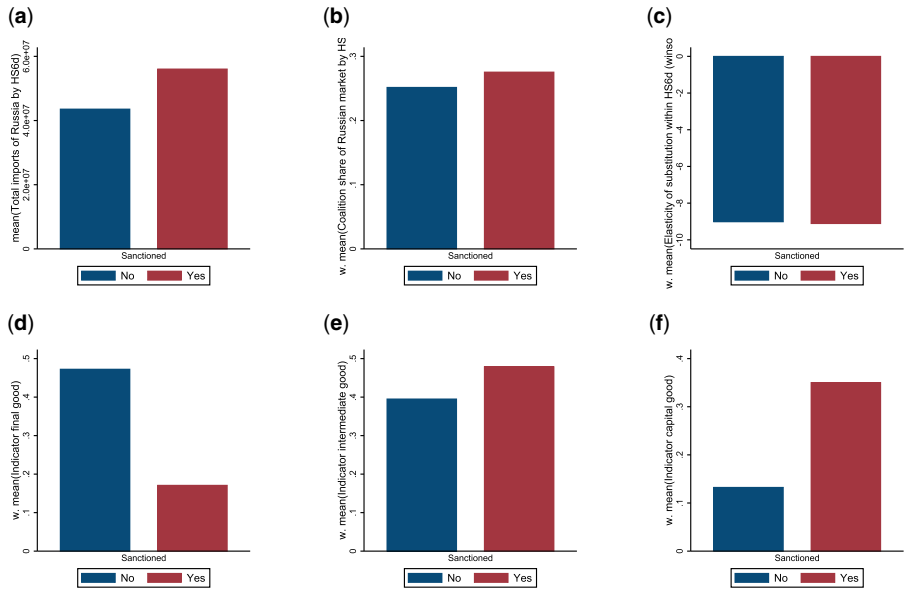

Figure 9. Characteristics of products with versus without EU export restrictions

Notes: The figure compares six-digit HS products with an EU export ban (blue, left bar) to those without an EU export ban (red, right bar) along the following dimensions: (a) Russian imports; (b) sh. coal. in Russian exports; (c) trade elasticity; (d) sh. cons. goods; (e) sh. intermediates; (f) sh. capital goods. Bars refer to weighted means with weights given by Russia's imports, with the exception of panel (a), which considers simple means.

Data: See Section 3.1.

for impactful additional sanctions. The arguments developed here may help identify such products.[18]

To examine further the differences between our ranking and the sanctions in place by the EU and the United States, respectively, Figure 9 explores the nature of the sanctioned products and compares them to non-sanctioned products along several dimensions that are relevant to the economic costs to Russia as shown in Proposition 1. 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 section 'Additional figures and tables' in Appendix 1. Consistent with our earlier findings in Figures 6 and 7, Russian total imports of a product are larger for products sanctioned by the EU compared to non-sanctioned products (panel (a)). In contrast, there are smaller to no differences when it comes to the

18 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. Section 'Robustness of product ranking' in Appendix 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.

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coalition market share in Russia (Ω^g_{CO}, panel (b)) and the trade elasticity ($\sigma^g - 1$, panel (c)). Sanctioned products are, however, heavily biased towards intermediates and, in particular, capital goods vis-à-vis consumer goods – see panels (d)–(f). When it comes to the economic costs to Russia, this suggests on the one hand that the sanctions were effective as goods tend to be less substitutable in production vis-à-vis consumption (θ^g low). On the other hand, the focus on capital goods may imply that it takes time for the sanctions to become fully effective. We will get back to this point in the next section.

In sum, Equations (3) and (4) provide theoretically grounded, transparent and easily implementable *ex ante* guidance on the economic cost from a ban on exports of a product to Russia by coalition countries. These criteria can thus be used to inform policy, but they rely on simplifying assumptions. We discuss these next.

4. DISCUSSION

Figures 5–8 reveal large differences between a sanction's regime based on our arguments and sanctions imposed against Russia by the EU and the United States. These differences may indicate a potential for sharpening the sanctions through improved coordination and a stronger focus on products with the highest economic costs to Russia. However, it is important to note that our analysis leaves out of account other dimensions that are important for the sanctions, as we now explain. We begin by discussing aspects that are relevant to the economic costs to Russia and that are not captured by our analysis. We then consider motives for the sanctions other than maximizing the economic costs to Russia.

4.1. Other factors influencing economic costs

To derive Equations (3) and (4), we assume an I–O structure with a production hierarchy, and then consider sanctioning one product at a time. That is, Equations (3) and (4) ignore potential interaction effects between the sanctions. Introducing such interactions would allow us 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 a case, there would be additional gains from concentrating bans at the industry level.

