INVESTIGATING 21ST CENTURY PROLIFERATION PATHWAYS

by

BRIAN STARKS

(Under the Direction of AMANDA MURDIE)

ABSTRACT

Weapons of mass destruction development programs often rely on clandestine procurement activities. The hidden nature of weapons proliferations leaves scholars with few sources of quantitative data to inform research designs. Using published government export violation cases, a novel dataset provides the first large-*n* sample of illicit military, dual-use, and commercial technology transfers. These data are converted into various networks to assess structural traits that describe how these different technologies illegally flow throughout the international system, reflecting actors' preferences regarding transaction costs and secrecy. Exponential random graph modeling reveals states' economic globalization and proximity affect their likelihood of being involved in illicit dual-use transfers. There is mixed evidence that increased membership in multilateral export control regimes increases the likelihood of a state receiving illicit dual-use transfers.

INDEX WORDS: PROLIFERATION, NONPROLIFERATION, DUAL-USE, ILLICIT TRADE, MILITARY, WEAPONS OF MASS DESTRUCTION, SMUGGLING, EXPORT CONTROL, HIDDEN POPULATION

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DEDICATION

I've only made it this far because of my friends, family, and the ones who blur the line between. During the last few years, I've been ill, homesick, exhausted, jet-lagged, frustrated, stressed, and just generally brought to my emotional and physical limits. Their kind words of encouragement, constant patience, and well-intentioned persistence have meant the world to me. I appreciate you all more than these words on a page can convey, but I hope this dedication page is the start of many, many years of returning the favor.

In particular, I'm eternally grateful to Andrea, who has listened to and participated in years of export control, nonproliferation, and network analysis discussions. This has been a long road, and I am lucky to have her walking this path side-by-side with me. I could not dream of a better partner who shares a love of learning, appreciation of libraries, and the satisfaction after reading a well-researched document. I'm excited for whatever adventures await- I'm sure it'll be exhilarating and at least a little bit chaotic. Love you, Meatball!

ACKNOWLEDGEMENTS

I want to thank Amanda Murdie, who has been an incredible academic and professional mentor. Amanda helped me find ways to develop my interest in network analysis- like suggesting I take courses offered by other departments and encouraging me to attend the Political Networks conference to meet other academics interested in making sense of messy network data. Over the years, Amanda has introduced me to multiple excellent nonproliferation and arm trade scholars. Those conversations fought back the imposter syndrome that haunted me at times, especially as I completed my dissertation while working and living away from Athens. I cannot say it more clearly than this research would simply not exist without Amanda's guidance and support.

I credit Chris Tucker for the spark that led to my academic and professional passion for nonproliferation. I had never intended to pursue a master's degree, much less a PhD but that spark continues burning, pushing me onward and onward. I met Chris after completing my business degree coursework and having finished my first international affairs course on terrorism. I didn't realize it at the time, but I was searching for a rewarding career path that had eluded me until that point. Export controls are chaotic at times; they are the noisy nexus of economics, security, and foreign policy. It has been over a decade since I first learned what "dual-use" means, and it's been a roller coaster ever since.

Amanda and Chris- I doubt I'll ever repay the positive impacts you both have had on my life, but I'll strive to follow your examples by helping others learn, grow, and find their own rewarding career paths.

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[1] Starks, B.M. To be submitted to a peer-reviewed journal

Abstract:

*Nonproliferation research has long been stymied by a lack of large-*n *quantitative data. Difficulties in data collection and operationalization pose challenges to quantifying the illicit spread of conventional arms and dual-use technologies. Relying on violation documents released by the United States' government, the Strategic Export Violation (SEV) dataset operationalizes over 800 cases that violate nonproliferation laws between 2007 and 2022. The SEV data adapt regulatory classification nomenclature to provide granular information concerning each violation's characteristics. SEV data are intended to facilitate future quantitative research designs that can more directly query proliferation-related hypotheses.*

Introduction

Proliferation of conventional military hardware and dual-use commodities (technologies with both civilian and military applications) exacerbates international security, such as arms traffickers fueling conflicts in Syria (Conflict Armament Research, 2018), Western electronics found in Russian weapons platforms against Ukraine (State Department Media Office, 2024), the use of VX nerve agent in a Malaysian airport (Nauert, 2018), and the continued threat of new countries developing nuclear weapons programs.[2]

Policymakers often refer to this group of miliary and dual-use items as "strategic goods," with many states implementing "strategic trade control" regulations to manage the flow of these

[2] Dual-use commodities can serve in weapons of mass destruction programs or legitimate civilian applications. Traditionally, dual-use commodities typically included items with nuclear, chemical, biological, or missile applications. The concept of dual-use has expanded to include other technologies, such as encryption. For more information, refer to Bauer, S. (2012). *For the bathroom or the missile factory? Why dual-use trade controls matter*. Stockholm International Peace Research Institute. Retrieved 06/02/2024 from https://www.sipri.org/commentary/essay/2012/bathroom-or-missile-factory-why-dual-use-trade-controls-matter

items. For the purposes of the dataset and this research note, *strategic* describes items with inherently military applications (e.g., cruise missiles) or dual-use commodities (e.g., carbon fiber).[3] Many states regulate the trade of at least some strategic goods to achieve certain economic, foreign policy, and national security objectives. Figure 1 below depicts the constituent terms of "strategic goods."

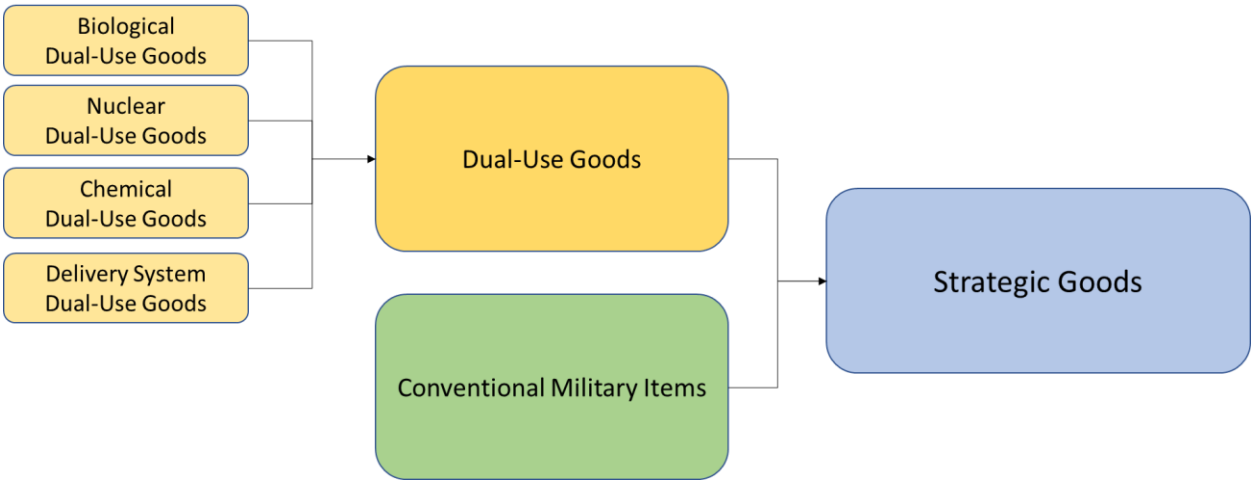

Figure 1: Constituent terms of "strategic goods"

The modern system of multilateral strategic trade controls traces its roots to the Coordinating Committee for Multilateral Export Control (COCOM), which was created 1949 to prevent the Soviet Union from procuring sensitive technologies from the United States and its allies(Casey, 2023; The Cox Report, 1999). As the Cold War ended, COCOM was retired in 1994, but four distinct multilateral export control regimes emerged to adapt to the multipolar environment. These regimes established lists of controlled commodities that participating states transposed down to their domestic legal frameworks. Furthermore, each UN member state is obligated to have domestic strategic trade controls. Under United Nations Security Council Resolution 1540

[3] It is common, although not universal, to see the private sector or government regulators use the term *strategic goods* to refer to both conventional military items and dual-use commodities. For example, refer to the Dutch government's "Control policy for strategic goods and services" web page at https://www.government.nl/topics/export-controls-of-strategic-goods/export-control-policy-for-strategic-goods.

(UNSCR 1540), United Nations members must adopt and enforce laws to prevent the spread of weapons of mass destruction technologies.

Proliferation scholarship predominantly falls into two categories: demand side and supply side. Demand-side proliferation literature questions what factors motivate states to seek weapons of mass destruction (WMDs), often focusing on motivations like military power, perceived security risk, international influence, or economic benefit (Debs & Monteiro, 2017; Miller, 2018; Sagan, 1996). Supply-side proliferation research identifies how states procure strategic goods (Fuhrmann, 2008; Koch, 2019).

Nonproliferation scholarship often relies on qualitative methodologies, such as assessing a multinational regime's efficacy (Koch, 2019) or identifying typologies of conduit countries for illicit trade (Salisbury, 2019). Because few nonproliferation-related datasets exist, scholars often lack the data to quantitatively probe nonproliferation hypotheses.

Large-*n* nonproliferation studies are relatively rare, often using proxies or limited observations for proliferation flows. Examples include the use of reported trade data to determine which factors are associated with higher amounts of potential dual-use exports from the United States (Fuhrmann, 2008)or descriptive network analysis of small arms trafficking in Africa(Kinsella, 2006). Although the field continues to develop quality nonproliferation scholarship, the lack of large-*n* datasets inhibits some quantitative research designs.

The SEV dataset introduces a novel unit of analysis that allows future research designs to probe deeper into supply-side proliferation studies. By breaking down a common export classification nomenclature, the SEV data parse between instances of illicit trade. This enhanced granularity within the data can enable scholars to investigate which types of strategic goods are most sought after, which states are most often used as conduits, and the network structures that have emerged as the primary smuggling routes for strategic goods.

Problem Formation

Export violations share similar difficulties with other attempts at quantifying "hidden populations," such as human trafficking victims (Scullion, 2015). Depending on states' legal frameworks, what constitutes an illegal export of strategic technology varies. Differences between states' capabilities to detect and successfully prosecute violations further obscure scholars' ability to observe the population of export violations. Because of these factors, a complete picture of illicit strategic trade remains out of reach, making it difficult to assess how well the sample data represent the true population. Lacking a clear picture of the population of illicit trade, a large sample size must serve as proxy.

Based on observed cases of illicit strategic trade, SEV data are coded and structured for models investigating supply-side proliferation. There are multiple approaches to quantifying illicit trade, each of which will emphasize certain traits while downplaying others. The SEV dataset establishes a baseline glimpse into the hidden population of illegal strategic goods. It will enable research designs to identify which technologies are more often targeted, in what manner they are

transferred (tangible vs intangible exports), any intermediate countries used as a conduit, and the final destination country.

The dataset establishes one perspective on operationalizing observed proliferation patterns, allowing for more detailed and substantiated discourse on the nonproliferation community's most pressing questions. Do certain industries need additional outreach and training to detect procurement attempts? If repeated patterns of diversion emerge, should pathways routing to or through certain countries merit additional scrutiny? Which states are the most common end destinations?

The initial version of the SEV data only contains violations from the United States because documented cases from other states' enforcement actions are limited. Owing to a Union-wide requirement to implement strategic trade controls, European Union (EU) member states would be a likely alternative source for export violation. Unfortunately, multiple factors limit the volume and scope of publicly available EU-origin violation cases (Bauer & Bromley, 2019).[4]

Collecting and Operationalizing Proliferation Data

For violations of U.S. strategic trade control laws, the U.S. Department of Commerce (DOC) provides the largest, most readily available source for export violation data. The DOC has jurisdiction over the export of all dual-use, commercial, and some military commodities. A

[4] The most common factors include mixed priorities for Customs officials (who are most likely to detect illicit strategic trade), judges with little to no experience in export control cases, and some states' regulatory language creates difficult burdens proof to levy charges.

specialized organization within the DOC, the Bureau of Industry and Security (BIS) implements the domestic regulation that govern the majority of US export volume.[5]

BIS, in compliance with the United States' Freedom of Information Act (FOIA), maintains a webpage that lists hundreds of documents concerning strategic export violation cases.[6] At the time of writing, the available cases extend back to January 2007, and new cases are added semiregularly. The SEV data rely on the BIS electronic FOIA (eFOIA) documentation as the primary source, forming the dataset's foundation. At times, the eFOIA documents fail to mention key traits needed for proper SEV coding. Secondary sources, such as other government agencies' reports or news media articles, are used to supplement the eFOIA documents.

SEV's Unit of Analysis- Proliferation Pathway

The SEV dataset introduces a new unit of analysis called the *proliferation pathway* (PP) to appropriately capture differences between cases' complexities.[7] Each proliferation pathway primarily consists of a specific strategic item and the countries involved in its route from source country to the end destination. These details derive from the BIS export violation documents, but one violation document may contain multiple distinct pathways. By identifying each distinct

[5] The U.S. export control system divides jurisdiction between the Department of Commerce, Department of State (DOS), Nuclear Regulatory Commission (NRC), Department of Energy (DOE). The DOS regulates the export of advanced conventional military equipment. Nuclear exports are split between the NRC and DOE. NRC regulates the export of nuclear commodities, while DOE regulates the export of nuclear-related technologies. See "Overview of U.S. Export Control System" for additional information.

[6] Some of the BIS cases involve exports under the Department of State's jurisdiction over export of conventional military goods because BIS revokes the violators' ability to export from the U.S. or to receive U.S.-origin goods if the violator is located in another country.

[7] Straightforward cases involve one individual or company exporting one strategic commodity directly to the final destination. Complex cases often contain multiple different strategic commodities that were exported and reexported through multiple intermediate countries before arriving at different destinations. By creating a unit of analysis at the commodity-route level, the SEV dataset can identify distinct pathways for particular commodities.

pathway, the data allow for an improved analysis over straightforward counts only measuring trafficked items or final destinations. By linking each attempt's targeted commodity and its route, scholars can more thoroughly investigate potential patterns between specific technologies and countries involved in illegal strategic exports.

To demonstrate the advantage of the proliferation pathway over straightforward counts, consider the following export violation:

An American company supplied controlled electronics to Russia military end users. According to Department of Commerce regulations, the electronics were given a specific export control classification number (ECCN) to denote their dual-use nature. Given the electronics' potential military applications, the American company would likely not receive approval by BIS to export the controlled goods to Russian military end-users. To avoid scrutiny, the electronics were shipped to an Estonian company. The intermediate company would then either export the electronics directly to Russia or use Finland as an additional conduit. Later, the American exporters directly shipped items to the Finnish entity for eventually reexport to Russia.[8]

If the SEV data followed a straightforward unit of analysis (depicted in Figure 2 below), the example case would constitute one observation of electronics to Russia from the United States.

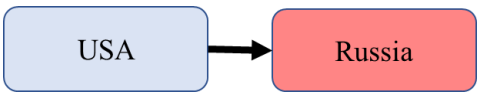

Figure 2: Straightforward approach to capture violations.

[8] Cases 800–802 in the SEV data.

By using the proliferation pathway as a unit of analysis, the SEV data more accurately operationalizes the nature of the violation. The proliferation pathway breaks down items by their export classification details and notes any intermediate countries. If multiple items are shipped along the same route or if one type of item is shipped along multiple routes, the proliferation pathway unit of analysis accounts for the variation and creates distinct observations. As shown in Figure 3, following proliferation pathway coding rules results in three different observations. This method captures how often Estonia and Finland are used as conduits to the ultimate destination, Russia.

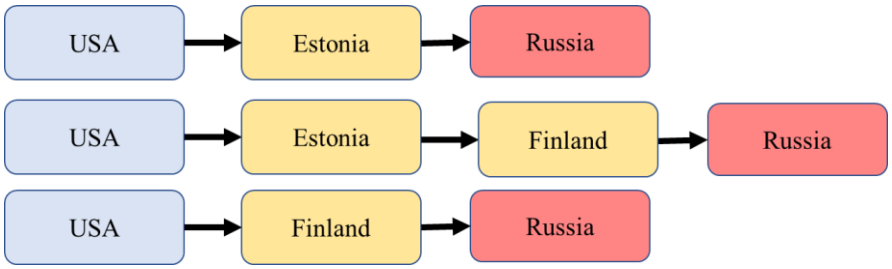

Figure 3: Proliferation Pathway's approach better captures the role of conduits.

Adopting the commodity classification nomenclature of regulatory agencies creates more intuitive results to audiences outside of academia (e.g., government and industry). Alternative data sources, usually harmonized system (HS) codes used in importing, are more commonly used since they are readily available. Unfortunately, HS codes only loosely correlate with strategic commodities which limits the ability of researchers and policymakers to implement changes based on those studies' findings (Chatelus & Heine, 2016).

Within the U.S. system, dual-use goods are given a specific five-digit, alpha-numeric export classification, called an export control classification number.[9] The ECCN nomenclature captures

[9] The ECCN structure is similar to the European Union's Dual Use List nomenclature. Both the U.S. and EU nomenclatures are based on multilateral export control regime lists. Since other countries employ nearly identical

granular information such as the item category (e.g., sensors and lasers), product group (e.g., test equipment or raw materials), and the reason for control (e.g., nuclear proliferation or missile technology). The first digit represents the category, which is always a number zero through nine. Next, the letter denotes the products group, which is always a letter A through E. The next digit is a number from zero to nine, which represents the primary reason for control. The reasons for control are often reflects of domestic implementation of multilateral regime control lists, although some reasons have been added unilaterally. Lastly, the remaining two digits serve as identifiers to differentiate between various items that fall under the same category, product group, and primary reason for control.

See the example below in Figure 4, which breaks down ECCN 2B350. This ECCN captures chemical reaction vessels that are made of corrosion-resistant materials and can blend different chemical precursors together under controlled conditions. Research and industrial applications often use export-controlled reaction vessels, but these items could potentially contribute to a chemical weapons production program.

export classification systems, future updates to the SEV dataset could include cases originating from multiple countries.

