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A Method of Estimating Global Supply Chain Risk and Predicting the Impacts of Regional Disruptions

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Samuel M. Goodman

Abstract

Recent trade disruptions have highlighted multiple weaknesses within the global value chains of multiple commodities. This paper presents a method of estimating the risks posed to the U.S. economy by trade disruptions across countries and regions. A mathematical model is proposed based on the global concentration of suppliers of a given commodity and the relative dependence of the United States on net imports from each global source. The resulting dataset is one tool researchers and analysts may use when evaluating the downstream impacts of current events and identifying portions of the supply chain that would benefit from risk mitigation actions.

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Please direct all correspondence to Samuel Goodman, Office of Industries, U.S. International Trade Commission, 500 E ST SW, Washington, DC 20436, telephone: (202) 205-3464, email: samuel.goodman@usitc.gov.

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Introduction

The global events of the past two years have revealed structural weaknesses within many global value chains. The COVID-19 pandemic disrupted access to consumer goods and inputs like semiconductors with backlogs and delays continuing to persist. The war in Ukraine has further highlighted the risks posed by regional disruptions. To-date, the conflict has threatened both high-volume, critical commodities like fertilizers and critical inputs like palladium used in advanced manufacturing.[1] Understanding global bottlenecks is an important first step to understanding the potential downstream impacts of a trade-disrupting event, especially if the goal is to proactively mitigate risks rather than react to disruptions after the fact. This paper explores a new approach for estimating the concentration risk index for U.S. supply chains and provides a preliminary estimate of this risk for all commodities at the six-digit harmonization level.[2]

Mathematical Framework

Several assumptions undergird the construction of this model. The first is that disruption in an industry that is highly concentrated (i.e., with fewer sources) poses greater risk than one with less concentration. Second, commodities with lower U.S. net imports are at lower risk of disruption due to a larger domestic production base as a share of total domestic consumption or lack of domestic consumption.[3] Finally, the model assumes fungibility between commodities sourced from different countries. In each assumption, risk is understood to be the threat that the material supply of a good will be disrupted, resulting in a shortage when demand exceeds supply (e.g., if a grain-producing region is less productive, the quantity of available grain is reduced). The following sub-sections describe the implications and implementation of these assumptions in greater detail.

Estimate of Global Concentration

A commodity with few producers means that any of them being shut down or impacted by some natural or political event will have substantial effects on global consumers of that product. This concentration may arise because of natural resource distribution (e.g., you can only mine a mineral where it exists), agricultural distribution (e.g., only certain climates can support certain crops), or the required industrial base to manufacture certain products (e.g., the concentration of advanced semiconductor manufacturing). It is harder to source replacement material from a highly concentrated supply chain due to a disruption than one where there are many potential sources. That difference in sourcing diversification must be factored into the analysis.

The first element of the model is an estimate of the global concentration of a particular commodity's production (equation 1). The functional form is based on the Herfindahl-Hirschman Index (HHI), which is used to estimate, for example, the level of market competitiveness in the context of anti-trust

[1] FAO, "The Importance," March 25, 2022; DeCarlo et al, "Disruptions to Global Supply," June 2022.
[2] Helbig, "An Overview of Indicator Choice," August 4, 2021. A spreadsheet summarizing the resulting dataset is available on the USITC Staff Publications page within the entry for this working paper.
[3] Lower U.S. net imports refers to situations where the United States has low imports for domestic consumption.

evaluations of mergers and acquisitions.[4] The maximum value, when there is no market competition, is 10,000; generally, values less 1,500 represent a competitive market, 1,500–2,500 indicate moderate concentration, and values greater than 2,500 mean an industry is highly concentrated. In this context, the function is used to estimate the level of industry concentration among countries within the global market. The term in the numerator calculates the trade balance (imports minus exports) for each country. Those with no net trade (i.e., they export the same amount that they import) or net importers are excluded from the calculation, since they are not contributing to traded global production and are not ultimately sources of the commodity available to the United States.

$$\gamma_i = \sum_{N \subset a} \left[100 \frac{\sum_c E_{i,a,c} - \sum_c I_{i,a,c}}{\sum_{N \subset a} \left(\sum_c E_{i,a,c} - \sum_c I_{i,a,c} \right)} \right]^2 \quad (1)$$

γ_i: the concentration factor of commodity *i*.
i: A commodity within the set of commodities of which the United States is a net importer.
$I_{i,a,c}$: Imports of commodity *i* by country *a* from country *c*.
$E_{i,a,c}$: Exports of commodity *i* by country *a* to country *c*.
N: The subset of all countries *a* that are net exporters of commodity *i*.