In our 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 Russia imposed as retaliation to sanctions following its annexation of Crimea in 2014. However, they do 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

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Belarus. Yet, there is suggestive evidence for re-routing through other countries including Turkey, Kazakhstan and Armenia (Borin et al., 2023). Such re-routing undermines the effectiveness of bans on exports to Russia, and Corollary 1 suggests that even relatively small amounts may have large effects. Yet, to the extent that there are no systematic biases across products in terms of how easy parallel imports are, our arguments for prioritizing sanctions at a disaggregated product level remain intact.

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 not aware of good data that would allow disciplining these at the granular level at which we rank products, and we, therefore, ignore them throughout. Analysing 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.

Our static analysis also ignores potential differences in the duration it takes for the economic costs of an export ban to materialize. In times of crisis, it is desirable to impose sanctions with immediate impact. In that regard, there is an important difference between capital goods and intermediates. The reason is that when it comes to the former, the pre-existing stock is used in production while current flow investments are used only to build up or replenish the depreciated capital stock. In other words, when confronted with a ban on imports of a capital good, Russia can still live off pre-existing stocks.[19] Figure 9(f) reveals that sanctioned products were heavily biased towards capital goods, suggesting that it may take time for the sanctions to become fully effective. The focus on capital goods may, however, reflect motives other than maximizing the economic costs to Russia, such as the ambition to undermine its war and energy capability or to limit the harm for the general population.[20] We will get back to this point in the next section.

A detailed account of capital goods is beyond the scope of 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

$$\hat{P}^g \approx (1 - \Omega^g_{CO})^{\frac{\delta^g}{1-\sigma^g}}, \tag{5}$$

19 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 as they go out of service'.

20 For example, out of the 21 two-digit HS chapters for which the EU has imposed no bans on exports on underlying six-digit HS products, 15 are among chapters 1–21, which cover food products. See Tables A.1 and A.2 in section 'Additional figures and tables' in Appendix 2 for a list of top-5 two-digit HS chapters by the share of six-digit HS products within the chapter that was subjected to an export ban by the EU and the United States, respectively.

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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.[21]

In sum, there are various factors impacting the economic costs to Russia that are not reflected in Equations (3) and (4).[22] These simplifying assumptions are in part driven by data limitations. For example, at the level of disaggregation considered here, there are no data on I–O linkages. Yet, these simplifications are, in part, also needed to increase the tractability of the problem. Even with better data, identifying an optimal combination of export restrictions with rich I–O linkages or a comprehensive account of capital goods would be difficult due to the high dimensionality of the problem and the non-linearities involved. Equations (3) and (4) may therefore represent a reasonable compromise that can provide valuable guidance on this issue in richer environments as well. Nevertheless, there are other motives that need to be taken into consideration when designing sanctions. We will discuss these first before providing a quantitative evaluation of our arguments in Section 5.

4.2. Other motives for sanctions

Proposition 1 focuses on the economic costs to Russia, but it ignores the costs to coalition countries. Equation (4) mitigates this concern by focusing on the impact per dollar of foregone exports, but still, the concern that sanctions might have negative repercussions on the imposing countries themselves matters for the sanctions. We will explore this in our quantitative analysis below and show that export restrictions are highly effective in this regard. A related concern is that 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 pre-crisis reliance on energy imports from Russia. 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 intact.

21 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.

22 To derive the rankings in Figures 6–8, we further assume that the entire coalition adopts the sanctions. Hence, strictly speaking, the red histograms consider the desirability of EU and US sanctions, if the entire coalition were to adopt them. This is not a limitation of the criteria in Equations (3) and (4), which can readily be recomputed for alternative coalitions, but it can help explain differences between our ranking here and sanctions against Russia in place by the EU and the United States.

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Our analysis also does not reflect potential difficulties pertaining to the coordination of sanctions among a coalition of countries. For example, such coordination may be challenging due to political economy reasons. In Section 3.2, 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.

More generally, Proposition 1 – and Corollary 1, for that matter – focus on the economic costs to Russia. Curtailing Russia's economic strength is an important motive for the sanctions, and 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). At a more general level, however, the sanctions were intended to undermine Russia's ability to project power, and important means to this end are sanctions that directly constrain Russia's fiscal resources and its war capability. These motives are also important for designing restrictions on exports to Russia but they are not reflected in Proposition 1.