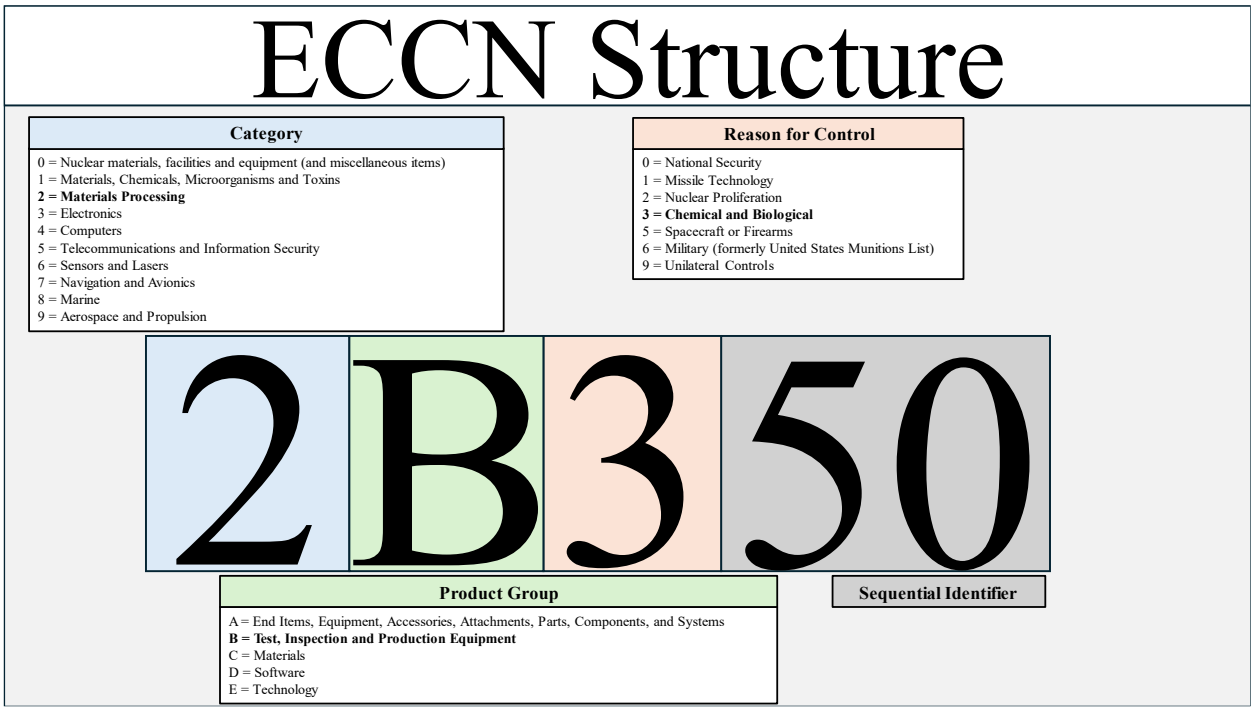

Figure 4: Structure of an export control classification number (ECCN)

The SEV data are the result of coding 816 eFOIA documents for 28 fields of information.[10] BIS continues to release more cases, providing additional observations to expand the dataset.

The SEV dataset's primary contribution derives from parsing out key information from the ECCNs described in case documents. The ECCNs are based on an international, widely adopted standard export classification nomenclature. Typically, only the BIS eFOIA documentation contains details on items' export classifications, with news articles or major Department of Justice press releases often omitting the ECCN. Whereas other approaches have mainly recorded descriptions of illicit exports (Kinsella, 2006), the SEV data allow research designs to differentiate between categories, product groups, and reasons for control. The additional

[10] Including item description, export classification, conduit country (or countries), final destination, end user, financial penalty, jail time, and length of debarment from exporting out of or importing from the United States. When source documentation lacked information, that observation's particular fields were marked "UM" to denote information that was unspecified or missing.

granularity into each observation enhances scholars' ability to investigate illicit trade patterns of particular goods.

Recording the involvement of any conduit countries in the proliferation pathways serves as the secondary contribution of the SEV data. The earlier example concerning exports to Russia demonstrated the benefit of identifying conduit states. In nearly all transactions, the country of destination determines if an export authorization is required. The electronics in the earlier example did not require prior government approval for export to Estonia or Finland but would have required an authorization from the U.S. government for export to Russia. Capturing the conduit states can help identify not only frequent diversion hubs but may also be used to investigate why certain states are more or less likely to be chosen to serve as proliferation conduits.

BIS documents released publicly through the eFOIA process serve as the foundation for each observation in the SEV dataset. At times, additional sources of information were used to supplement insufficiently detailed eFOIA documents. These additional sources typically include Department of Justice press releases and BIS's publicly available annual reports to Congress. Many cases, especially the smaller-scale or older violations, did not have additional sources to supplement the BIS documents.

Data Reliability and Validity

The SEV dataset is new and will be useful to test hypotheses such nonproliferation such as which types of technologies are most often targeted (e.g., nuclear vs missile equipment). Descriptive

analysis of the dataset reinforces some long-held assumption about how the illicit trade occurs (Bove & Böhmelt, 2021; Chyzh, 2016), but puts into question other beliefs relating to smuggling activities in general (Naím, 2006).

Given that illicit trade is less efficient than legal trade, it is assumed that illegal exports are most often destined for countries with direct trade barriers, such as licensing requirements, embargoes, or sanctions (Bove & Böhmelt, 2021; Chyzh, 2016). Although some observations detail exports to end destination countries with favorable licensing requires and fewer trade barriers (e.g., Canada or Japan), those cases are relatively rare compared to violations involving destinations like Iran, China, and Russia.

Figure 5 (below) displays the ten most common end destinations for all SEV observations. These ten states account for 806 of the total 1397 observations (57.70%). Over one third of all violations (504, or 36%) were destined for Iran, Mexico, or China. A vast majority of the violations to Mexico concerned firearms and ammunition which differs from the majority of the other top end destinations' violations concerning dual-use or commercial items.[11]

[11] 128 of Mexico's 169 observations concerned firearms, firearms accessories, or ammunition. For comparison, only 5 of China's 141 observations concerned firearms, related accessories, or ammunition. None of Iran's 194 observations included firearms, related accessories, or ammunition.

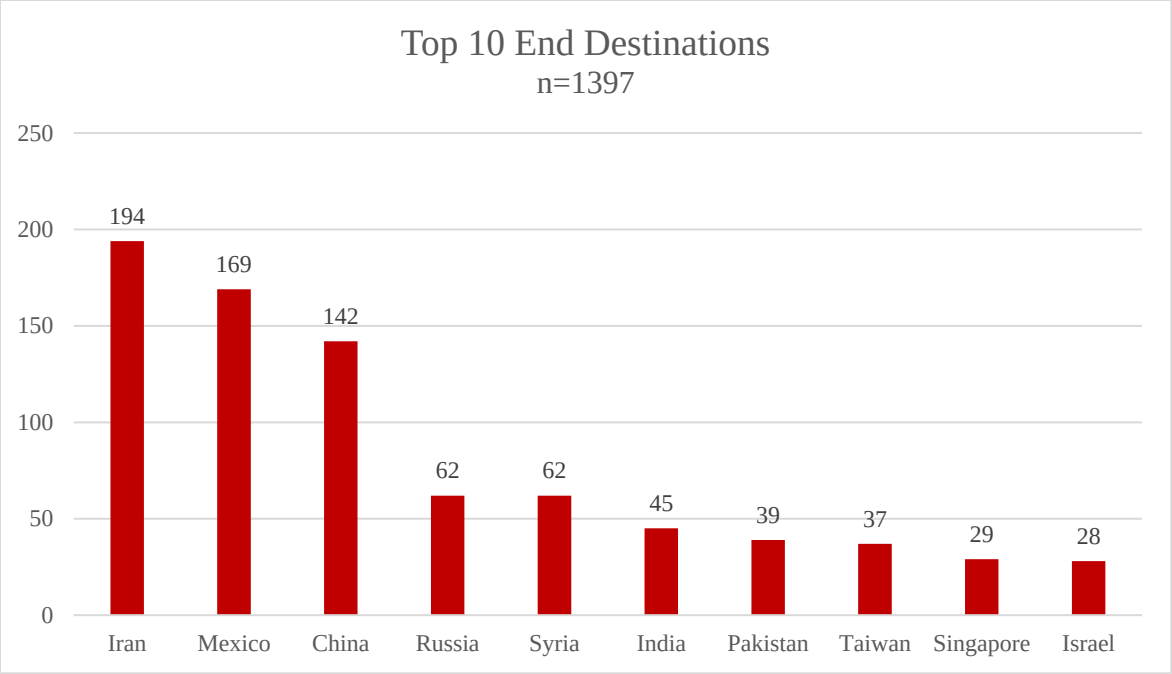

Figure 5: Ten most common end destinations.

Figure 6 (below) displays the ten most frequent conduits found in the SEV data. The United Arab Emirates (UAE) represent over a quarter of all instances of a conduit being used to the diversion of strategic goods within the SEV data. The remaining top conduit states vary with regard to geography and trade barriers with the USA.

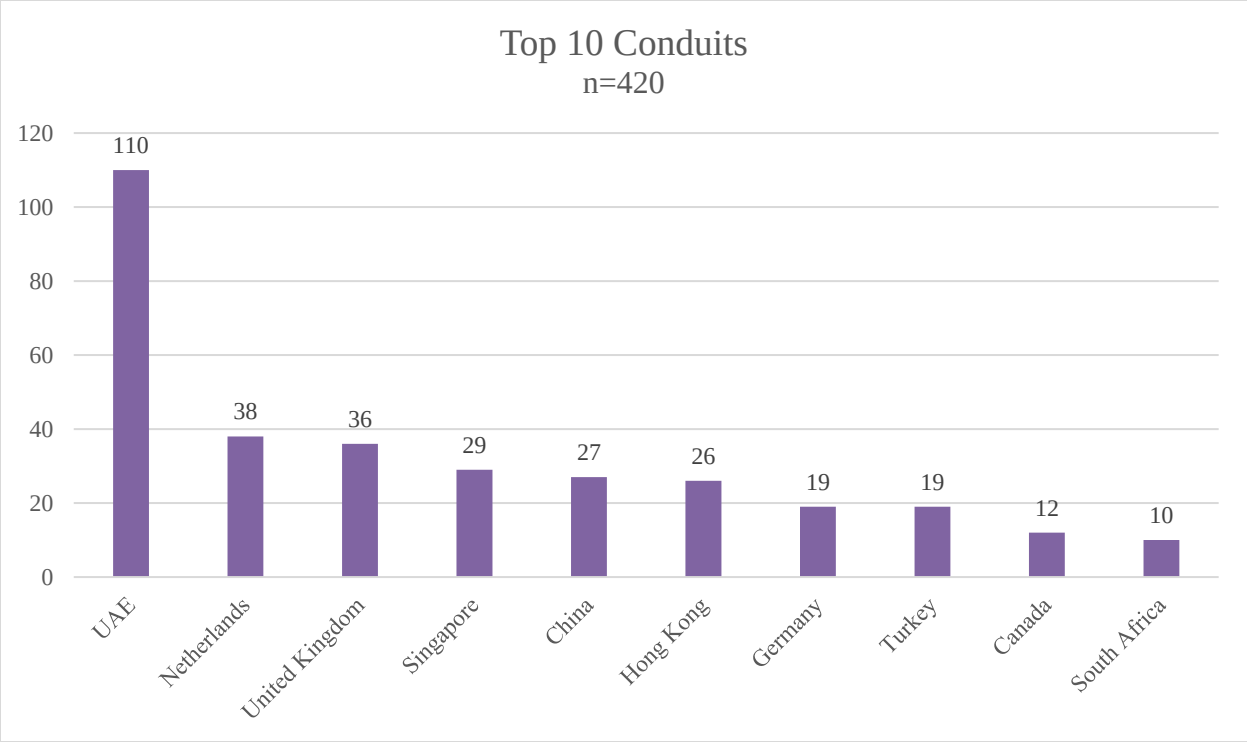

Figure 6: Ten most common conduits.

Figure 7 distinguishes between observations that relied on direct shipments to the end destination and indirect shipments that used one or two conduit states. Roughly 70% of SEV observations were exported directly from the USA to the end destination. The remainder of the observations rely on at least one conduit before diverting to the end destination. According to the SEV data, less than 3% of observed violations involved two conduits.[12]

[12] There were no observations that involved more than two conduits.

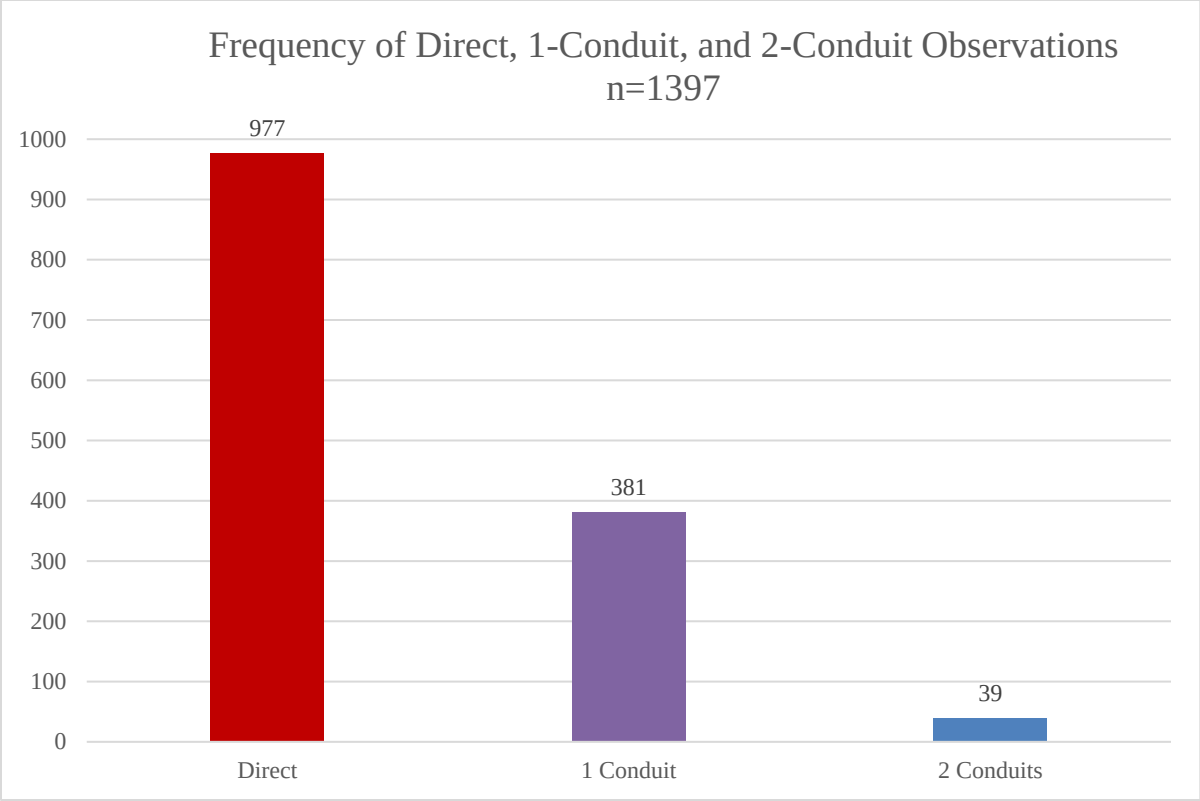

Figure 7: Frequency of cases involving direct exports, single conduits, and two conduits.

Figure 8's heatmap (below) shows that a majority of states have been the end destination for at least one observation, including states with few trade restrictions (e.g., Canada or the United Kingdom) appear to have been the end destination for some illicit transfers leaving the United States. Although many states have some activity as the end destination, there appears to be a high degree of concentration among a small subset of states.

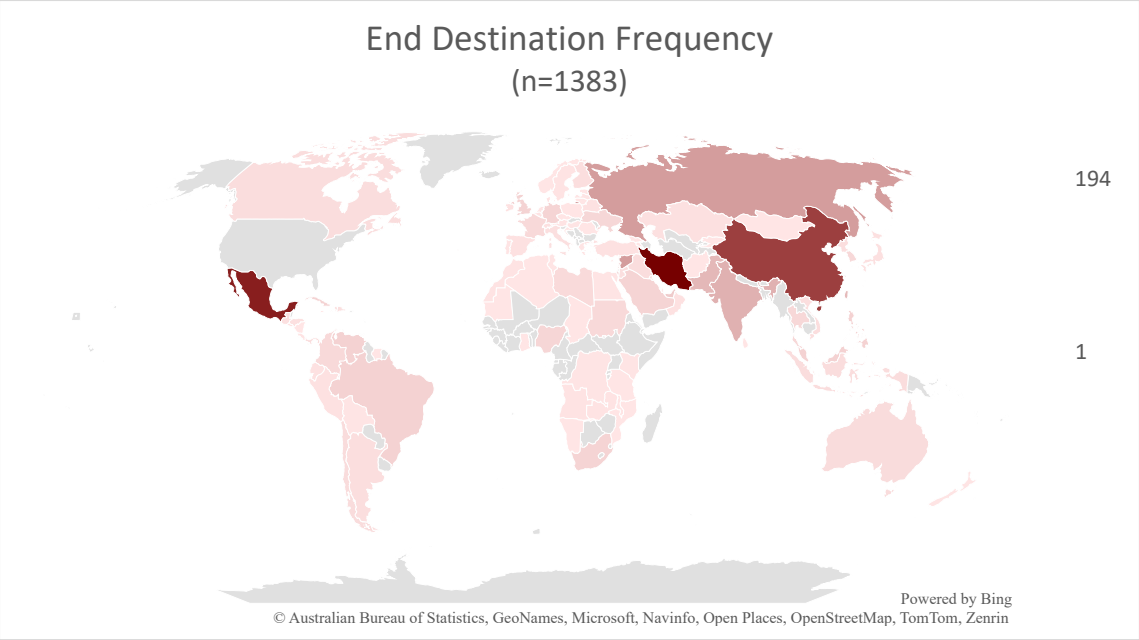

Figure 8: Heatmap of end destination frequency.

Figure 9's heatmap (below) depicts the frequency of states who appear as intermediate destinations within the SEV dataset. Like Figure 8's heatmap for end destinations, Figure 9 distribution appears to follow a similar, but more drastic, pattern with a small subset of states serving as major conduits while a handful of others have infrequently been observed as conduit.