A variant of this equation can be used where actual production data ($P_{i,c}$) is available. In equation 2, the ratio reduces to the sum of production in a given country by the total global production.[5]

$$\gamma_i = \sum_{c} \left[100 \frac{P_{i,c}}{\sum_c \left(P_{i,c} \right)} \right]^2 \quad (2)$$

U.S. Import Dependence

The concentration of a commodity does not necessarily imply a risk to U.S. supplies, nor does each country carry the same risk. Even in a concentrated market, a minor player experiencing problems carries a lower risk than a major one. Similarly, if the United States is itself a major producer and exporter, there is less risk to domestic consumers when foreign supplies are disrupted. The second part of the model considers these factors.

The specific risk posed to the United States by a disruption in another country is calculated in two parts ($S_{i,c}$) equation 3). The first term quantifies what fraction of a given commodity is sourced from each country, being the ratio of imports from a given source to all imports of that type. In general, the model is structured to assign greater risks to commodities imported from fewer sources. That risk is modulated by the second term, which is a measure of the total net trade in that commodity that is used as a proxy

[4] USDOJ, "Herfindahl-Hirschman Index," updated July 31, 2018.
[5] An example using this form is not included in this paper.

for domestic production in the model.[6] The numerator calculates the trade balance, that is, imports from all sources minus exports. When there are net exports, it is assumed that the United States is self-sufficient in producing a given commodity and the risk is assigned a value of zero.[7] Finally, the net trade is normalized by total imports, both to make it dimensionless and to quantify what fraction of imports is required to meet the demands for internal consumption.

$$S_{i,c} = \left(\frac{I_{i,US,c}}{\sum_c I_{i,US,c}}\right)\left(\frac{\sum_c I_{i,US,c} - \sum_C E_{i,US,c}}{\sum_c I_{i,US,c}}\right) \quad (3)$$

Final Risk Matrix

The risk assigned to each country and commodity pairing is simply the product of the terms *S* and *γ* ($R_{i,c}$, equation 4). The output should be treated as a relative measure rather than yielding a specific quantifiable shift. In general, larger numbers mean the United States is more import dependent in a more concentrated market. A maximum value of 10,000 means there is only one global source, and the United States is dependent upon it. A minimum value of 0 indicates the United States is self-sufficient. The output can be sorted by partner country to determine what commodities are at risk due to disruptions in that region or by commodity to evaluate the critical nodes within the global supply chain.

$$R_{i,c} = \left(\frac{I_{i,US,c}}{\sum_c I_{i,US,c}}\right)\left(\frac{\sum_c I_{i,US,c} - \sum_C E_{i,US,c}}{\sum_c I_{i,US,c}}\right)\left(\sum_{N\subset a}\left[100\frac{\sum_c E_{i,a,c} - \sum_c I_{i,a,c}}{\sum_{N\subset a}\left(\sum_c E_{i,a,c} - \sum_c I_{i,a,c}\right)}\right]^2\right) \quad (4)$$

Multiple rounds of risk calculation could be used to provide deeper insights into the global supply chain of a given commodity. The first-pass model of U.S. imports does not necessarily capture goods that are re-exported from an intermediary instead of the original manufacturing country. Applying the calculation to U.S. trade partners would elucidate those shipping steps and help identify the ultimate sources of risk for a commodity. One could do a similar analysis on the inputs raw materials used to manufacture a good that a U.S. trade partner uses to manufacture its exports to capture more of the overall lifecycle risk.