On the one hand, Russia's economy heavily relies on energy exports, and revenues from related taxes accounted for 45% of Russia's federal budget pre-crisis.[23] Targeting Russia's energy sector 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., 2022a,b), and by the end of 2022 the EU had made impressive progress on that front, e.g. reducing its natural gas imports from Russia by 80% vis-à-vis 2021.[24] 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.[25]

On the other hand, the sanctions were designed to undermine Russia's military capacity.[26] An important instrument in this regard is to restrict exports of inputs for the

23 *Source*: https://www.iea.org/articles/frequently-asked-questions-on-energy-security (accessed 11 January 2023).

24 *Source*: https://www.bruegel.org/dataset/european-natural-gas-imports (accessed 10 January 2023).

25 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 11 January 2023).

26 Andrew Griffith, Economic Secretary to the UK Treasury, for example, said 'We have imposed the 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 9 January 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 United States, respectively.

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Russian defence industry.[27] The strong bias of the sanctions towards capital goods – see Figure 9 – is indicative that such motives were indeed important. Analysing the effectiveness of 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.[28]

Our analysis does also not take into account ethical considerations and distributional consequences of the sanctions. For example, coalition countries directly targeted individuals with political power, executive positions in the defence 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 summary, there are aspects important for the economic costs of sanctions and other important motives for the sanctions that are not covered by our analysis. Yet, Proposition 1 might provide a theoretically grounded, transparent and easily implementable tool that can help inform a more comprehensive analytical process by shedding light on the implied economic costs to a sanctioned party. To corroborate this, we provide a quantitative analysis next that shows the relevance of our economic arguments in an environment with richer I–O structures and when simultaneously considering export restrictions on many products that are large in aggregate.

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

27 Undermining Russia's war capability also involves restricting exports of goods that directly serve military purposes such as goods covered by the Common Military List of the EU or dual-use goods. Our sanction data cover these to the extent to which they were included in the list of HS codes of banned products in the regulations on the sanctions, but this is not necessarily the case for all products that are already covered by other regulations. For example, these lists do not cover HS 8710 – 'tanks and other armored fighting vehicles' and only a fraction of chapter 92 – 'arms and ammunition'. Considering that already in 2013, i.e. prior to the annexation of Crimea, Russia imported *globally* only $56 million (8710) and $135 million (93), respectively, of these products (compared to $300 billion total imports), this is less of a concern for our analysis here which is focused on the economic impact. Such product categories might be more important when examining the effectiveness of the sanctions in terms of undermining Russia's war capability.

28 The WIOD data cover I–O linkages for the energy sector as well, but at an aggregated level. These or similar data have 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 defence 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 analysis.

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restrictions by the EU and the United States were imposed at the level of six-digit HS products, and there are no data on I–O linkages at this level of disaggregation. We therefore aggregate six-digit HS export bans to 15 goods industries present in the 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) and Çakmakli 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 2, 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 2, however, there are no HS products. Instead, we assume that every country is equipped with a distinct variety in every industry, which is 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 section 'Details on economic environment of Section 5' in Appendix 2.

To capture the richness of the international I–O structure in the data, we assume that varieties are produced by combining industry-specific labour with industry-specific intermediate input bundles in a CES production function with constant elasticity of substitution $\phi \leq 1$. $\phi \leq 1$ implies that labour and intermediate inputs are complements in production.[29] 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 United States 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 United States or the transport equipment industry in other countries. We calibrate our model such that these input shares within and across industries match the data.[30]

29 We use sector-specific factors to capture the short-run effects, following Baqaee and Farhi (2021) and Çakmakli et al. (2021).

30 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.

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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 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 analyse export restrictions in place by the EU and the United States and compare them to export restrictions based on our analysis of Sections 2 and 3, 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 2.[31] That is, an 'Armington' economy, where origin-specific varieties are combined in six-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 section 'Derivation of Equation (6)' in Appendix 2 this is the case if

$$\tau^d = \left(\frac{\left[\sum_{g \in \mathcal{G}^d} \mathcal{B}^d \Omega^{gd} + \sum_{g \in \mathcal{B}^d} \Omega^{gd} (1 - \Omega^g_{CO})^{\frac{1-\theta^d}{1-\sigma^g}}\right]^{\frac{1-\xi^d}{1-\theta^d}} - (1 - \Omega^d_{CO})}{\Omega^d_{CO}} \right)^{\frac{1}{1-\xi^d}}. \qquad (6)$$

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.[32]

31 An alternative would be to consider a more granular economy as, e.g. in di Giovanni et al. (2022b). 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 analysing trade restrictions at the six-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 six-digit HS products – see Proposition 1. We therefore opt for computing shocks to Russia at the six-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 section 'Derivation of Equation (6)' in Appendix 2 for further details.