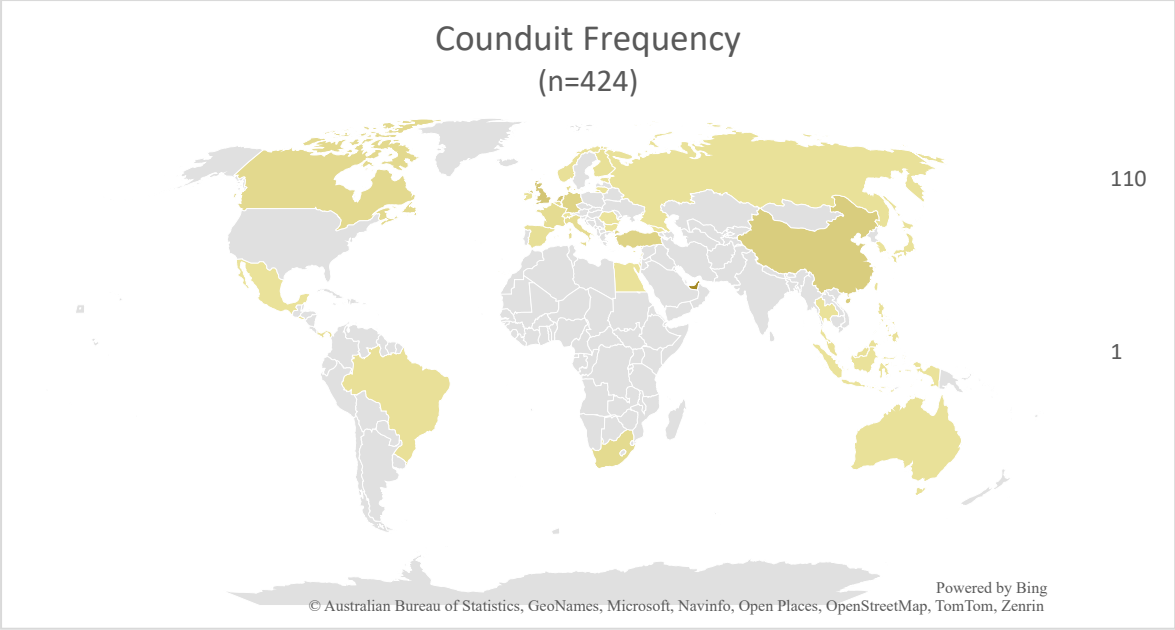

Figure 9: Heatmap of conduit frequency

Regarding the dataset's information on the illegally transferred goods themselves, promising patterns emerge for future study. The SEV data identify that certain military categories (Figure 10 below) and dual-use categories (Figure 11 below) are more often targeted than others. The prevalence of violations involving firearms and ammunition is intuitive to understand considering those items are likely easier to procure and logistically simpler to clandestinely transport than larger or more complicated military products.

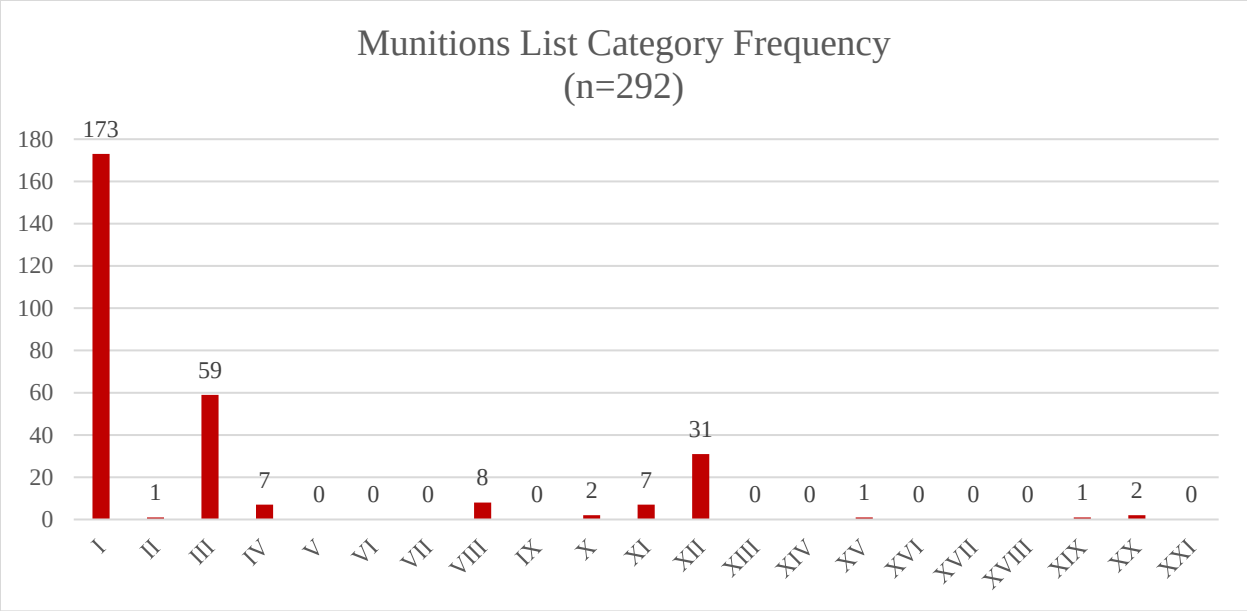

Figure 10: Count of munitions list equipment by category.

Concerning dual-use categories within the SEV data (Figure 11 below), a majority of cases involve nuclear-related items, materials, materials processing, or electronics. Some scholars have suggested that the dual-use items with wider commercial or research applications are more often sought after (e.g., corrosion-resistant valves, carbon fiber, and machine tools) because their ubiquitous use in multiple industries (Dunnicliff & Izewicz, 2015).

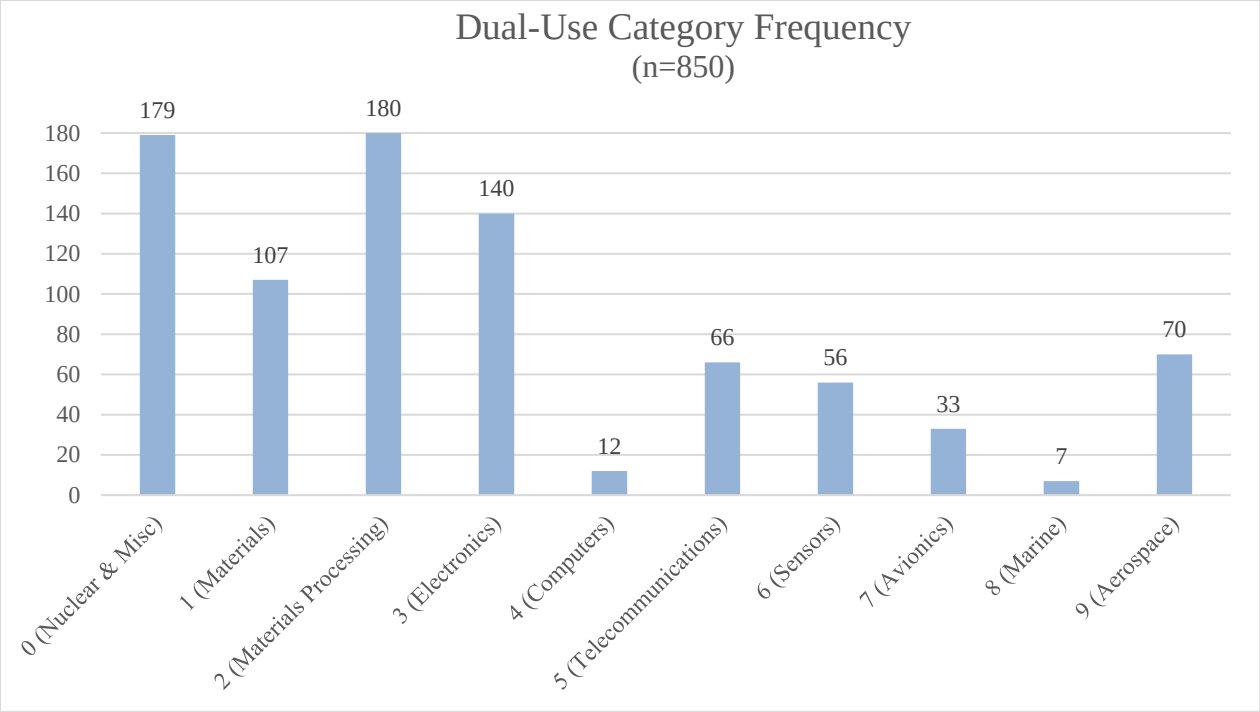

Figure 11: Bar plot of dual-use categories.

Within the dual-use product groups, over half of the observed cases included Product Group A which contains end-items, accessories, subcomponents, etc. Figure 12 (below) depicts the prevalence of hardware; test and production equipment; and materials within the SEV observations that account for over 90% of all observed dual-use violations.

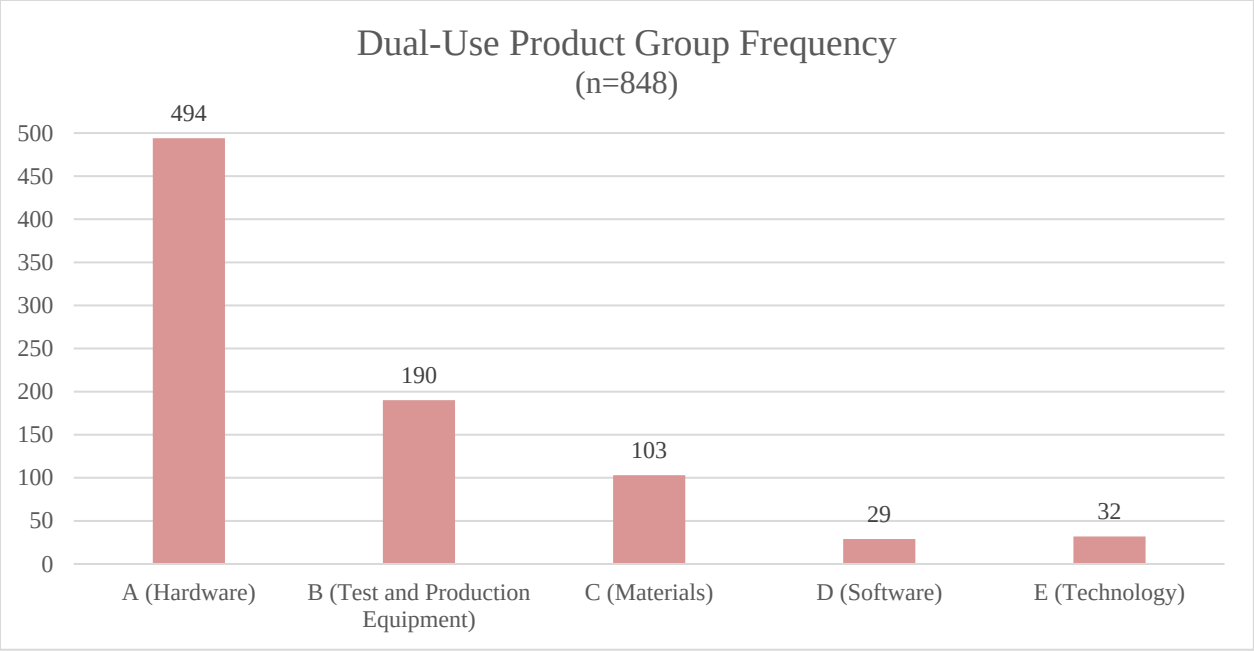

Figure 12: Bar plot of dual-use product groups.

Lastly, the SEV data show a large difference in the number of cases involving tangible and intangible exports. Intangible exports pose more challenges for regulators since information can be disseminated faster and with fewer opportunities to detect illicit activities. It's long been assumed that tangible transfers of strategic goods are easier to regulate, detect, and prevent compared to intangible exports like sharing electronic files through email or in-person technical assistance (Heau & Brockmann, 2024). There were 61 observations for dual-use software and technology and 11 observations for military technology, totaling 72 observations out of all of the SEV dataset's 1397 observations (see Figure 13 below).

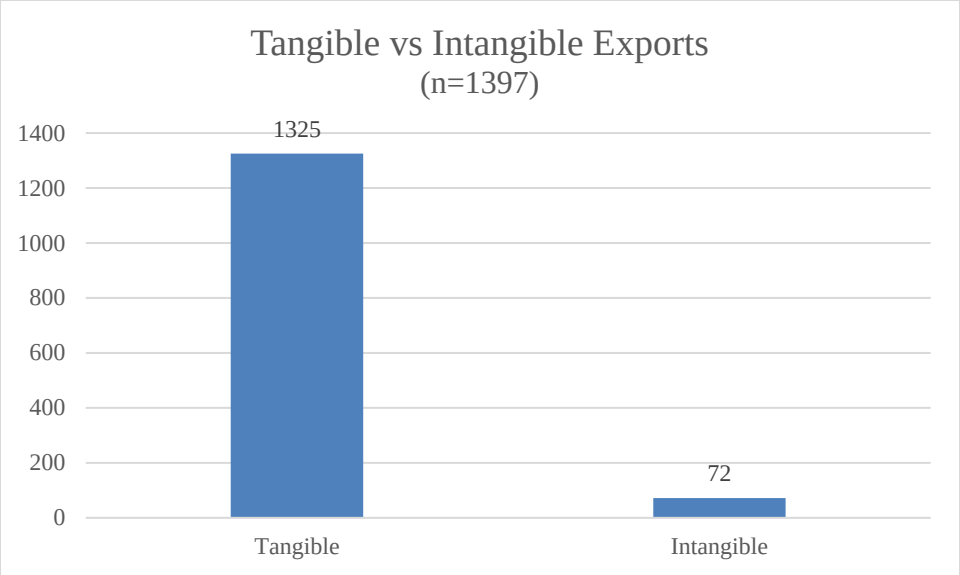

Figure 13: Bar plot of tangible and intangible illicit exports.

Although these initial results are simply descriptive, they offer the dataset a degree of surface legitimacy, meriting further investigation with inferential methods. The SEV dataset has the potential to become a valuable resource for large-*n* quantitative research designs in nonproliferation studies. The data can be used to validate existing nonproliferation theories and also support new research designs that have been stymied by a lack of sufficient data.

Data Limitations and Caveats:

Since the SEV data originate primarily from U.S. Department of Commerce eFOIA documents, they come with several caveats. The SEV data cannot be used to assess global trends or compare illicit trade out of the United States to any other country's illicit exports. Relatively few export violation cases are publicly available from other countries' export control regulators. Many of the non-U.S. cases contain fewer key details, severely limiting their utility within the SEV data. Limited published information provides specifics causing the lack of non-U.S. cases, with some notable exceptions that explore the challenges EU regulators face to successfully prosecute and

publicize export violation cases (Bauer & Bromley, 2019). For example, a European Commission report disclosed that EU members recorded 78 breaches of export control regulations, including seven criminal penalties (European Comission, 2022). Unfortunately, the report did not disclose additional details and those breaches were unable to be included in the SEV data.

The inherent "hidden population" nature of illicit trade creates a situation where the amount of missing data will forever remain unknown. Without knowing the true population of all illegal exports, researchers are unable to determine how many observations are missing from the sample or why those cases are missing (Scullion, 2015). The likely reasons behind missing information include: failure to detect the illegal activity, the details behind detected violations are not publicly released, or the prosecution of an alleged violation failed to result in a confirmed observation.

The SEV dataset does not contain any variable for actors' motivations. Few case documents ascribe motivations to the violating parties. Some are intentional proliferators, while others were ignorant of export control regulations and were oblivious to the illicit nature of their exports. In those cases of ignorance, sometimes the importing party was also ignorant of export control regulations. Other times, the importing party intentionally misled the supplier about the product's end destination or end use to avoid scrutiny by the exporting company and authorities. Uneven reporting undercounts military export violations, severely hampering the validity of any cross-comparisons between trafficking military technologies and trafficking dual-use technologies. Given the primary source is the Department of Commerce, 1027 of the 1397

observations (73.51%) refer to exports of commercial or dual-use items. The violations concerning military technology are included because the Department of Commerce debars entities (revokes their privilege to export) who violated the State Department export regulations.[13] The SEV data can be used to make comparison between different dual-use items or comparisons between different military items; but the SEV data should not be used to compare patterns between dual-use and military items.

Export violation-related documents often lack details on the end user, typically only specifying the final destination country. Unless the end user is placed on a restricted party list (e.g., subject to certain sanctions or embargoes), the source documents often omit the specific party who received the item(s). Therefore, the SEV dataset is unable to tie most violations to specific companies or government organizations. Although the SEV data do contain some specified end-users, the SEV data are structured to be used in country-level analyses.

Conclusion and Direction for Future Research

The SEV dataset creates a new unit of analysis using a common export classification that has so far, remained largely outside the scope of nonproliferation scholarship. By operationalizing the ECCN, the SEV lays a foundation to support large-*n* supply-side proliferation studies. The enhanced granularity of the SEV data will allow future research designs to discern between illicit transfers of nuclear-related and missile-related goods and identify which states are observed in proliferation networks (and what role those states serve. Scholars can take advantage of recent advancements in network analytical models to better explore the relationship between conduit

[13] The U.S. State Department also publishes export violation cases, albeit with significantly less frequency. For example, only 20 violations were published on the State Department website for the years spanning 2014-2023.

and end destination states, as well as which types of commodities are more likely to be illicitly exported along which routes.

As mentioned above, the ECCN shares its 5-character alphanumeric nomenclature with the European Union's export control system and many other non-EU states. The SEV dataset could be expanded to include illicit transfers originating from other states besides the United States, allowing for a better glimpse into the hidden population of global proliferation of strategic commodities. Since the SEV dataset relies on an export classification commonly used in industry and government environments, it should also enhance scholars' ability to share their findings with audiences outside of academia.

The SEV dataset can also contribute to the broader international political economy research on illicit activities. Shifting away focusing on proliferation scholarship, the data can be compared to other areas that face similar "hidden population" difficulties, such as the human trafficking or drug trafficking literatures.

CHAPTER 2: MAPPING ILLICIT STRATEGIC TRADE NETWORKS[14]

[14] Starks, B.M. To be submitted to a peer-reviewed journal

Abstract:

Strategic Export Violation (SEV) illicit trade data are well-suited for social network analysis. Converting the data into networks creates intuitive images that identify patterns of 21st century proliferation, such as frequent conduit and end destinations. Parsing the SEV's overall network into subnetworks of military, dual-use, and commercial observations reveals distinct patterns in how different categories of goods are illegally traded. Proliferators likely model their preferred routes based on transaction costs and risks of detection. Military goods are nearly always directly exported to the destination state, whereas dual-use and commercial goods more often rely on conduit states for illegal procurement. Only the dual-use network displays reciprocity between conduits, suggesting a more complicated pattern compared to illicit commercial trade networks. The increased complication likely adds costs to illicit procurement at the benefit of reducing risk of detection. Similarities between dual-use and commercial networks suggest possible underlying mechanisms, while the illicit military network's near complete lack of conduits suggest a substantially different set of drivers. Understanding the different network structures can help scholars better understand the underlying factors driving different patterns to emerge within various illicit networks.