Results

The utility of the model was tested by applying it to real-world data. Import and export data at the harmonized system (HS) 6-digit level was sourced from the Global Trade Atlas Database. This source consolidates trade data from 94 reporting countries. A single year, 2021, was chosen for analysis

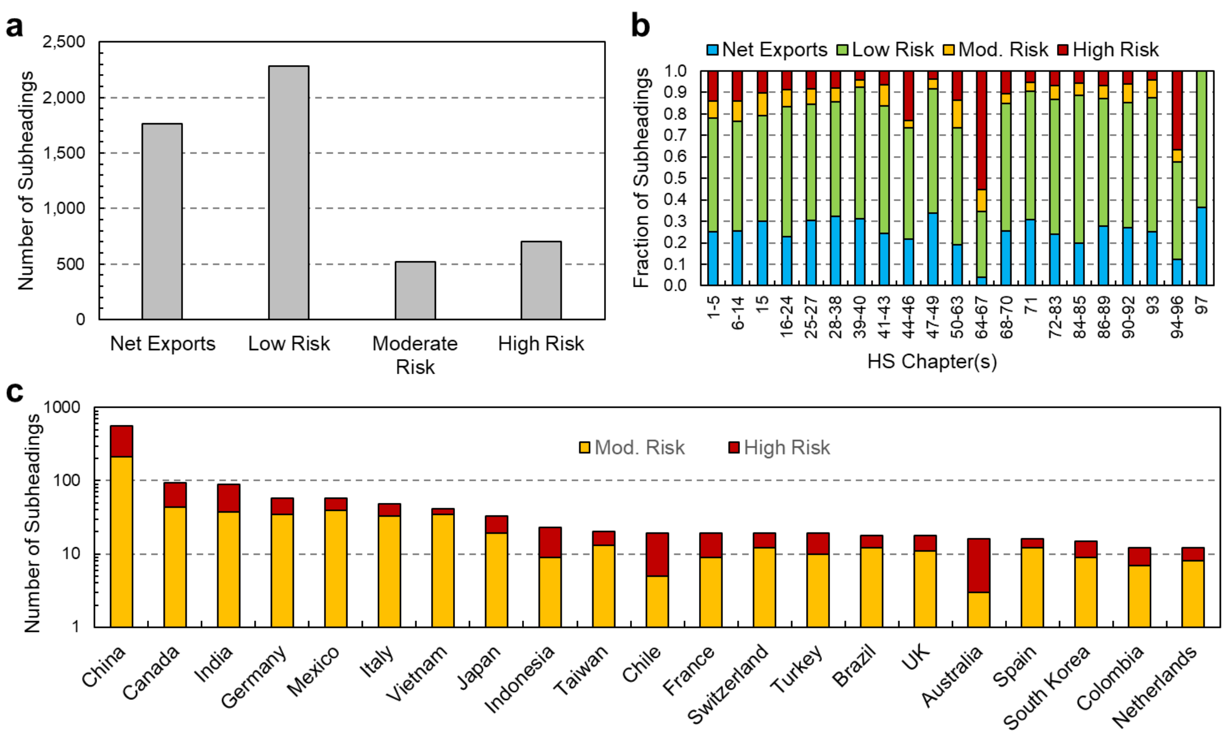
[6] An alternative form of the second term based on production and consumption could be used when that data is available. The ratio could switch to imports for consumption (I_C) divided by the sum of I_C and production, which would measure what fraction of total U.S. consumption is dependent on imports. The ability to perform that kind of calculation would be very product-dependent, as the necessary production data is difficult to access for many commodities at the HTSUS 6-digit level and higher.

[7] Alternatively, keeping the negative outputs of the model could be used in a different formulation to identify which trading partners are critically dependent on imports from the United States.

because it would provide the most current results on the state of global trade. The results of the calculations are summarized in the spreadsheet associated with this paper linked on the USITC website.