32 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.

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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 I–O linkages, coalition shares in Russia, and elasticities of substitution as introduced in the previous sections.

We take industry-level trade data with international I–O linkages from the WIOD, which provides us with information for 41 countries and 30 industries.[33] To decrease the computational burden, we aggregate countries into 18 country groups.[34] Further, we aggregate industries into 16 by collapsing all service industries. A list of countries and industries can be found in Table A.3. We combine the WIOD data with the product level trade data as discussed in Section 3.1, from which we observe the coalition shares in Russia at the six-digit HS level (Ω^{g}_{CO}) and the share of six-digit HS products in the total Russian expenditure on a WIOD industry (Ω^{gd}).

This leaves us with six 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).[35] For the upper-tier elasticities across input bundles from different industries, we follow Baqaee and Farhi (2021) and Çakmakli 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 labour and intermediate inputs in production, we choose $\phi = 0.6$ (Baqaee and Farhi, 2021; Çakmakli et al., 2021; di Giovanni et al., 2022a). 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 (6) to the data, we further need elasticities from the 'disaggregated' economy. We take the elasticities across varieties of six-digit HS products from Fontagné et al. (2022), as discussed in Section 3.1. Last, 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 six-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 six-digit HS product categories. This suggests that $\theta^d \leq \xi^d$. To err on the 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 Appendix 3, we use different values for these elasticities as a robustness exercise.

33 We use the WIOD data processed by Baqaee and Farhi (2021).

34 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 and Taiwan and Mexico and Brazil, respectively.

35 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.3 lists ξ^d for the industries in our sample.

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Table 2. Elasticities

Parameter	Value	Description
σ^g	Fontagné et al. (2022)	Elasticity of substitution across HS-6 level country 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 labour and intermediates
e^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.

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.[36] 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 and the US sanctions remain in place, but in addition, all coalition countries (i.e. including the EU and the United States) adopt optimal sanctions according to Equation (4) in Section 3. That is, we add the top products according to the ranking in Figure 7. 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 7, 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. Last, 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 times those of scenario 2.[37]

Figure 10(a) shows the economic impact of the sanctions on the coalition (left, blue bar) and Russia (right, red bar), under the six different scenarios.[38] In all scenarios, the economic cost of the export bans is much larger for Russia than for the coalition. This

36 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 United States only, and do not account for sanctions imposed by other coalition members.

37 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 (6), considering one coalition member at a time. We then scale these shocks proportionally to ensure that Equation (6) is satisfied with all shocks combined.

38 In Appendix 3, we run this exercise with different parameter choices for the elasticities of substitution, to find patterns consistent with Figure 10.

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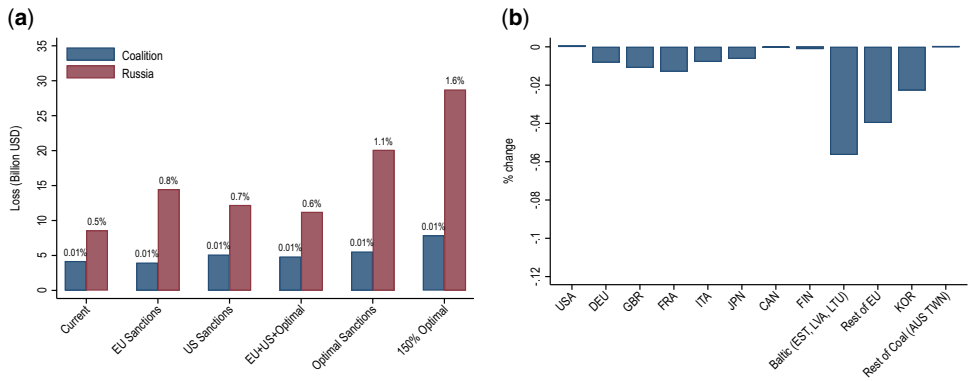

Figure 10. Different sanction scenarios

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

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 of 2 larger for Russia and, in case of sanctions based on our criterion – scenario 5 – even a factor of more than 4 – 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 quantification exercises 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 cases 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 improved coordination (scenario 2 versus scenario 4) are as big or even bigger than the extra cost from an expansion of the sanctions (scenario 4 versus scenario 1), in line with our theoretical reasoning of Section 2.[39]

Interestingly, even with perfect coordination and for a given amount of total banned exports, there is a 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 3. In such a case, the cost to Russia increases by an

39 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 3, which also increases their effectiveness as shown in scenario 5.