Introduction

The Strategic Export Violation (SEV) dataset contains over one thousand observations detailing how strategic goods are illegally exported from the United States. The terms "strategic goods" or "strategic items" refer to technologies that are either inherently military in nature (e.g., cruise missiles) or dual-use, with both civilian as well as applications in weapons of mass destruction (WMD) programs. Some violations within the SEV data concern standard commercial items that

have been shipped to restricted destinations or entities, such as groups designated as terrorist organizations by the United States. The observed illicit trade patterns naturally create a network of states serving as sources, conduits, or end destinations. Social network analysis offers intuitive and powerful tools for describing recurring proliferation pathways in the 21st century. Parsing the SEV data into subsets allows for enhanced glimpses into differences between the proliferation of military equipment, dual-use goods, and commercial items.

Compared to dyadic approaches, network analysis offers tools better suited to visualizing the role conduit states play in the proliferation of strategic goods. Previous studies note that trade restrictions (e.g., sanctions or arms embargoes) incentivize target states to circumvent market barriers, often relying on intermediate states to procure restricted goods (Bove & Böhmelt, 2021; Chyzh, 2016). Since illicit trade may rely on third party states serving as intermediaries, research designs solely accounting for the source and destination lose crucial information about the role of conduits in proliferation networks.

A handful of previous studies have described the illicit arms trade in network terms, but those studies were limited in sample size and centered only on one continent (Kinsella, 2006). Others have theorized on how network structures may vary depending on the network's purpose, such as selling small arms on the black market or clandestinely developing weapons of mass destruction (Kinsella & Montgomery, 2017). Unfortunately, these networks remained theoretical due to a lack of data, in part because it's suspected that proliferators prefer security over efficiency. Others have focused on the role of third party states used as conduits, employing qualitative methods to assess a single state's role as a conduit in the infamous A.Q. Khan proliferation

network (Salisbury, 2019). Some of the most thorough, recent nonproliferation scholarship relies on qualitative methods to explore the factors influencing a state's decision to begin pursuit of weapons of mass destructions (Debs & Monteiro, 2017) or what development strategies are best suited given a particular state's political and security environments (Narang, 2022).

Thus far, no study has had sufficient quantitative data to build a comprehensive picture of the proliferation of strategic goods. The SEV data are able to construct the first descriptive view of illicit strategic trade at the transactional level, which could then support inferential models to evaluate long-held hypotheses regarding the proliferation of military and dual-use technologies. While there has been a lack of large-*n* studies on illicit strategic trade, much has been written about legitimate trade due to a variety of expansive and easily accessible datasets that record much of global trade. Since the early 2000s, more international institutions have released trade data that supports quantitative scholarship into legal commercial networks.[15] Some scholars have even gone so far as to describe various international organizations' trade databases as a "gold mine for empirical analysis" (De Benedictis et al., 2014, p. 288). The United Nations' Comtrade data is widely regarded as the best record of international trade flows, breaking down trade flows by state and harmonized system (HS) code. The data enable trade studies to narrow their scope based on country, years, and HS code. This vast and detailed dataset serves as the foundation for much of the international trade scholarship.

[15] For example, in 2003 the United Nations Department of Economic and Social Affairs began publicly releasing UN Comtrade data. The Comtrade data contain trade records dating back to 1962, recording the trade flows by country and harmonized system (HS) code.

Although the UN Comtrade data are extensive, they suffer from missing data when states do not report their trade flows. To mitigate some of the missing trade data, French researchers have published a modified version of the UN Comtrade data called the BACI (Base pour l'Analyse du Commerce International) dataset. The BACI dataset uses reported trade flows to impute unreported imports and exports, allowing for a more complete accounting of global trade flows (CEPII, n.d.).

Comparing Legitimate and Illicit Trade Networks

Unfortunately, there is no gold mine for illicit strategic trade data to compare with the UN Comtrade or BACI datasets. The lack of data complicates comparisons between legitimate trade illicit strategic trade. According to the U.S. International Trade Administration, roughly 95% of all U.S. exports do not require a license (International Trade Administration, n.d.). Export licenses are only required when a shipment's contents and destination meet specific criteria laid out in the various export control regulations, often based foreign policy considerations and influenced by multilateral export control regime guidelines. These regulatory requirements reflect established findings within the arms trade and dual-use trade literatures; trade in military equipment or dual-use equipment is often based more on political and security considerations rather than economic factors (Fuhrmann, 2008; Koch, 2019; Krause, 1992; Kroenig, 2009). Assuming that traditional trade flows are based primarily on economic interests, we should expect that the legitimate commercial trade will substantially differ from illicit trade patterns. The data on legal trade reveal a complex, global economy with trade flows between states creating a densely interconnected network. Reproduced in Figure 14 below, De Benedictis et al. (2014) created a World Trade Network (WTN) that displays directed ties to each state's two largest export partners based on 2007 BACI data. Their constructed WTN results in a

heterogeneous network, with 17 states accounting for a quarter of trade. In particular, the WNT prominently features major economies such as the USA, China, and Germany. The authors note that the Netherlands, Belgium, and Hong Kong appear high in the trade volumes due to the "Rotterdam Effect" of transshipment (De Benedictis et al., 2014). These states are major logistical hubs, often serving as transshipment or intermediate points for goods to be loaded onto another vessel or aircraft before being transported to their final destinations. Their prominence in global supply chain logistics causes a misleading representation within the WTN since not all goods destined to these states are intended for domestic use.

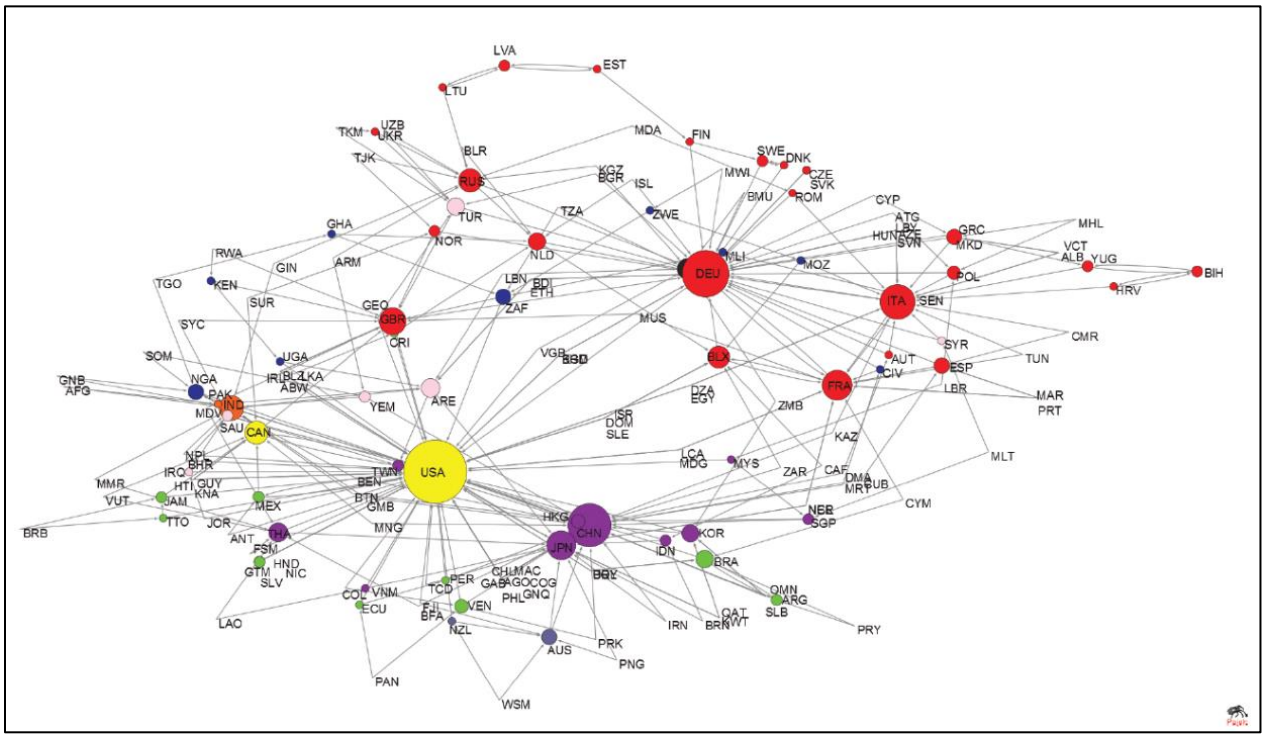

Figure 14: World Trade Network constructed using 2007 BACI data. The network is formed of edges between each state and its top two export partners (De Benedictis et al., 2014).

Jang and Yang (2022) offer another, more specific example of legitimate trade networks in their analysis of nuclear-related trade within the European Union. The resulting network, reproduced

below in Figure 15 below, uses 2019 UN Comtrade data to identify trade flows in items like nuclear reactors and fuel rods. Similar to the 2007 world trade network, the intra-EU nuclear trade is fairly heterogenous, with Sweden, Germany, and Spain appearing as the largest exporters of nuclear goods. The Netherlands occupies a highly interconnected, but small position within the network that suggests it has many small exports to multiple EU member states.

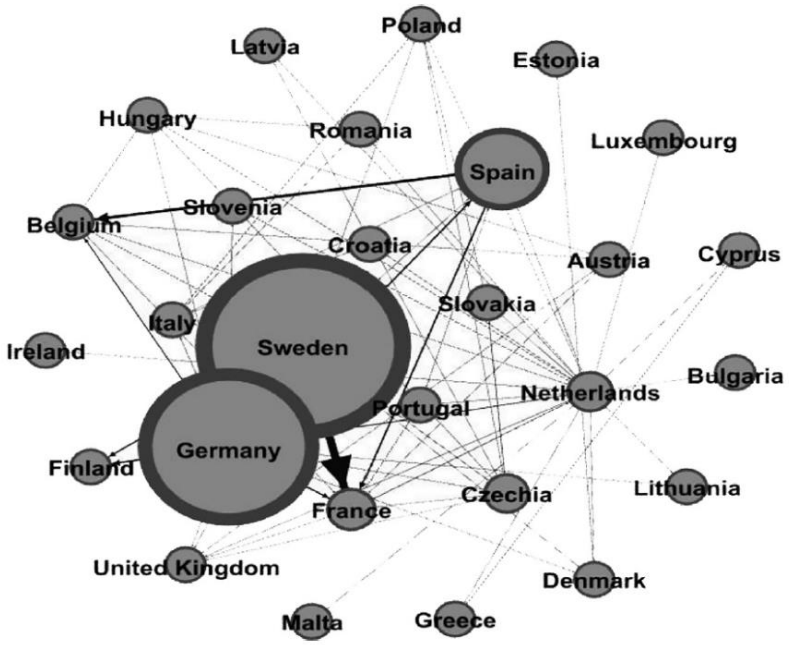

Figure 15: Intra-EU trade flows of nuclear-related goods using 2019 UN Comtrade data (Jang & Yang, 2022).

Caution should be taken when attempting to compare the observed illicit strategic trade network to networks of legitimate trade, since the SEV data reflect only a small amount of trade originating from the Untied States. The secret nature of illicit trade data also presents a "hidden population" problem (Scullion, 2015). Since the SEV data are based on published U.S. cases, it represents an unknown proportion of the true population of illicit strategic trade. Consider the SEV data and these resulting networks as glimpses into which countries are more often involved in US-origin, illicit strategic trade.

Defining and Measuring the SEV Network

Since the SEV dataset captures each state involved in an observation (source, conduits, and end destinations), the entire dataset can be converted into a network graph. Network graphs depict actors and their interactions using nodes and ties. Translating the SEV data into network terms, the states are represented as nodes and exports from one state to another will form an edge (also referred to as a tie). These nodes and edges can be numerically summarized using an edge list, which uses two columns to represent which nodes share an edge.[16] Networks that are both directed and valued rely on edge lists with an additional column to denote the weight (or observation count) between the two nodes. The first column contains the node that sends the signal, while the second column contains the node that receives the edge. The third column indicates how many times that particular node sends a signal, or forms an edge, with the same recipient node. An edge list can then be converted into a visual depiction, relying on arrows to denote the direction of an edge and varying thicknesses to indicate the edge count between two nodes.

Figure 16 (below) depicts a simple three-node network of trade between State A, State B, and State C. Like the SEV data, this network is both valued and directed. The edge list's first column represents the exporting state, while the second column represents the importing state. In network analysis terminology, the exporter is called the "sender" and the importer is referred to as the "receiver." The third column contains the edge's weight, or in this case how often the first state exported to the second state. Directed dyads without any shipments are omitted from the

[16] Networks can also be represented in adjacency matrices, which are matrices of a number of rows and columns equal to the number of nodes. Given the SEV network's size and sparsity (most cells within the matrix have a value of 0), an edge list is a more succinct representation.

edge list. The simplified network contains no edge from State C to State B, reflecting a lack of exports from State C to State B. In the simplified example in Figure 3, State C has no exports to State B so there is no row in the edge list with a directed dyad representing State C exports to State B. This sample edge list can be converted into a network image, using circles (nodes) to represent each state and arrows (edges or ties) of varying thicknesses to denote direction and frequency of trade.

Edge List		
Exporter	Importer	Weight
State A	State B	1
State A	State C	2
State B	State A	3
State B	State C	2
State C	State A	4

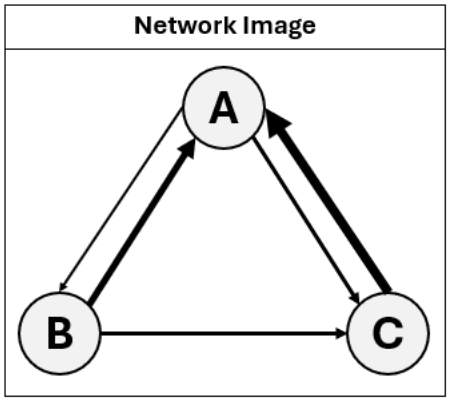

Figure 16: Example edge list and network graph. An edge list (left) contains a row for each pair of nodes as well as the weight (or count of edges) between the two nodes. A network image (right) is a visual representation of the same information contained within the edge list.

Because the SEV data record illicit shipments from an exporting state to an importing state, the resulting connection between the two states is considered "directional" (Scott, 2013). The dataset also records multiple observations between the same states, cumulating the number of illegal export events within a directed dyad. Unlike networks that measure binary activities, such as bilateral trade agreements, the SEV network has valued edges that record the count of repeated proliferation pathways flowing from the same exporting state to the same importing state. Unfortunately, networks that are both directed and valued are the most complex to measure (Scott, 2013). Undirected and/or binary networks have inherent bounds of activity. For example, a network depicting presence of bilateral trade agreements will only have edge values of 1

(representing a mutual, undirected agreement) or 0 (representing a lack of agreement). By comparison, the SEV network edges are directed and range from 0 to 169, depending on the frequency of observed illicit trade between two states.

Due to limits on non-US source documentation, the SEV data all have the USA as the source. Although the network is valued and directed, the complexity is somewhat mitigated by the data's egocentric nature. In traditional network analytical terms, egocentric networks are centered around one actor (the "ego") with a set of other nodes (called "alters") that have connections to the ego and other alters (Wasserman & Faust, 2016).

Plotting large networks with many nodes and edges in a graph presents obstacles on where to place them in a graph's space. Patty and Penn (2017, pg. 153) consider networks "messy" because "unlike real numbers, they do not have a natural ordering." Without a natural ordering, network-specific descriptive statistics summarize key traits. Depending on the research question, different descriptive measures are used to summarize aspects of a network. The SEV network is best defined with four network descriptives: density, reciprocity, transitivity, and centralization. Density is a measure of the general level of linkages among nodes within a network. The higher the density score, the more often multiple nodes are connected to other various nodes.

Calculating density is complicated for valued networks without a clear ceiling on the maximum value for an edge connecting two nodes (Scott, 2013). For example, there is no limit to the maximum number of proliferation pathway observations for illicit exports from the USA to any one state. Furthermore, caution should be taken when comparing different networks' densities if

there are significant differences in the number of actors or nodes within the networks (Scott, 2013).

Reciprocity measures the proportion of symmetrical edges in a directed network. Symmetry occurs when two nodes send a signal to each other. Reciprocity is typically used as a measure of interconnectedness within a directed network. In the SEV network, reciprocity signifies how often states who export to another particular state also receive imports from that same particular state.

Transitivity measures the number of triads within a network. The concept is often described as "a friend of a friend is a friend," meaning that if State A and State B share a tie and State B and State C share a tie, then it's likely that State A and State C also share a tie. These three connected nodes are referred to as a "triad." Networks with high transitivity contain many triads, often manifesting multiple clusters of interconnected nodes within the graph.

Centralization, sometimes referred to as "network centrality," measures how concentrated a network's edges are around a single node or group of nodes. Since the SEV data all have the same source state (USA), the resulting networks will likely have a "floor" or minimum centralization score to reflect the vast majority of nodes will have a tie to the USA.

Creating the SEV Network

The SEV dataset includes 122 states, which generates a fairly congested network image. Each of the 122 nodes have been color-coded based on their role as a source, conduit, or end destination.

Since the SEV data are derived from US Department of Commerce documents, the USA is the only source state and is coded green. States are considered conduits if they more often serve as intermediaries than final locations. Conversely, states are labelled end destinations if they are more often the final point in a proliferation pathway. If a state appears equally as often as a conduit or end destination, the state is considered an end destination. In the following network graphs, red circles represent end destinations while yellow circles represent conduits.
Since the SEV network is both valued and directed, its connections between nodes are represented with pointed arrows of varying thickness. The direction of the edge's arrow between two nodes indicates the direction of illicit trade. The edge's thickness indicates the value, or count, of observed trade between the two nodes. The thicker the edge, the more frequently illicit trade between those two nodes was observed.

Lastly, there are multiple types of methods for determining node placement within a network. The Fruchterman-Reingold layout method is best suited for the SEV data considering the size of the network, its egocentric nature, and frequent connections between the alters. This layout is ideally suited for large, messy networks because it treats nodes as metal rings and edges as springs, then tries to minimize the energy within the network's system (Fruchterman & Reingold, 1991). The minimization of network "energy" results in a fairly well laid out distribution of key nodes based on edge weight, or how often a particular export route appears in the SEV data.[17]

[17] Using the Fruchterman-Reingold layout method generates an improved but still fairly messy network image. To improve the cleanliness of the network graph, the "tkplot" command from the "igraph" R package was used to customize node placement.