The overall results indicate that a minority of products imported by the United States are at risk of substantial disruptions. Figure 1a breaks down the number of 6-digit subheadings into risk categories based on traditional ranges of the HHI.[8] Commodities are low risk when the model assigns a value less than 1,500 to all countries, moderate risk when at least one country is in the range of 1,500–2,500, and high risk when at least one country is greater than 2,500; products that are net exports are separated from the low-risk category for clarity and reference. On average, about 20 percent of the 6-digit subheadings within a product category are moderate or high risk (figure 1b), with some outliers. The majority of products covered under HS chapters 64–67 are high risk (55 percent) as are a third of goods in chapters 94–96.

Figure 1 Breakdown of risk by subheadings



Note: (a) Breakdown of all 6-digit subheadings by risk category; (b) breakdown of risk by product digest; (c) breakdown of risk by partner country on a logarithmic scale. See the section headings on the HTSUS website for more information about the products in each digest.

A subset of countries carries heightened risks to U.S. trade based on the number of subheadings they are critical components of. Figure 1c summarizes the riskiest partners based on that quantity. China is the leader by an order of magnitude with 212 moderately risky and 346 highly risky commodities. The global distribution of risk follows a Pareto-like distribution, where most countries have no moderate- or

[8] Values following the USDOJ benchmarks are useful enough for qualitative analysis and do not require one of the logarithmic normalization approaches summarized in Helbig, "An Overview of Indicator Choice," August 4, 2021.

high-risk exports to the United States; only 76 countries have at least one commodity in those risk categories.

One of the goals of the calculation is to identify the potential impacts of specific trade disruptions. The recent political instability in Sri Lanka offers a test case. Sri Lanka supplies two products in the high risk category (coconut textile fibers [5308.10] and un-ground cinnamon [0906.11]) and one in the moderate category (coconut oil cake [2306.50]). All of these products have high global concentration indices and most of the U.S. imports are for consumption. Thus, one would expect the present political situation to impact downstream users of these products most severely if they lead to trade disruptions.[9]

Limitations

The primary constraint of implementing this model is acquiring the necessary data. Global trade data is often incomplete, because not every country reports the necessary statistics in an accessible way. That gap means countries that may be major sources are not properly accounted for in the concentration term. An issue with the data set used for the above calculation is that some products are not net exports of any reporting countries, making the concentration index zero; this result is neither useful nor physically possible. Some countries, like Russia, have also ceased providing this data entirely, complicating up-to-date analyses of many critical goods.[10] Using mirror data could partially alleviate those gaps, but it would have to be treated carefully due to the increase in uncertainty it would introduce.

Where data is available, it may not be at the granular level desired. Many harmonized tariff codes are basket categories that cover myriad products. For example, the inputs and capital used in semiconductor manufacturing are often classified in basket categories at the harmonized level, while ten-digit tariff lines used by different countries record variations destined for specific end-users. When a commodity is very low volume and folded under one of these lines, specific risks may be obscured. Similarly, limited global production data for most commodities precludes that version of the analysis.

The results of the model presented here are also limited by the assumption of fungibility. The ability to swap suppliers is not always the case, especially for advanced manufacturing. Continuing with the semiconductor example, inputs from each source often must be rigorously qualified to ensure they work with a given manufacturing process, which can take months and lead to temporary production halts as the transition occurs. The risk matrix would thus underestimate the risk in this situation.

Finally, the model is not concerned with price effects. The calculation is only concerned with the ability to source tangible goods, that is, what is the risk to having the physical material the economy needs. It does not speak to instances, for example, where disruptions in the global market increase prices even when the United States is nominally self-sufficient. The effects of increased global scarcity on competition for the remaining product is also not captured.

[9] Kugelman, "Sri Lanka's Economic Crisis," October 6, 2022.
[10] Reuters Staff, "Russia Suspends," April 21, 2022.

Conclusions

The numbers that come out the other side of this calculation are, ultimately, a guide for researchers and analysts, not an answer in and of themselves. The criticality of each material and the probable downstream effects of any disruption must still be determined by someone with the experience to understand their full context. For example, a disruption may affect different commodities differently, meaning additional dimensions or risk are required to fully capture the potential consequences of any one event. These values are thus a tool to help sort through the chaff as part of a larger analytical process.

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