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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 criterion – allow us to increase the cost to Russia by $\sim 80\%$ with little to no extra cost to the coalition (scenario 5 versus scenario 4).

In scenarios 2, 4, and 5, $\sim 45\%$ of all coalition exports to Russia are banned. This suggests that there is scope for tightening the sanctions even further, as shown in scenario 6. In this scenario, we again consider sanctions following our criterion of Section 3, 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 10(b) 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 ten smaller when compared to Russia (see Figure 10(a)). All other countries face much smaller losses or they even gain.

While the cost to Russia is much larger than the cost to coalition countries, the welfare loss of 1.1% in scenario 5 is nevertheless moderate. This loss is of the same magnitude as similar numbers in related work (e.g. Bachmann et al., 2022; Evenett and Muendler, 2022*b*). 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 favour 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.[40] 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 overestimate 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 quantification exercises suggest that improved coordination and targeting

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

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sanctions based on the ranking in Section 3 could increase the economic cost to Russia by $\sim 80\%$ at little to no extra cost to the coalition.

6. 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 is the international sanctions against Russia in response to its invasion of Ukraine starting in February 2022, which are the main focus of our analysis. These sanctions are the most comprehensive in modern history, and initial forecasts anticipated a double-digit contraction of Russian GDP. But yet, Russian GDP declined by 2.1% in 2022 and as of May 2023 it was anticipated to grow by 0.7% in 2023.[41]

Important parts of the sanctions against Russia are restrictions on international trade. Their moderate economic effect is thus broadly in line with the remarkable resilience of many European countries to energy shocks in 2022 and before (Fontagné et al., 2023; Moll et al., 2023) and with a large literature on quantitative trade models that typically predict relatively small effects of trade shocks. Indeed, we provide a quantitative evaluation of the restrictions on exports to Russia to also find moderate effects. This does, however, not imply that the sanctions against Russia – and economic sanctions in general – are ineffective vis-à-vis a counterfactual without sanctions for at least three reasons: First, sanctions can serve multiple purposes, and in the case of Russia, for example, they are designed to particularly harm elites and to also undermine the Russian war and energy capability. As a result, the effectiveness of the sanctions cannot be evaluated based on GDP alone. Moreover, the sanctions are biased toward capital goods which might imply that it takes more time for the sanctions to develop their full impact. Second, while the overall economic effect of sanctions may be moderate, our quantitative analysis suggests that the associated costs are much higher for Russia than for the sanctioning coalition. This is an important goal for the sanctions, and our analysis thus suggests that bans on exports are a very effective policy instrument in this regard.[42] Third, there may be scope for increasing the economic impact by redesigning and expanding the sanctions and by coordinating them among a broad coalition of countries, which we have shown to be critical for the effectiveness of the sanctions.

Designing economic sanctions is an intricate task: There is a multitude of instruments available; sanctions serve multiple purposes; they are particularly effective when coordinated among a broad coalition of countries; the effects of sanctions are difficult to predict; and sanctions also impact the sanctioners themselves. To support the design of

41 *Source*: https://www.imf.org/en/Countries/RUS#countrydata (accessed 30 June 2023).

42 See e.g., https://www.bundesregierung.de/breg-de/service/bulletin/regierungserklaerung-von-bundeskanzler-olaf-scholz-2041828 (accessed 31 August 2022).

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effective sanctions, we provide a theoretically grounded, transparent and easily implementable criterion that allows prioritizing export restrictions based on their economic impact on a targeted country. 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 an easily implementable input into a more comprehensive analytical process.

APPENDIX 1: EMPIRICAL APPENDIX

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.

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 imputation of the Russian home share in a product (see Section 3.1.). 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 0.99 for panel (a) and 0.98 for panel (b), and out of the top-1000 products according to the main ranking, 934