The network image depicted in Figure 17 below results from combining color-coding based on nodes' roles, adjusting edge arrow's thickness based on frequency, and the Fruchterman-Reingold layout. This network is the visualization of over 1,300 export violation cases from the SEV data.[18]

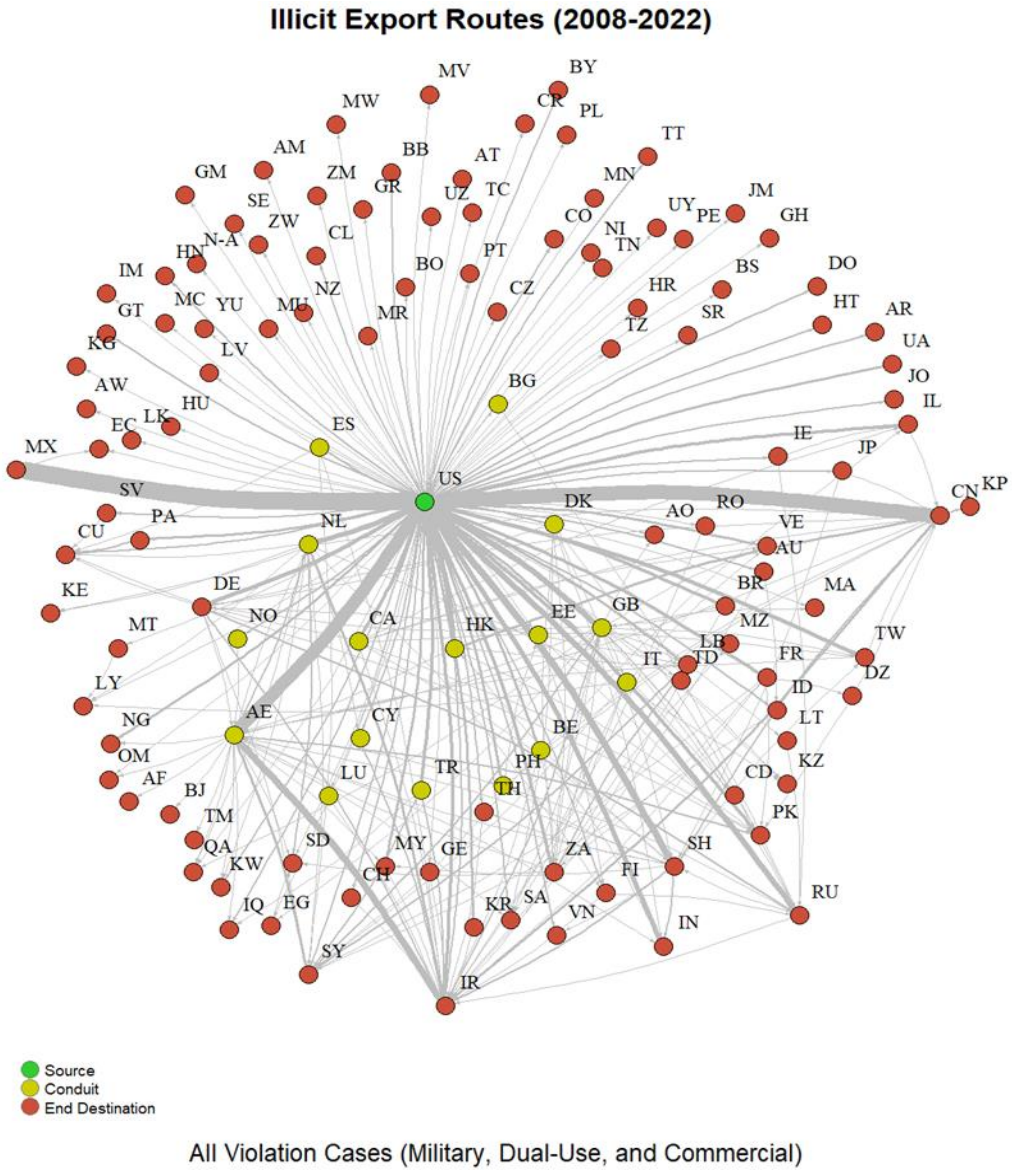

Figure 17: The Strategic Export Violation Network.

[18] A total of 34 observations from the SEV dataset are not included in the SEV network graph due to multiple cases that lacked sufficient details to specify the conduits or end destinations involved.

The overall SEV network contains 122 nodes representing the number of different states in the dataset. Between the nodes, 1,784 different exports are represented along the edges connecting each node. The number of edges (1,784) is higher than the number of export violations (1,364) because some violations involved multiple exports from conduits in addition to the original export from the USA.

The SEV network descriptive statistics (Table 1 below) reflect the graph image with a low density, reciprocity, and transitivity scores. The low density score reflects the rare instance that conduits and end destinations form edges to other nodes besides the USA. Even the most active conduits and end destinations only form a handful of ties, which is partially a result of the data limitations.[19] While there is some reciprocity within the network, it's rare to see states exporting to each other to form symmetrical edges. The low transitivity scope indicates that the SEV network does not contain many triads, or clusters. This is represented by the high numbers of end destinations that do not have any exports. Transitivity can only occur when three interconnected states all export to at least one other state in the would-be triad. The SEV network's egocentric nature accounts for the centralization score, with all nodes either directly to the USA or at most separated by two conduits.

[19] Since the SEV source documentation only reflects cases of goods originally exported from the USA, every observation will include the USA as the source. Put another way, any illicit trade between countries that does not involve US-origin goods will not appear within the SEV network.

	Overall SEV Network Descriptives
Node Count (Number of States)	122
Edge Count (Observations)	1,784
Density	0.01842569
Reciprocity	0.02941176
Transitivity	0.0856206
Centralization	0.4563896

Table 1: Overall SEV network statistics.

Despite the visual clutter of 122 separate nodes, a small number of thick edges are easily observed (USA-Mexico, USA-China, UAE-Iran, etc.). Remembering that the USA is the only source country, 86% of nodes qualify as end destinations (105 out of 122) and 13% of the nodes qualify as conduits (16 out of 122). Based on the majority of edges appearing relatively thin, it seems most end destinations appear infrequently among the 1364 observations.

Figure 18 shows a histogram of edge weights for the SEV network, indicating that a majority of edge weights have low values. The average edge weight in the SEV network is 6.57 observations. The histogram reflects that low average, with few edges appearing past the first column.

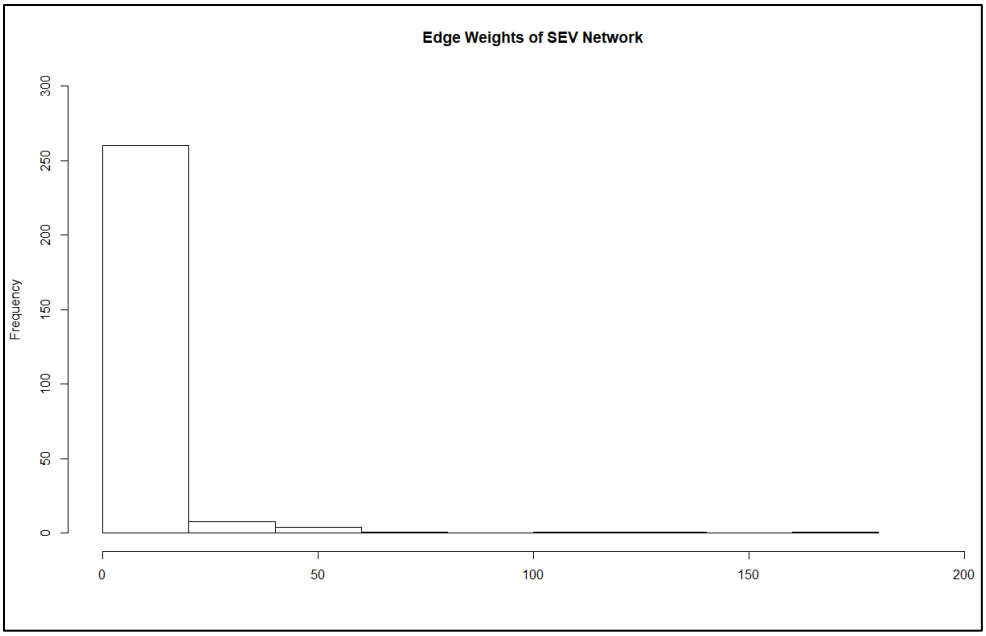

Figure 18: Histogram of SEV Network edge weights.

Large, messy networks can be filtered to reduce visual noise and enhance the prominence of the more frequent patterns. Pfeffer (2017) recommends reducing visual noise by removing edge weights under a particular network's mean edge weight.

For the network depicted in Figure 19 below, the SEV network's average edge value of 6.57 is rounded up to 7 and all edges with less than 7 observations have been removed. The new network contains 11 conduits and 32 end destinations. The number of conduits fell by 31% (16 to 11) and the number of end destinations fell by nearly 70% (105 to 32). This indicates that while the number of conduits is smaller than the number of end destinations, these intermediate states tend to be more active within the SEV network than most of the observed end destinations. The highest valued edges are now easier to track with the reduced number of nodes mapped in the network graph. Mexico, China, the UAE, and Iran all retain prominence, although some of

the most frequent end destinations have lost ties to conduits that fell below the average edge weight (e.g., Hong Kong's connection to Iran).

Conversely, some conduits remain but have lost all their ties to end destinations. Belgium, Canada, Denmark, Italy, Spain, and the Philippines all remain due to their edge values connecting them to the USA. However, none of these six conduits retain their edges with end destinations. This suggests that while these conduits are often used as intermediate shipment points, there are no heavily recurring patterns from any of these conduits to a particular end destination.

Excluding Hong Kong, the conduits with remaining edges to end destinations all maintain an edge connecting to Iran.[20] The Netherlands' tie connecting to the UAE is unique in this filtered network. The original SEV network had a series of edges connecting conduits to other conduits, but only the Netherlands-UAE directed tie remains among conduit nodes once all the lower valued edges have been removed. This suggests that the Netherlands often acts an initial conduit for US-origin goods before they are reexported to the UAE as a second conduit along a proliferation pathway.

Excluding North Korea, every remaining end destination maintains a direct edge with the USA. The network's prevalence of direct illicit trade from the USA to end destinations reflects the high, overall percentage of SEV observations that did not include any conduits (70%). The top 10 most frequent end destinations relied primarily on direct exports from the United States, with

[20] These conduits are Hong Kong, the Netherlands, Turkey, the United Kingdom, and the United Arab Emirates.

the exceptions of Iran and Syria.[21] These two end destinations also relied heavily upon conduits such as the UAE, Hong Kong, the Netherlands, the United Kingdom, and Turkey.

As discussed earlier, previous scholarship into legitimate trade reveals both global, general and regional, specialized trade networks reflect highly interconnected economies (De Benedictis et al., 2014; Jang & Yang, 2022). Both types of networks are heterogenous, with a handful of states representing a disproportionately high amount of trade. Despite the skewed distribution of trade, the networks are fairly defense and display signs of reciprocal trade among states. Highly reciprocal trade networks aligns with expectations around comparative trade within a globalized world. States may develop comparative advantages within certain industries, while suffer comparative disadvantages in other industries. The network of global trade allows states to export goods to the same states that they rely on to import other types of goods.

We should expect illicit trade networks to function quite differently from legitimate trade networks. It's understood that barriers to trade create incentives for black markets, and efforts to circumvent restrictions increases transaction costs (Blanton et al., 2018; Chyzh, 2016). Given these higher transaction costs, illicit networks should only be used when legitimate trade networks are unable to achieve the same result. Additionally, given the risk of detection and punishment, actors are likely to hide their illicit trade as best they can to avoid penalties (Bauer & Bromley, 2019). We should expect illicit networks reflect actors' efforts to balance high transaction costs for complicated, indirect trade with the risk of detection by government authorities. Given the desire for efficiency, illicit networks are unlikely to share legitimate trade

[21] The top ten end destinations in the SEV network are: Iran (194), Mexico (169), China (142), Russia (62), Syria (62), India (45), Pakistan (39), Taiwan (37), Singapore (29) and Israel (28).

network's tendency for densely connected networks with at least moderate amounts of reciprocity. Since each illegal export incurs additional transactional costs and a higher risk of detection, actors are likely to minimize the number of states involved in any given transaction. It's also likely that only a handful of states meet proliferator's preferences for efficiency and security, leading to those states appearing disproportionately often within the observed network. Therefore, illicit networks are more likely to be even more heterogenous than commercial networks, with heavily skewed distributions showing many states with little activity within illicit trade networks.

The exact number of involved states within illicit networks may vary depending on the item being exported and if exports from the source country are easier if the initial destination is to state that will incur less scrutiny from government regulators. Illicit exports with high scrutiny regardless of destination (e.g., military equipment) may be more prone to direct shipments, whereas exports subject to reduced scrutiny (e.g., dual-use or commercial goods) may rely more on conduits to obfuscate the true end user.

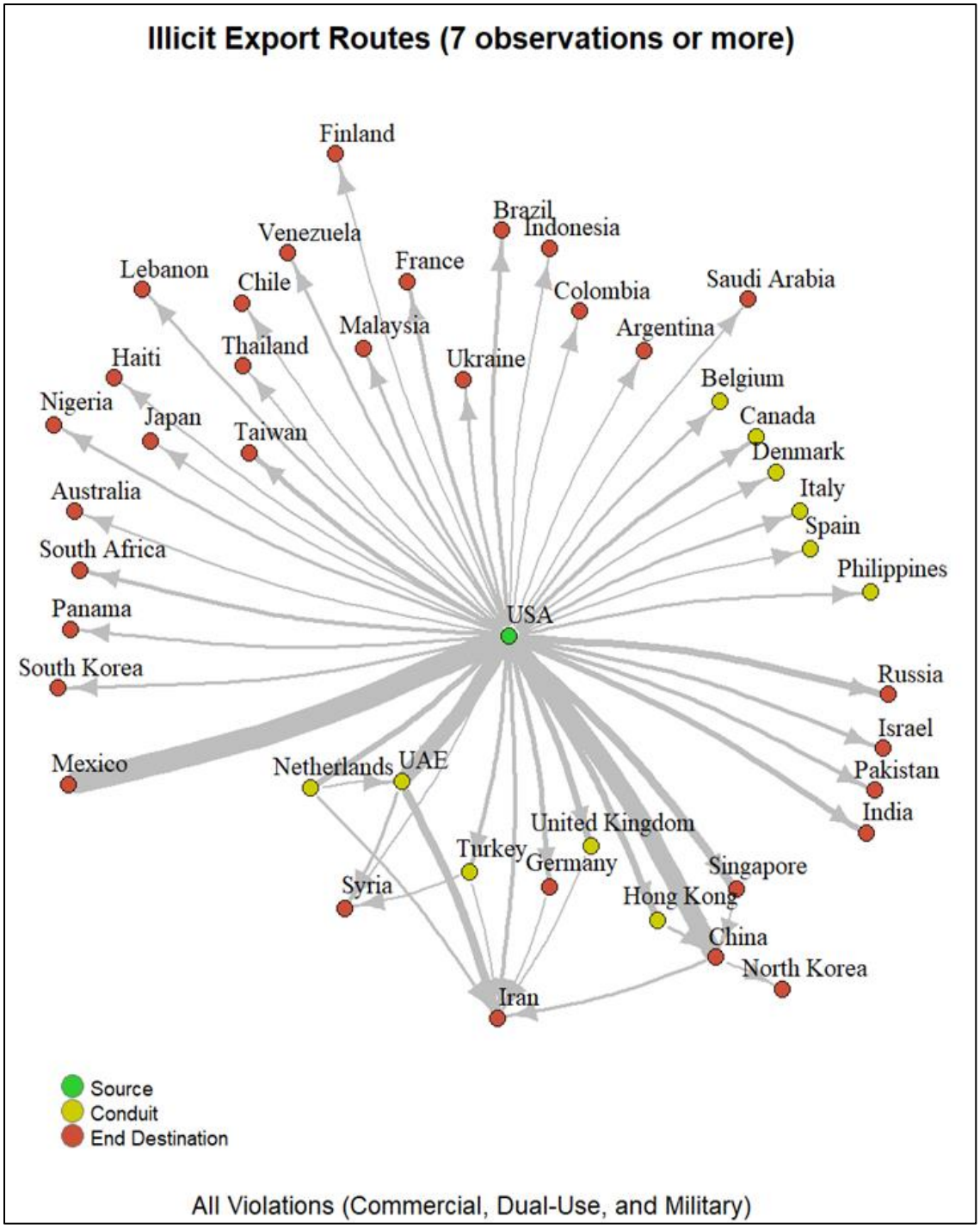

Figure 19: The SEV network with all edges less than 7 removed.

Subsetting the SEV Data

The SEV's holistic approach to illicit exports provides the widest lens to view the available observations. This broad perspective has its strengths, but also weaknesses. There may be significant differences lost when aggregating how different goods proliferate.

Each observation in the SEV data distinguishes between three distinct types of goods: military, dual-use, and commercial.[22] Military goods are designed to perform an inherently offensive or defensive function, such as large caliber firearms or avionics equipment for fighter aircraft. Dual-use goods are capable of peaceful uses (e.g., research or industrial applications) as well as applications in weapons of mass destruction (e.g., chemical weapons production). Finally, commercial goods are any items that do not meet the control specifications for either the military or dual-use export control lists. Commercial items appear within the SEV data in the event that the shipment was destined to restricted individuals or organizations (e.g., entity-based sanctions). While the entire SEV network provides a broad account of illicit exports, subsetting the data enhances visibility into differences between illicit military, dual-use, and commercial trade. Parsing the SEV data between these three categories (military, dual-use, and commercial) improves visibility into each subnetwork, allowing for more informed research designs and enhanced hypotheses testing. For example, some have suggested that all illicit networks operate similarly regardless of the specific activity (e.g., nuclear technology smuggling, arms trafficking,

[22] Within the SEV data, each observation receives a "List Code" determination to distinguish between military, dual-use, and commercial goods. The SEV data considers an item "military" if it falls under the jurisdiction of the United States' United States Munitions List (USML). Items considered "dual-use" are listed on the United States's Department of Commerce's Commerce Control List (CCL). Lastly, commercial items are goods that are not enumerated on any U.S. export control lists.

etc.) (Naím, 2006) while others have theorized nuclear technology proliferates differently than conventional weapons (Bunn & Potter, 2018).