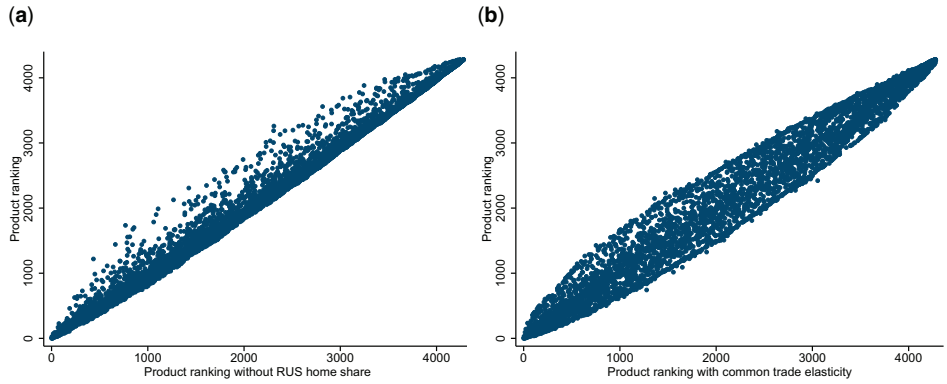

Figure A.1. Robustness of product ranking

Notes: This figure shows robustness checks for a product ranking according to Equation (3). Panel (a) locates each product in a scatter plot with its baseline ranking on the vertical axis and a ranking without Russian home shares 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 six-digit HS level in Fontagné et al. (2022).

Data: See Section 3.1.

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(panel (a)) and 880 (panel (b)) are also among the top-1000 products in the respective robustness check.

Additional figures and tables

Figure A.2 replicates Figure 9 from the main text, but considering export restrictions imposed by the United States instead of the EU.

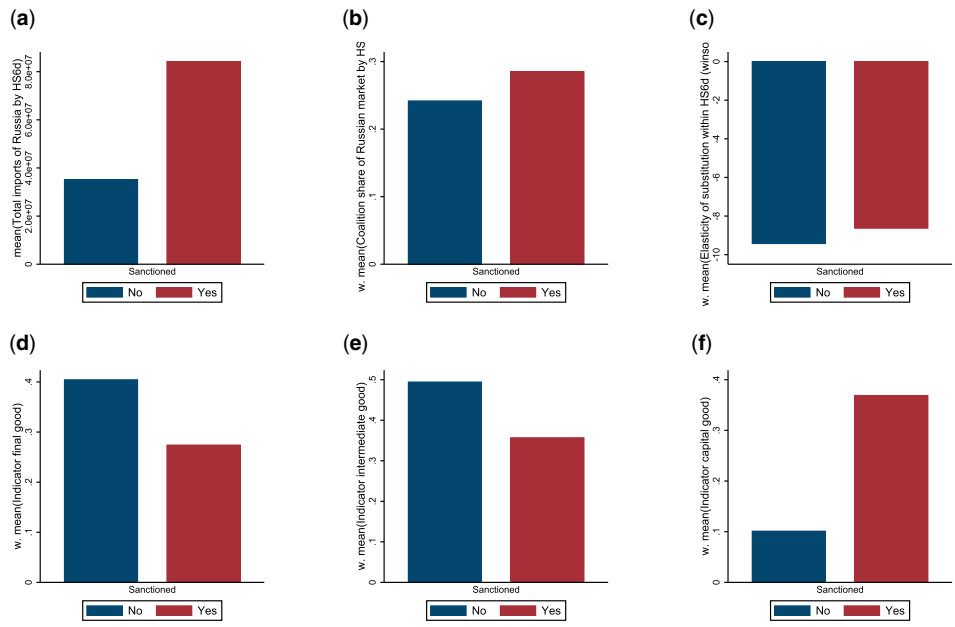

Figure A.2. Characteristics of products with versus without US export restrictions

Notes: The figure compares six-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 following dimensions: (a) Russian imports; (b) sh. coal. Russian export; (c) trade elasticity; (d) sh. cons. goods; (e) sh. intermediates; (f) sh. capital goods. Bars refer to weighted means with weights given by Russia's imports, with the exception of panel (a), which considers simple means.

Data: See Section 3.1.

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Table A.1 lists the top-5 two-digit HS chapters by the share of six-digit HS products within the chapter that was subjected to an export ban by the EU. Table A.2 shows the same table for US sanctions.

Table A.1. Top-5 two-digit HS chapters by share of products with EU sanctions

HS chapter	HS chapter description	Share sanctioned EU
88	Aircraft	1
29	Organic chemicals	0.99
28	Inorganic chemicals	0.99
75	Nickel	0.81
81	Other base metals	0.79

Notes: This table lists the top-5 two-digit HS chapters by the share of six-digit HS products within a chapter that were subjected to an export ban by the EU.
Data: See Section 3.1.

Table A.2. Top-5 two-digit HS chapters by share of products with US sanctions

HS chapter	HS chapter description	Share sanctioned US
24	Tobacco and tobacco substitutes	1
43	Furskins and artificial fur	1
50	Silk	1
57	Carpets and floor coverings	1
91	Clocks and watches	0.98

Notes: This table lists the top-5 two-digit HS chapters by the share of six-digit HS products within a chapter that were subjected to an export ban or general export restrictions by the United States.
Data: See Section 3.1.

Overview of countries and industries in Section 5

Table A.3 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.3. List of countries and industries

	Countries	Industries	ξ^d
1	United States	Agriculture, Hunting, Forestry and Fishing	9.1
2	Germany	Mining and Quarrying	16.72
3	United Kingdom	Food, Beverages and Tobacco	3.55
4	France	Textiles and Textile Products	6.56
5	Italy	Leather, Leather and Footwear	6.56
6	Japan	Wood and Products of Wood and Cork	11.83
7	Canada	Pulp, Paper, Printing and Publishing	10.07
8	Finland	Coke, Refined Petroleum and Nuclear Fuel	52.08
9	Estonia, Latvia and Lithuania	Chemicals and Chemical Products	5.75

(*continued*)

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Table A.3. Continued

	Countries	Industries	ξ^d
10	Rest of EU	Rubber and Plastics	5.75
11	Republic of Korea	Other Non-Metallic Mineral	3.76
12	Australia and Taiwan	Basic Metals and Fabricated Metal	8.99
13	China	Electrical and Optical Equipment	11.6
14	India	Machinery, NEC	2.52
15	Turkey	Transport Equipment	1.37
16	Mexico and 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).

APPENDIX 2: MATHEMATICAL APPENDIX

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

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

where here and below $\check{x}$ 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 the notation, let the six-digit HS producer both produce the domestic variety from labour and combine this variety with imported varieties in the CES aggregator. Let $\mathcal{G}$ be the set of all such six-digit HS producers, $\mathcal{D}$ be the set of downstream producers and $\mathcal{H} := \mathcal{G} \cup \mathcal{D} \cup L \cup Y$, 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

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

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

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

$\check{\boldsymbol{\Psi}}$ measures the direct and indirect dependence of l on g. Intuitively, the second-order term in Equation (A.1) 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

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

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

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

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

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

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Hence,

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

and

$$\check{\Omega}^{kl}\check{\Psi}^{lg}\Delta\ln\check{A}^g = \begin{cases} \check{\Omega}^{kl}\Delta\ln\check{A}^g & \text{if } k \in \mathcal{D} \text{ and } l = g \\ \alpha^l\check{\Omega}^{lg}\Delta\ln\check{A}^g & \text{if } k = Y \text{ and } l \in \mathcal{D} \\ 0 & \text{otherwise} \end{cases}. \tag{A.2}$$

Using Equations (A.2) in (A.1) and the fact that $\epsilon^k = 0$ for the final-good producer yields

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

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 4,000 six-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

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

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

$$\Delta\ln\check{A}^g = -\Delta\ln P^g \approx \frac{1}{1-\sigma^g}\ln(1-\Omega^g_{CO}), \tag{A.3}$$

by Equation (1), and (ii) the fact that $\lambda^g = \check{\lambda}^g$.[43]

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

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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

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

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

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

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 Çakmakli et al. (2021).

Production. We consider an 'Armington'-type model with I countries, D industries, rich international I–O 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.[44] 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 labour using the following calibrated CES aggregator

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

where Υ^d_i is the total output of country i's variety in industry d, L^d_i is its endowment with sector-specific labour and γ^d_i is country i's value-added share in industry d, which we calibrate to match the data. $\phi < 1$ captures the elasticity of substitution between the intermediate input and labour, which we take as complementary. We denote the country–industry-specific intermediate input bundle with M^d_i. These bundles are

44 For the purpose of this appendix, it is important to make an explicit distinction between a buying and a selling industry. For example, an industry-e bundle that is used as intermediate input for production in industry d in country i is denoted by M^{de}_i. This bundle aggregates country varieties with elasticity of substitution ξ^e. As opposed to that, in the remainder of the paper, we simply use a superscript ^{d} to refer to an industry (without the need of distinguishing buyers and sellers) and, accordingly use e.g. ξ^d to refer to the elasticity of substitution across country varieties.

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formed using two-tier CES aggregators: The lower tier combines country varieties to industry bundles with constant elasticity of substitution

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

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

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

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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

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

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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 labour.

Solving the model. We are interested in the impact of the bans on exports to Russia by coalition countries. To that end, we introduce iceberg trade shocks from coalition countries to Russia that mimic the sanctions introduced at the six-digit product level. Details on these shocks are given in the following section. 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.

Derivation of Equation (6)

In this appendix, we derive Equation (6).