Arms scholarship often highlights the important relationship between supplier states and purchaser states. The long service life of conventional weapon platforms like aircraft or armored vehicles often means replacement parts and maintenance are required decades after the initial transaction. Additionally, states often face challenges suddenly shifting weapon platforms or support systems due to interoperability issues. Modern weapon platforms and related support systems (e.g., aircraft and ground-based radar) may not be interchangeable, so an abrupt change in a key supplier may have larger impacts across a state's military efficacy (Kinsella, 1998; Krause, 1992). This creates opportunities for the arms exporter to exert influence on their customers, who must maintain good relations with the exporting state or risk endangering their military equipment's supply chain (Kinsella, 1998; Krause, 1992). Given these high costs of switching military equipment suppliers, states may seek to illicitly procure equipment from the original supplier state instead of opting to purchase substitute systems from alternative arms producers.

Nuclear goods and other dual-use equipment are likely targeted differently due to their wider applicability in research or industrial applications. Unlike the limited number of viable suppliers in the event of disrupted trade in conventional weapons, actors may have more potential substitutes for some of the sought-after goods. Given the difficult task of differentiating dual-use from commercial goods, it's likely that proliferators disguise illicit dual-use shipments by misrepresenting shipment details to government authorities such as the relevant export licensing

body or customs authority (Bauer & Bromley, 2019). Conversely, it's likely more difficult to misrepresent military equipment during the shipment process as some have learned from attempting to illegally export firearms hidden in washing machines (Department of Justice, 2016). Given the higher risk of detection each time a hidden arms shipment passes through a customs authority, it's likely that illicit military trade is more often direct to minimize government scruntiny.

Splitting the SEV data into three subsets inevitably leads to smaller sample sizes and smaller networks. See Table 2 below for a comparison of the networks' number of states and observations, represented by nodes and edges, respectively. Some observations in the SEV data did not contain sufficient information to determine the item's export classification. Those observations were used in the overall SEV network but were unable to be used in any of the subset networks.

	Overall SEV	Military	Dual-Use	Commercial
Node Count (Number of States)	122	49	110	32
Edge Count (Observations)	1,784	274	1,107	291

Table 2: Comparison of the SEV and three subset networks' node and edge counts. The total counts of the military, dual-use, and commercial networks is less than the SEV network due to some observations in the overall SEV data missing sufficient details to identify if the violation involved military, dual-use, or commercial goods.

Military Network

Narrowing the focus to observations of illicit transfers of military goods results in a drastically different network graph, as depicted in Figure 20 below. The military network is noticeably smaller than the SEV network, with 49 different nodes and 269 observations. Mexico receives the most illicit arms transfers, represented by the thickness of the edge connecting the USA to Mexico on the side of the network graph. Other noticeably thicker lines directly connect the USA

to states like Russia and China. Compared to the overall SEV network's 16 conduits, the military network only has one conduit- Hong Kong. This indicates that illicit military transfers are often directly exported to the end destination without the use of conduits to obfuscate the transaction. Hong Kong, the military subset's sole conduit states, exports to end destinations China and Iran. This suggests that sometimes there are some factors that cause proliferators to see shipments through Hong Kong as better than direct exports to China and Iran. It's likely that exporting military equipment to those two countries poses particular, unique challenges that are not present when exporting to other end destinations.

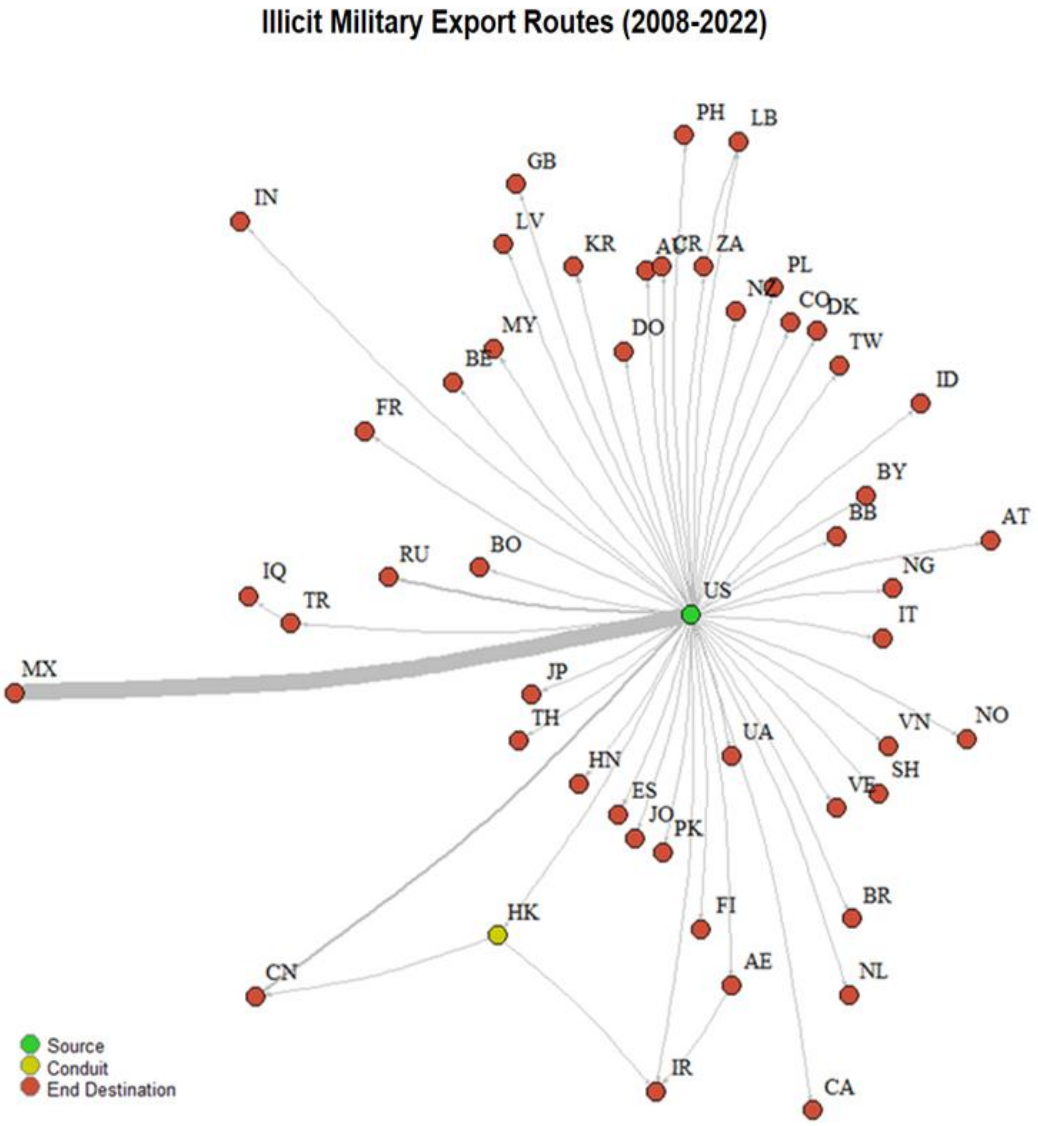

Figure 20: Military subset network graph. Mexico is by far the most common destination for illicit military goods leaving the USA. The military network is less interconnected than the SEV network. There are fewer conduits and fewer connections between non-USA nodes.

The military network descriptive statistics (Table 3 below) illustrate a structurally distinct network from its counterpart depicting all SEV observations. While the two network graphs are visually different, descriptives help clarify the severity of discrepancies between networks. The military network's reciprocity and transitivity are lower than the SEV network. The military network contains no reciprocity, indicating that there are no instances where multiple observations have two states illegally exporting military equipment to the other. The low

transitivity suggests minimal clustering, which reflects the military network graph's preponderance of end destinations with only one single tie to the USA and no other ties to conduits or additional end destinations. The military network's density and centralization were slightly higher than the overall SEV network, suggesting a higher proportion of possible connections among the military nodes and fewer ties between conduits and/or nodes. The higher density and centralization scores are likely driven by the fewer nodes within the military network (49) compared to the SEV network (122 nodes).

	Military Network Statistics
Node Count (Number of States)	49
Edge Count (Observations)	274
Density	0.02210884
Reciprocity	0
Transitivity	0.01098901
Centralization	0.4772135

Table 3: Military network descriptive statistics.

Similar to the SEV's skewed distribution of edge weights, the military subset's edge weights tend to cluster at the low end of the histogram depicted in Figure 8 below. The mean edge weight for the military network is 5.27, lower than the SEV overall network's mean edge weight of 6.47 observations per pair directed dyad.

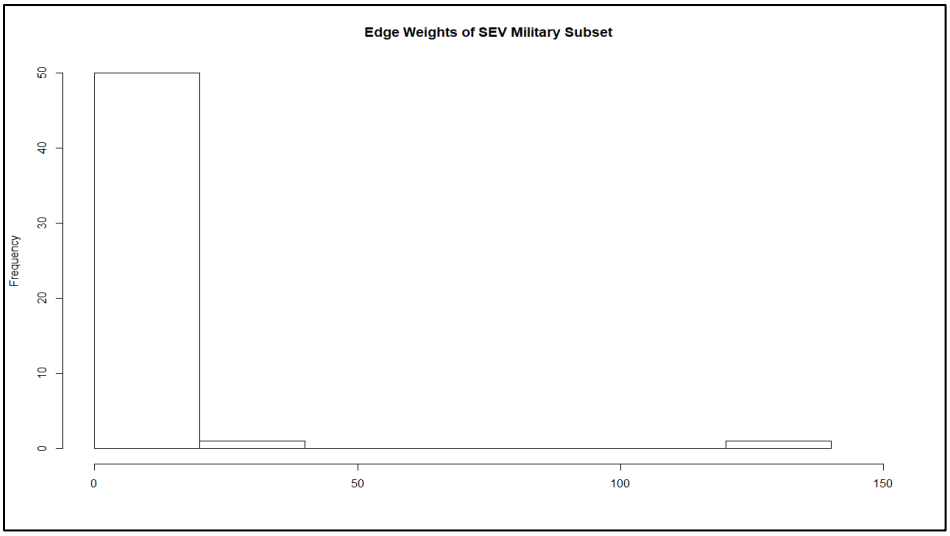

Figure 21: Histogram of military subset network's edge weights.

Removing all military network edges less than 5 provides a simpler network, depicted below in Figure 22. Only seven end destinations remain out of the 47 end destinations in the original military network. Mexico remains by far the largest destination for military equipment, with China and Russia appearing as distant second and third most common end destinations. The sole conduit (Hong Kong) has been removed with the filtered military network, indicating that Hong Kong was used as a conduit for military equipment less than 5 times in the observed network.

The data suggest illicit military exports are more often direct transfers from the USA to the end destination, with rare exceptions for transfers using a conduit. Considering the histogram and filtered network graph, a few end destinations account for an overwhelming majority of all observed illicit military exports.

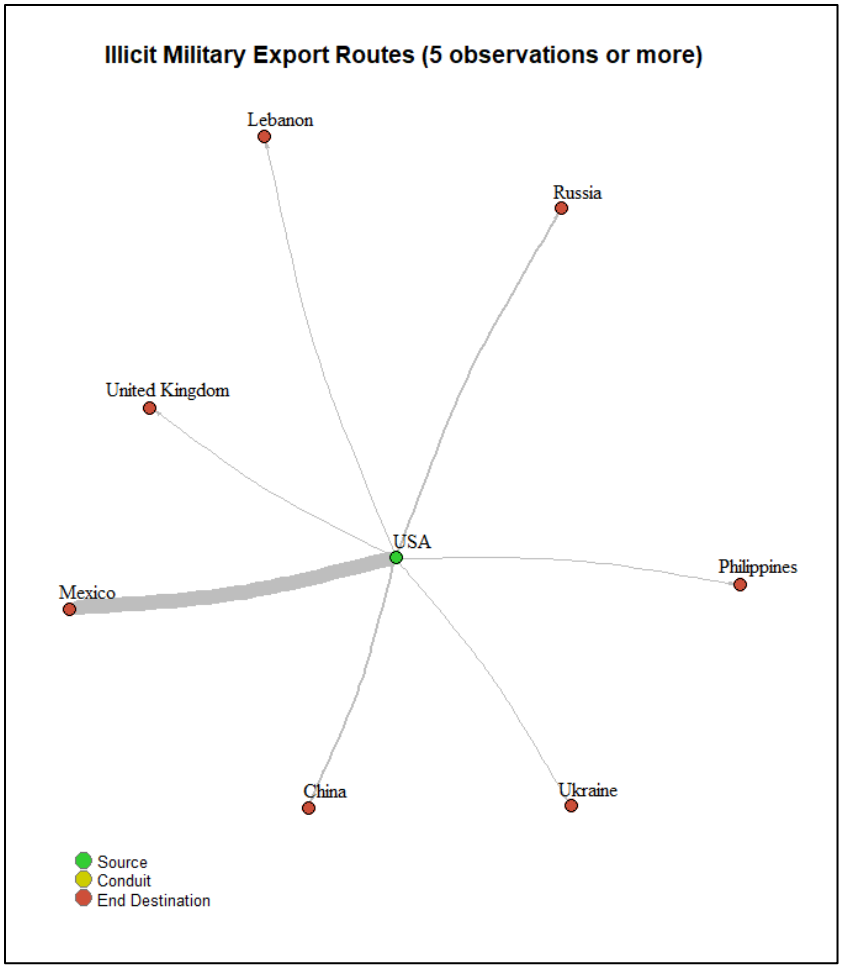

Figure 22: Military subset network with all edges less than 5 removed.

Dual-Use Network

The majority of the SEV observations capture illicit exports of dual-use goods, but those proliferation pathways are somewhat obscured by the inclusion of military and commercial observations. Out of all three subset network graphs, the dual-use subset network depicted in Figure 23 (below) most closely resembles the overall SEV network. This subsetted network represents 826 observed dual-use smuggling cases involving a total of 110 different nodes. Unlike the military subset, the dual-use subset contains multiple conduits. Most of the 16 conduits appear to have ties to multiple end destinations, creating a fairly interconnected graph. The majority of the 93 end destination nodes have direct ties to the USA, although there are some ties between various end destinations.

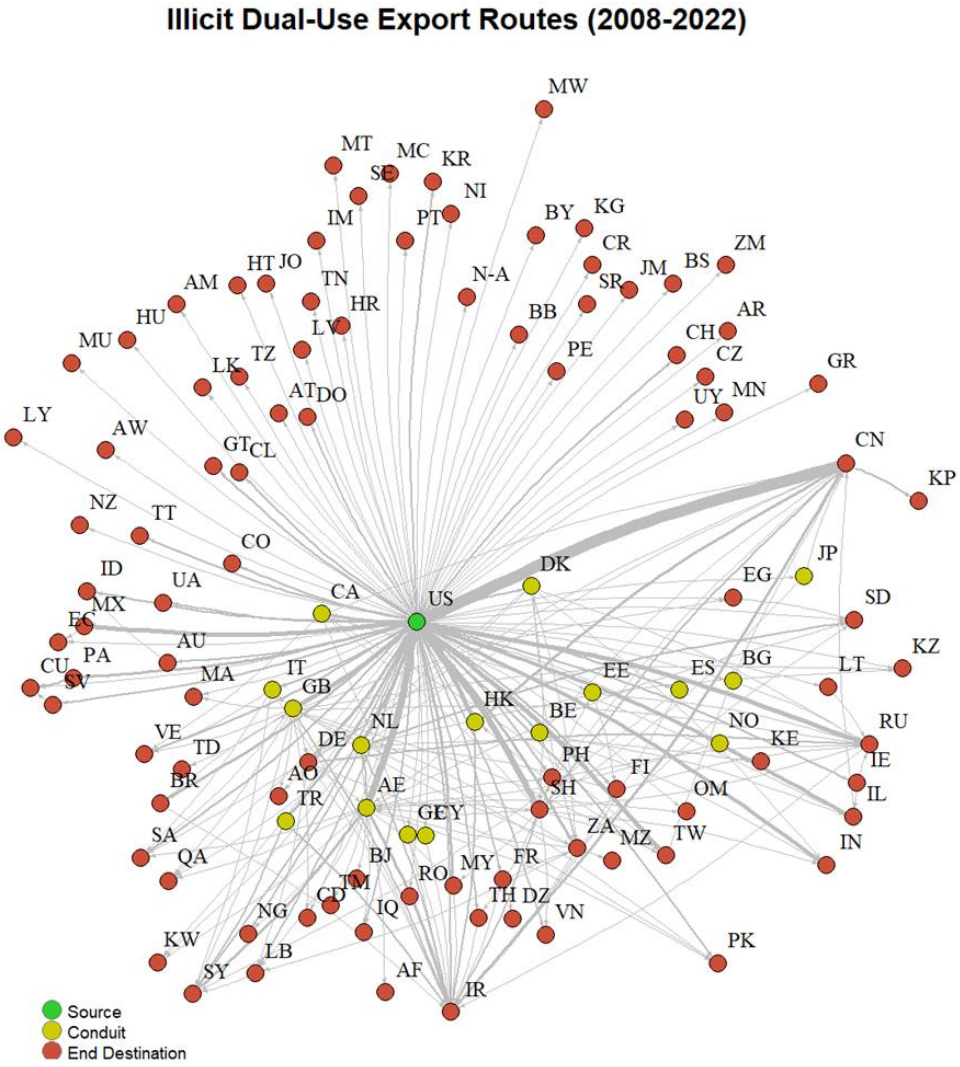

Figure 23: Dual-use subset network graph. This subset network closely resembles the overall SEV network due to its number of nodes, high sample size, and increased network complexity. While many end destinations have direct ties to the USA, there are a number of highly active conduits within the dual-use subset network.

Out of the three subset networks, the dual-use network is the closest to the overall SEV network in terms of node count and edge count. The similarity is likely driving the nearly identical density and centralization scores between the dual-use and SEV networks. The dual-use network scores slightly lower in transitivity, suggesting there are less clusters or triads of interconnected nodes. The dual-use network's higher reciprocity score is noteworthy, suggesting that the dual-

use exports are more likely to flow both ways between two states when compared to the SEV network.

	Dual-Use Network Statistics
Node Count (Number of States)	110
Edge Count (Observations)	1,107
Density	0.01926606
Reciprocity	0.03463203
Transitivity	0.08145225
Centralization	0.4481104

Table 4: Dual-Use network descriptive statistics.

A histogram of the dual-use subset's edge weights (Figure 24 below) reveals a more evenly spread distribution of ties compared to the heavily skewed military network. While there are still a small number of ties with close to 100 observations, there are more ties spread across the 0-60 range than the military subset.

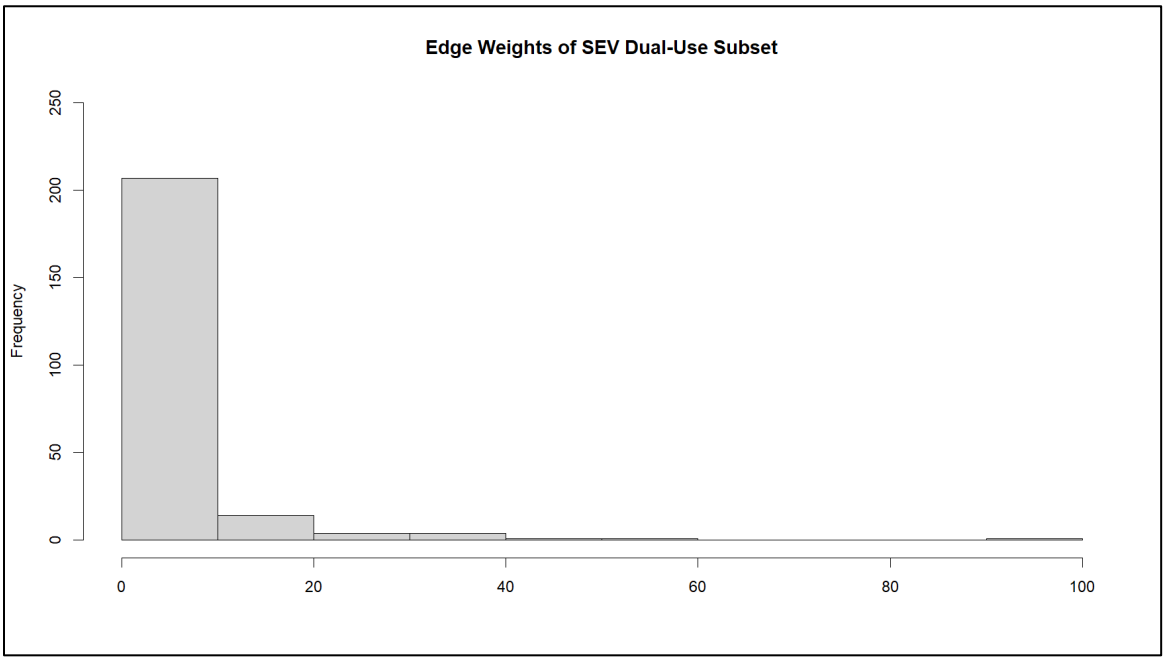

Figure 24: Histogram of dual-use subset network's edge weights.

As before, a filtered network helps reduce the dual-use subset's messiness. Since the dual-use subset's average edge weight for the dual-use network is 4.79, Figure 25 (below) depicts only edges with a value of 5 or higher. The resulting network consists of 10 conduits and 34 end destinations.

A majority of the 34 end destinations had a single tie directly from the USA. Despite the initial dual-use subset network's interconnectedness, the filtered network reveals that 22 of the 34 most common end destinations rarely rely on conduits to receive illicit dual-use goods.
Unlike the military subset's filtered network, conduits remain in prominent locations across the filtered dual-use subset. Half of the remaining conduits lack any ties to end destinations, signifying frequent use as a conduit from the USA but without a recurring history of repeated exports to particular end destinations. Four of the conduits have ties to Iran, suggesting a varied proliferation network stretching across Europe and the Middle East. Only one conduit, Hong Kong, retains its tie to China.[23]

[23] Although there were a number of transfers from Singapore to China, Singapore more often functioned as an end destination instead of a conduit.

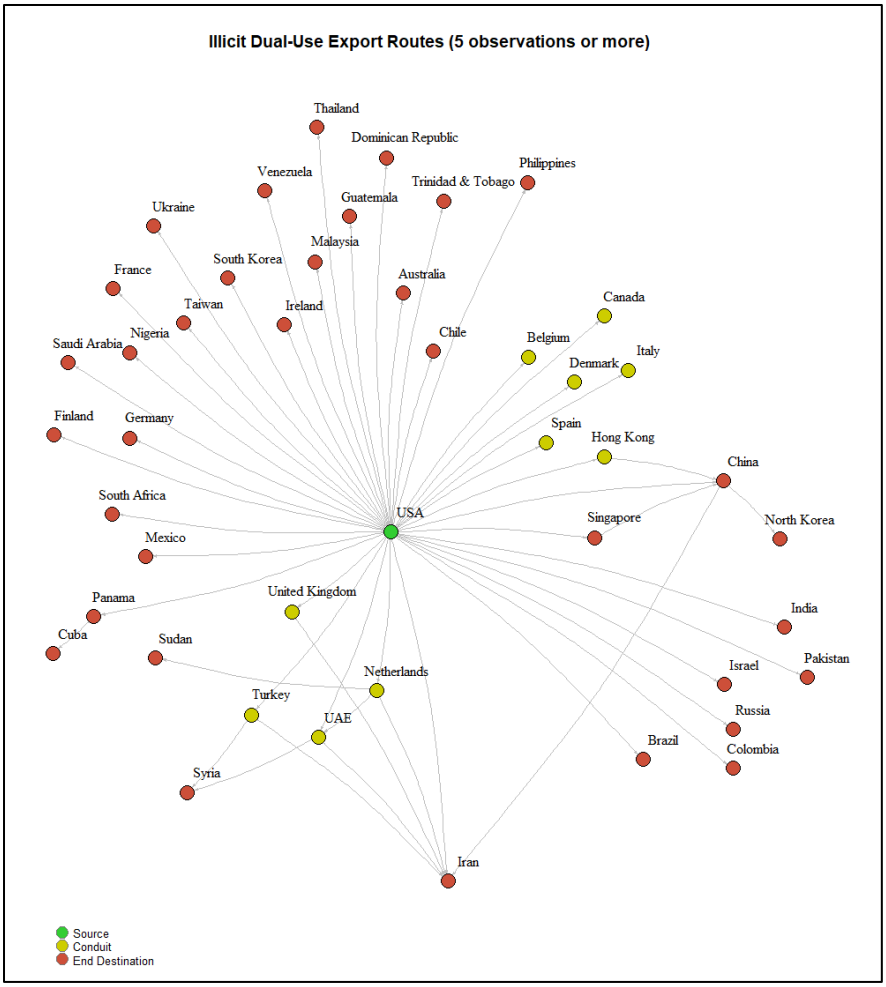

Figure 25: Dual-use subset network with all edges less than 5 removed. The dual-use subset network's average edge weight was 4.79 observations. The filtered network more clearly identifies the most common proliferation patterns for dual-use goods, especially which conduits have high frequency ties with specific end destinations.

Commercial Network

The third and final subsetted network, commercial goods may seem relatively unimportant compared to military and dual-use commodities. While some of the commercial goods in the SEV dataset are benign (e.g., empty wooden pallets exported to Cuba), others are similar enough to their dual-use counterparts that proliferators opt to "go below or around" control thresholds established in export control regulations (Albright & Stricker, 2018; United Nations Panel of

Experts, 2014).[24] The commercial subset network (Figure 26 below) consists of 171 observations involving a total of 32 nodes, making it the smallest subset network. As before, significant differences appear between the commercial subset and its military and dual-use counterparts. The commercial subset network is the only one containing more conduits than end destinations, 16 and 13, respectively. Iran and Syria appear to have a diversified network of conduits, compared to other end destinations like Pakistan and India who only maintain edges between the USA and one conduit. There are few instances of rare inter-conduit trade, including reciprocal ties between the Netherlands and the UAE.

[24] For example, single-axis electrical discharge machines typically fall below export control thresholds, but certain models can be upgraded via software to operate in additional axes to meet export control thresholds. Proliferators have been documented trying to procure the less sophisticated models in order to avoid regulator's scrutiny over dual-use exports.

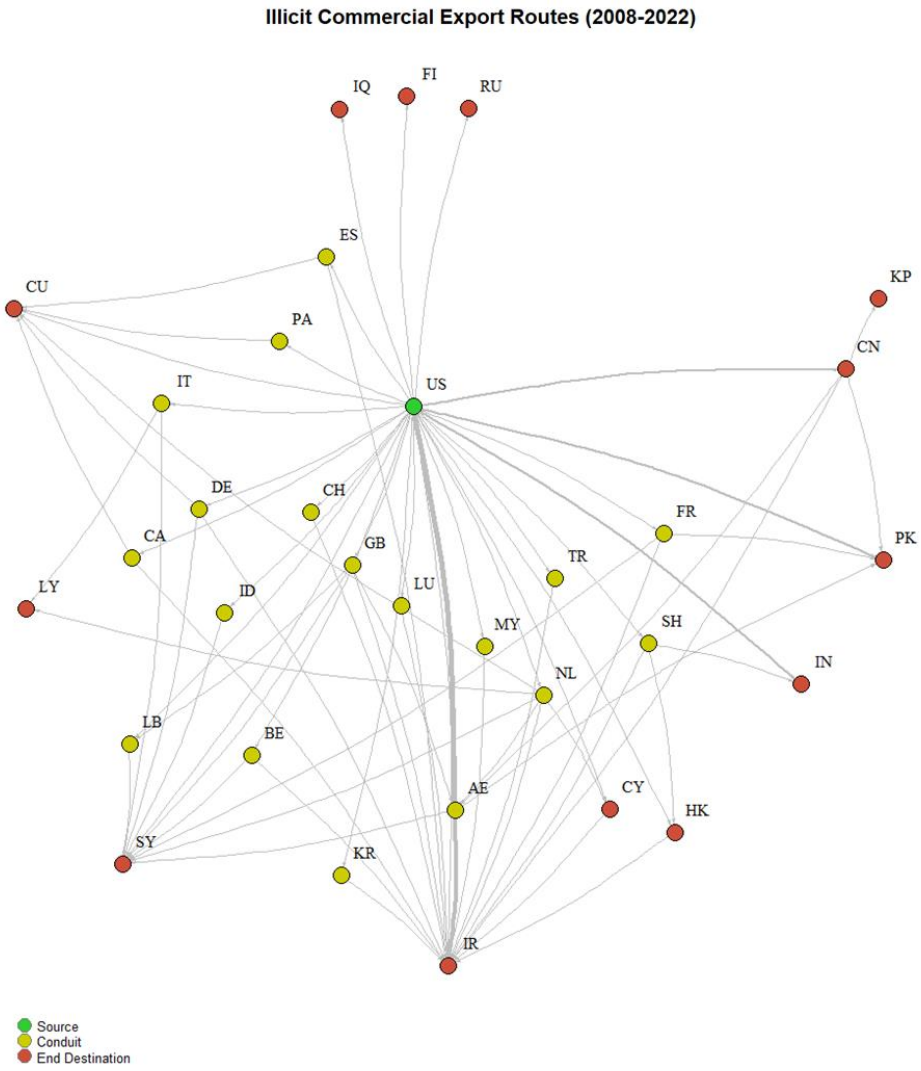

Figure 26: Commercial subset network graph. The commercial network has the highest ratio of conduits to end destinations, consisting of 18 conduits and 13 end destinations.

The commercial network descriptives describe a unique structure with the least transitivity and most centralization among all the networks. The smallest network consists of 32 nodes and 171 observations. The reduced node count and higher rates of edges formed between conduits and end destinations result in a diffused network with clusters of nodes forming ties amongst themselves. The diffusion of edges amongst the nodes causes a high density score, reflecting the high proportion of observed edges compared to the overall potential number of edges amongst the 32 nodes. That diffusion also reduces the network's density, since the higher frequency of

edges among conduits and end destinations comes at the expense of a reduced proportion of edges connecting to the USA. The frequent clustering creates a network that's more transitive than any of the previous networks. Similar to the military network, the commercial network's zero reciprocity suggests that illicit commercial exports never flow between two states in both directions.

	Commercial Network Statistics
Node Count (Number of States)	32
Edge Count (Observations)	291
Density	0.07358871
Reciprocity	0
Transitivity	0.2040816
Centralization	0.4068678

Table 5: Commercial network descriptive statistics.

A histogram of the commercial subset's edge weights (Figure 27 below) reveals another skewed distribution, closer to the military subset than the dual-use subset. A vast majority of edges have low weight, with the highest edge counts between 40-50 observations.

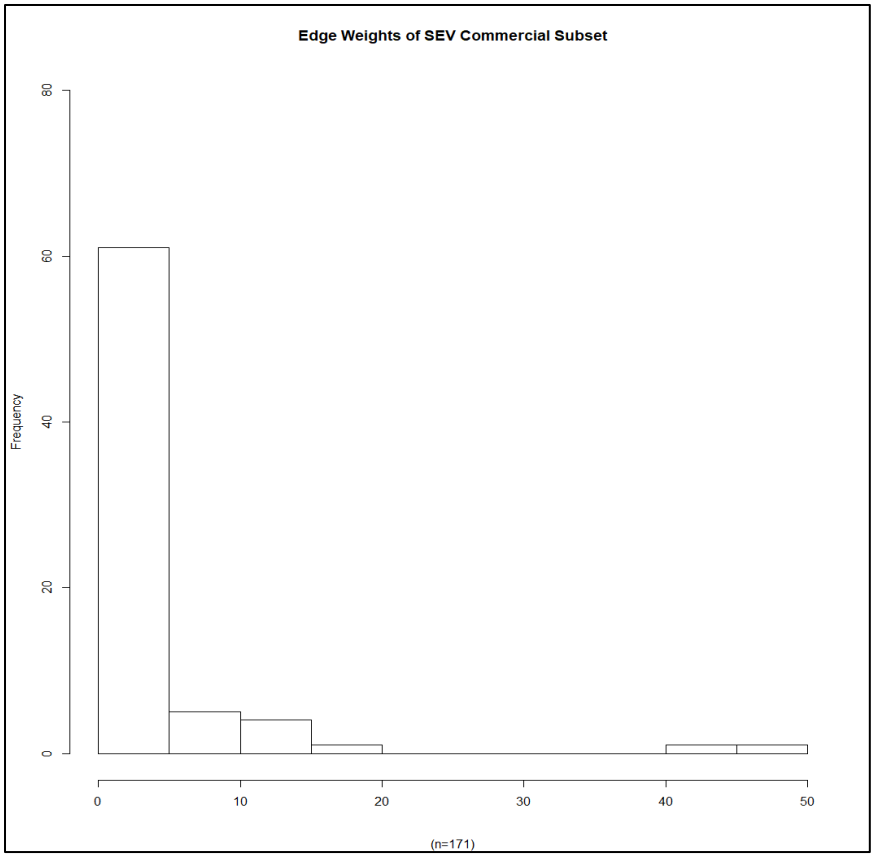

Figure 27: Histogram of the commercial subset network's edge weights.

The last filtered network depicted in Figure 28 reveals the crucial role of conduits within the commercial subset. The commercial subset averages an edge weight of 3.99, creating a cutoff value of 4. The resulting network consists of 7 conduits and 5 end destinations, again with the unique pattern of more numerous conduits than end destinations.

While the filtered commercial network consists primarily of conduits, the edge weight cutoff eliminates all inter-conduit trading patterns. This suggests that while there is some reciprocity within the commercial subset, those instances occur less than 4 times. Some conduits lose all of their ties to end destinations, suggesting they are infrequently used as conduits for multiple end destinations. Interestingly, Lebanon remains a conduit for observations destined to Syria despite losing its tie to the USA. Lebanon frequently acts as a secondary conduit for goods originating

from the USA, although the primary conduits for goods bound for Lebanon are never observed more than 3 times. This suggests that at least some of Lebanon's illicit trade is routed through another conduit before its re-exported a final time to Syria.

Three of the five end destinations (China, India, and Pakistan) lose their conduits with the edge weigh cutoff threshold, indicating that most of the illicit commercial transactions to these states are direct exports from the USA. Most commercial export violations are illegal due to specific end users or end uses. There is substantial legitimate trade to these countries, but certain entities have been placed on restricted lists that impact their ability to receive US-origin goods and technology. Often, exports of even commercial goods require authorization prior to export to these entities. The direct ties from the USA to these countries likely indicate instances where the end user was subject to some sort of restrictions that did not apply to the entire country. It's possible these shipments hid the intended end user or the exporter was unaware of the trade restrictions.

Instead of entity-specific restrictions, the U.S. has comprehensive, country-wide restrictions on export to Iran and Syria. These broad restrictions are likely why both Iran and Syria retain their diversified procurement patterns. By relying on multiple conduits for access to commercial goods from the USA, these shipments can be hidden from government regulators. Since the commercial items do not typically require prior authorization to most destinations, shipments to conduits like the UAE or Germany are unlikely to garner scruntiny from regulators. After the commercial items arrive in the conduit state, they are likely easy to re-export to Iran and Syria if the conduit state imposes different trade restrictions than the United States.

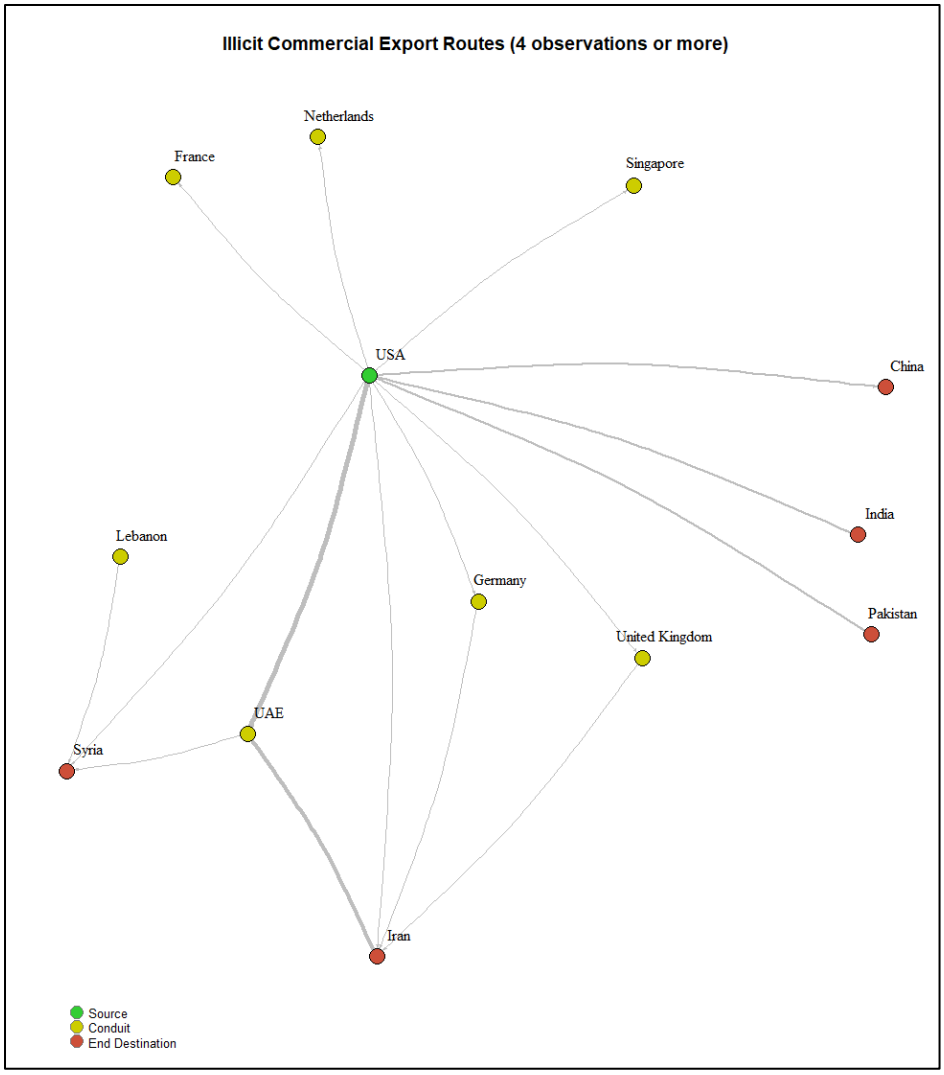

Figure 28: Commercial subset network with all edges less than 4 removed.