Consider an 'aggregated' economy with 15 WIOD industries and rich I–O linkages. Let $\tilde{P}^d$ be the direct 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 2, this effect is given by

$$\tilde{P}^d = \left(1 + \Omega_{CO}^d \left[\tau^{d\,1-\xi^d} - 1\right]\right)^{\frac{1}{1-\xi^d}}, \tag{A.4}$$

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

Consider a 'disaggregated' economy analogous to Section 2 instead. In this economy, origin-specific varieties of six-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

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

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

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$g \in \mathcal{G}^d$, we then get for the direct effect of the export bans on the industry-d price index

$$\hat{P}^d = \left(\sum_{g \in \mathcal{B}^d} \Omega^{gd} (1 - \Omega^g_{CO})^{\frac{1-\theta^d}{1-\sigma^g}} + \sum\nolimits_{g \in \mathcal{G}^d \setminus \mathcal{B}^d} \Omega^{gd} \right)^{\frac{1}{1-\theta^d}}, \tag{A.5}$$

where Ω^{gd} is the share of product g in industry d in Russia. Equation (6) then follows from equating Equations (A.4) and (A.5) and solving for τ^d.

APPENDIX 3: ROBUSTNESS OF QUANTITATIVE RESULTS

In our baseline specification, we follow Baqaee and Farhi (2021) and Çakmakli 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 six-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 C.1 shows a summary of our elasticity choices in the two robustness exercises.

As shown in Figure C.1, regardless of these elasticities, our main results remain qualitatively 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.

Table C.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.

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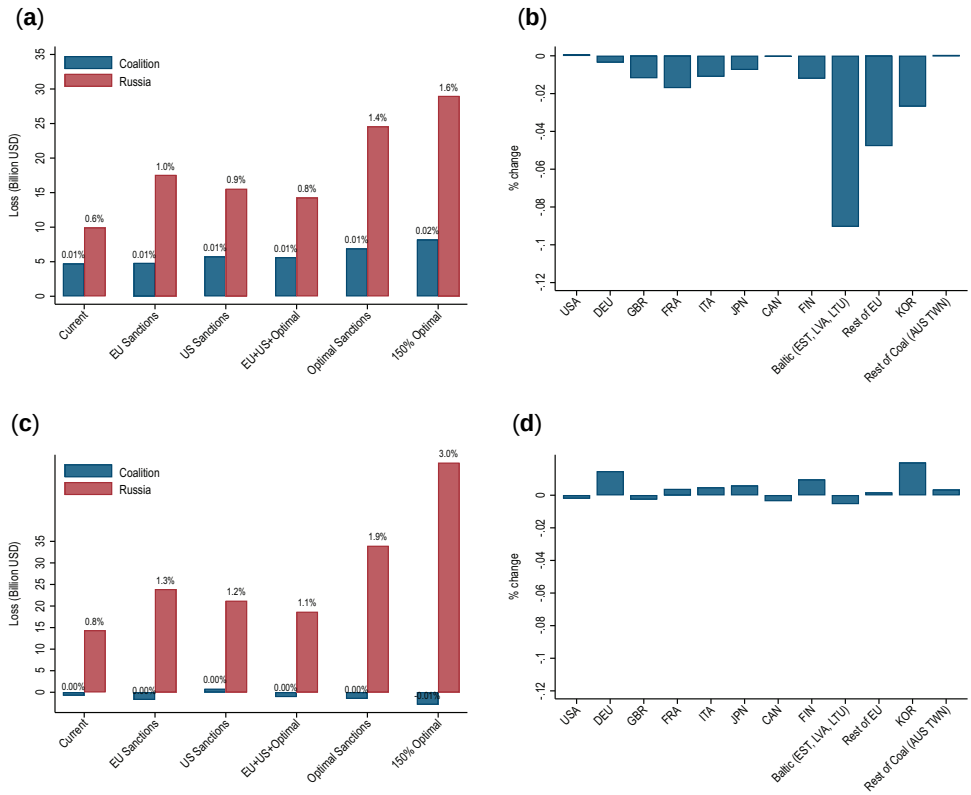

Figure C.1. Sanction scenarios

Notes: This figure replicates Figure 10 for the elasticity choices as summarized in Table C.1. (a) Robustness 1 – coalition versus Russia; (b) Robustness 1 – coalition countries; (c) Robustness 2 – coalition versus Russia; (d) Robustness 2 – coalition countries.

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Economic Policy, 2025, 39, 109–153
https://doi.org/10.1093/epolic/eiad043

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