Conclusion

Converting the SEV dataset into networks provides novel insights into 21st century proliferation, identifying the states acting as conduits and end destinations. Subsetting the overall SEV data into military, dual-use, and commercial networks expands potential research designs interested in those particular proliferation patterns. Striking differences emerge between the complexity and size of the SEV network and its three subset networks, especially the smaller military and commercial networks. While the dual-use subset most closely resembles the over SEV network, the military and commercial subsets' sample size, node count, and distribution of conduits versus end destinations varies dramatically from the overall SEV and dual-use subset networks. This reinforces the importance of granular data and sufficiently detailed observations that allow scholars to focus on particular illicit networks of interest. These initial descriptive findings refute earlier assumptions that illicit trade networks often operated similarly regardless of the type of illegal trade (Naím, 2006).

Table 6 below contains the node count, edge, density, reciprocity, transitivity, and centralization of all four networks. Density is a relative to network size, limiting its utility when comparing networks of significantly different sizes (Scott, 2013). Density may be a more meaningful measure in future descriptive analyses if additional source countries' data become available and result in comparably sized networks. For now, the different density levels provide empirical measures that the subset networks within the SEV data are fundamentally different.

The low reciprocity in the overall SEV and dual-use subset networks reflect the rare instances of symmetrical ties between conduits. It's possible that the use of multiple conduits within a dual-use proliferation pathway reflects proliferators' prioritization of security over efficiency. By

relying on complicated networks of trade flowing between conduits, proliferators likely reduce the likelihood of detection by hiding the intended end user or misdeclaring dual-use goods as commercial items. Notably, this inter-conduit trade did not result in reciprocity within the military and commercial subsets. This is likely due to the increased transaction cost for each additional node within a proliferation pathway. Illicit military exports rarely rely on conduit states, probably due to the difficulties in obfuscating military equipment. Given the risk of detection at each shipment point, it's reasonable that illicit arms networks consist primarily of direct exports. Conversely, illicit commercial exports are likely far easier to hide within legitimate trade. Since the commercial items are so ubiquitous, direct exports or pathways involving single conduits are likely sufficient to satisfy proliferators' need to balance security for efficiency.

The military subset network consisted nearly entirely of end destinations, containing only a single conduit. Nearly its mirror image, the commercial subset was the only network to contain more conduits than end destinations. The centralization scores across all four networks remained fairly consistent, likely due to the egocentric nature of the networks' reliance on the USA as the source for each observation. The military subset network's slightly higher centralization score reflects the relative lack of conduit activity, creating a network with the highest proportion of ties connecting end destinations directly to the USA. Conversely, the commercial subset network's lowest centralization scores result from its high amount of conduit activity. These differences likely reflect the difficulty in disguising illicit shipments of military equipment compared to the relative ease of circumventing restrictions on US-origin commercial goods destined to proscribed states or entities.

Given the wide variation between the subset networks and their structures, the benefit of parsing the SEV observations by commodity type will likely provide better data for any future inferential models interested in specifics regarding the illicit trade in military, dual-use, or commercial goods. However, significant value remains in using the SEV data in its entirety for research designs broadly interested in export control violations.

	Overall SEV	Military	Dual-Use	Commercial
Node Count (Number of States)	122	49	110	32
Edge Count (Observations)	1364	269	826	171
Density	0.01842569	0.02210884	0.01926606	0.07358871
Reciprocity	0.02941176	0	0.03463203	0
Transitivity	0.0856206	0.01098901	0.08145225	0.2040816
Centralization	0.4563896	0.4772135	0.4481104	0.4068678

Table 6: Overall SEV, Military, Dual-Use, and Commercial network statistics.

This initial descriptive mapping of proliferation patterns establishes a foundation that is ripe for expansion. Using existing SEV data, further parsing the observations by reason for control (e.g., nuclear or chemical) can create subset depicting proliferation networks specializing in particular technologies or industries. These subsets could be crucial in testing long-theorized differences between nuclear and other types of proliferation.

If other governments begin more frequently publishing detailed summaries of export violations, the SEV data could be expanded to include more than US-origin observations. Comparing multiple states' ego-centric proliferation networks could identify similarities and differences between the illicit trade challenges facing each state.

In addition to other states' proliferation patterns, the SEV data could be compared to already mapped networks of other types of illicit activities such as money laundering or human trafficking. Considering the difference within the SEV network's subsets, it's likely that additional distinct patterns emerge that differentiate how various "hidden populations" are smuggled throughout the international system.

Finally, the SEV data and the three subsets (military, dual-use, and commercial) can be used in inferential modeling to explore the factors contributing to edge formation between the nodes. Until recently, inferential network modeling lacked the ability to account for valued networks. Given these methodological advancements, there is ample opportunity for innovate research designs to test long-held assumptions on illicit strategic trade.

CHAPTER 3: DETERMINANTS OF DUAL-USE PROLIFERATION NETWORKS[25]

[25] Starks, B.M. To be submitted to a peer-reviewed journal

Abstract:

Nonproliferation scholarship has been stymied by poor data. The recently developed Strategic Export Violation (SEV) dataset provides sufficient observations of illicit transfers of dual-use goods. Using the data, a Count Exponential Random Graph Model (Count ERGM) identifies which covariates impact a state's likelihood to appear within the observed dual-use proliferation network. Contrary to previous theoretical work, model results indicate that increased globalized economic integration decreases a state's likelihood of appearing in the observed proliferation network. Surprisingly the effect of multilateral export control regime participation finds mixed results, with some model specifications indicating the regime participation increases the likelihood of receiving illicit dual-use technology. This paper serves as the first use of a Count ERGM model for nonproliferation studies, demonstrating the potential benefits of the SEV data and the adoption of more inferential network models within the supply-side nonproliferation literature. Broader implications include potential utility in other areas with "hidden populations" within the humanities, such as sanctions or arms trafficking.

Introduction

Since the end of the Cold War, actors pursuing weapons of mass destruction (WMD) have reached beyond their national borders to obtain key components necessary to advance their nuclear, chemical, biological, or missile programs (Bunn & Potter, 2018). Many of these key components are often "dual-use" which means a particular technology has valid peaceful applications as well as potential utility in aspects of a WMD program. Recognizing the need for coordination among states concerned about WMD proliferation, various international efforts emerged in hopes of stemming the unauthorized flow of dual-use technologies while balancing

economic advancement and scientific development. These efforts have often relied on multilateral agreements among states who already possessed the scientific and industrial know-how that would-be proliferators sought. These agreements established common thresholds for dual-use technology and promoted shared trade guidelines. As nonproliferation mechanisms evolved, so did illicit procurement strategies. Proliferators attempted to avoid scruntiny from government regulators by hiding their illicit transactions, often disguising the transactions by falsifying paperwork and shipping dual-use goods among legitimate commercial trade under false pretenses.

Within international affairs literature, notable scholarship has investigated known proliferation programs, using in-depth qualitative or theoretical research designs. Quantitative research designs have unfortunately been largely precluded by a lack of suitable data. Unlike the extensive datasets of legal international commerce, there have been no large-*n* datasets concerning illicit dual-use trade. The lack of data stems from the "hidden population" problem. Since illegal exports are inherently secretive, it's difficult to detect and enforce dual-use export regulations. Few governments have published sufficient details on those known cases that are successfully detected and prosecuted, often omitting the dual-use item's description or the intended end destination (Bauer & Bromley, 2019). Given the lack of quantitative data, nonproliferation scholarship has typically relied on qualitative case studies or theoretical discussions to describe likely illicit procurement patterns (Kinsella & Montgomery, 2017; Salisbury, 2019). These nonproliferation studies use concepts and terms to describe actors that form interconnected patterns but remain unable to precisely define the structure of dual-use proliferation networks.

I use a novel dataset designed for inferential network analysis of illicit dual-use trade. The data were hand-coded from hundreds of published government cases documenting each illegal export of dual-use technologies. Each observation within the dataset accounts for the source and end destination states, and also any intermediate states that serve as conduits. Accounting for these conduits provides a more complex and accurate sample of how dual-use goods are smuggled throughout the international system. These data provide a first-of-its-kind glimpse into the hidden population of dual-use proliferation networks. The dataset contains 100 states and 1,039 observed illicit dual-use exports that can be represented into a single network reflecting nearly 15 years of observed proliferation pathways.

By constructing a network with such a large sample, I am able to conduct first-of-its-kind hypothesis testing using a count Exponential Random Graph Model (ERGM), an inferential analysis tool specially designed for networks with weighted edges (Krivitsky et al., 2024). Earlier ERGM variations were unable to test networks with dependent variables using counts, requiring research designs to flatten their data into binary measures (Krivitsky, 2012). I construct two models, testing long-held theories regarding how the globalized economy, national capability, and nonproliferation agreements all affect the likelihood of a state's involvement within the observed illicit dual-use trade network.

I find evidence that a small number of states account for a majority of illicit all exports, and those particular states often export to many other states instead of a few common destinations. Contrary to expectations and previous theoretical work, both models reveal empirical support

that as states grow more economically interconnected to global trade, they are less likely to be involved in an illicit dual-use transaction. Perhaps most surprisingly, I find mixed results for the effect of states' participation in the multilateral nonproliferation agreements. It's often been assumed that members of these multilateral regimes are better prepared to detect and penalize dual-use proliferation attempts. One model finds no effect of regime participation, while another model specification finds evidence that states who are members of more multilateral regimes are more likely to receive an illegal transfer of dual-use technology.

My findings contribute to the overall international relations literature by identifying how globalized trade and international agreements affect state's likelihood of becoming part of illicit dual-use networks. To the best of my knowledge, this is the first instance of a count ERGM used within the nonproliferation literature. Furthermore, this study serves as a proof of concept for the novel dataset and how recent advancements in ERGMs may be useful for other related disciplines facing a hidden population problem such as sanctions or arms trafficking.

The Challenge of WMD Proliferation Scholarship

Although scholars often emphasize the globalized supply chain involved in WMD programs, few supply-side papers investigate the actual pathways that proliferation occurs. Often, these papers emphasize a handful of case studies but give relatively little attention to the role of conduits within proliferation networks. Notable exceptions include a case study on the role of Malaysia in the infamous AQ Khan proliferation network (Salisbury, 2019) and theoretical work exploring the likely goals of intermediaries within WMD proliferation networks (Kinsella & Montgomery, 2017). As the international system and states grow increasingly concerned about the spread of

WMD technologies, the nonproliferation scholarship has mirrored their interest, but its quantitative analysis has lagged behind. The difficulty in obtain sufficiently large datasets has likely influenced recent nonproliferation scholarship's emphasis on theoretical or qualitative research designs.

For nearly a century, the international system, multilateral organizations, and individual states have sought to prevent WMD proliferation. Following in the wake of chemical warfare during WWI, the 1925 Geneva Protocol prohibited the use of chemical and biological weapons (United Nations Office for Disarmament Affairs, n.d.). Over time, the WMD threat expanded to include nuclear weapons and the unmanned delivery systems designed to carry warheads across vast distances. In the decades following World War II, four multilateral export control regimes (the Nuclear Suppliers Group, Missile Technology Control Regime, Australia Group, and Wassenaar Arrangement) emerged to establish common understanding among members regarding which dual-use technologies posed such threats that their export should subject to additional controls.[26] These regimes established a nonbinding set of guidelines and control lists to manage the spread of certain nuclear, chemical, biological, and aerospace technologies. By 2004, the growing concern of WMD proliferation led to United Nations Security Council Resolution 1540 (UNSCR 1540). The resolution required "all States to adopt and enforce appropriate laws" to prevent the spread of WMD technology to non-state actors (United Nations Security Council, 2004). Alongside these international and state-level nonproliferation efforts, scholars have explored the motivations and mechanisms behind WMD proliferation. Nonproliferation scholarship falls

[26] The term "dual-use" refers to items or technologies that have peaceful uses in industrial or research environments as well as applications within military of WMD programs. For example, due to its high strength and low weight, carbon fiber may be used in nuclear and military aerospace applications as well as commercial settings like sporting equipment.

broadly into two categories: demand-side proliferation and supply-side proliferation (Debs & Monteiro, 2017; Koch, 2019; Narang, 2022; Sagan, 1996). Demand-side research focuses on *why* states decide to pursue weapons of mass destruction (WMDs), with supply-side research focusing on *how* states attempt to develop WMDs.

A foundational contribution to demand-side scholarship by Sagan (1996) posits that domestic politics, security concerns, norms and prestige all contribute to a state's pursuit of nuclear weapons. Others have suggested that economic development, security guarantees from great powers, and indigenous technical capacity also heavily influence a state's demand for nuclear weapons programs (Debs & Monteiro, 2017; Singh & Way, 2004). Recently, scholars have revisited the multilateral export control regimes' mechanisms and their impact on states' calculations to proliferate WMD technologies (Enia, 2020).

Supply-side studies shift away from states' motivations, instead focusing on how states implement their WMD ambitions. Recently, Narang (2022) develops a theory on proliferation strategy that considers different factors that impact states' strategies for developing nuclear programs. Others theorize that actors within a WMD proliferation network likely place a premium on secrecy at the expense of efficiency (Kinsella & Montgomery, 2017). This concept that proliferation networks prioritize secrecy at the expense of efficiency is mirrored in recent analysis on the Nuclear Suppliers Group (NSG), a non-binding, consensus-based multilateral export control regime that establishes guidelines on the export of nuclear and nuclear-related dual-use technologies. NSG members are expected to create and implement domestic export regulations based on shared controls lists and expectations regarding transfers of nuclear

technology to non-NSG member states. A qualitative assessment of the regime's efficacy suggests that the multilateral export control regimes establish common barriers to trade that force proliferators to rely on costly and inefficient methods to circumvent (Koch, 2019).

Other work assesses how well states have complied with UNSCR 1540 requirements to implement laws regulating the flow of strategic goods, but notes that enacting legislation is not the same as enforcing the related regulations (Crail, 2006). It remains unclear how well or how often these regulations are implemented. Instead of focusing on illicit procurement, Fuhrmann (2008) uses data on U.S. dual-use export licenses to identify that approved exports are more often destined to democratic states. Interestingly, the same study found no statistically significant impact on licensing determinations for applications destined to states who had acquired or pursued WMDs in the past.

Most states rarely publish details on successful enforcement actions relating to strategic goods. The states that do publish enforcement actions often do so with press releases and news articles, but do not main a central repository of cases available to the public. Relatedly, nonproliferation scholars identified common challenges in detecting, prosecuting, and publicizing strategic trade violations (Bauer & Bromley, 2019). They find that enforcement agencies face significant difficulties in detecting potential strategic export violations since dual-use items often appear similar to standard commercial counterparts. Further compounding the enforcement problem, some states' privacy laws inhibit government enforcement agencies from publicizing details about successfully prosecuted violations. These enforcement challenges further limit the possible sample size for nonproliferation research.

Social Network Analysis for Proliferation Studies

Political science and international relations have long recognized the potential utility of social network analytical frameworks but were initially constrained by limited methodological tools. Innovations like the exponential random graph model (ERGM) and its later variants allowed researchers to consider observations that were interdependent (Victor et al., 2017). Political science has seen ERGMs used in research studies across multiple subfields such as refugee patterns (Abramski et al., 2020), interest group coalition formation (Box-Steffensmeier et al., 2018), foreign direct investment flows (Schoeneman et al., 2022), and the global arms trade (Thurner et al., 2019).

Contemporary network studies in global trade patterns often trace back to Davis and Weinstein (2001), which relies on 1995 Organization for Economic Cooperation and Development (OECD) data to test a long-standing economic theory. This seminal paper relies on OECD data for 10 countries of interest and aggregates the remaining 20 countries' data as the "Rest of the World" (Davis & Weinstein, 2001, p. 1430). While limited to only eleven actors (10 OECD states of interest and the "rest of the world"), the paper called for additional, future quantitative research in bilateral trade flows.

Since the early 2000's, international institutions have publicly released export-import data that has allowed network analysis of trade flows to flourish. Scholars described these trade data as a "gold mine for empirical analysis" (De Benedictis et al., 2014, p. 288). The United Nations' Comtrade data is widely regarded as the best record of international trade flows, breaking down trade flows by state and harmonized system (HS) code. This granular trade data allows for

targeted trade studies. Scholars have relied on the UN Comtrade data to identify causes behind intra-European Union trade in nuclear commodities (Jang & Yang, 2022). Others have used the UN Comtrade data to focus on a broad definition of "strategic" trade to explore the relationship of bilateral trade in certain goods affects the likelihood of conflict (Goenner, 2010; Zeng, 2024).

Although the UN Comtrade dataset is extensive, it suffers from missing data when states do not report their trade flows.[27] To mitigate some of the missing trade data, French researchers have published a modified version of the UN Comtrade data called the BACI (Base pour l'Analyse du Commerce International) dataset. The BACI dataset uses reported trade flows to impute unreported imports and exports, allowing for a more complete accounting of global trade flows (CEPII, n.d.). Using BACI data from 2007, scholars reconstructed the global flow of goods in a "World Trade Network" to provide descriptive statistics of international commerce (De Benedictis et al., 2014).

Sanctions scholarship suggests that increased trade restrictions incentivize the growth of black market networks. As sanctions implement trade restrictions, rent-seeking opportunities grow as well (Blanton et al., 2018). These rent-seeking opportunities create incentives for actors within third party states to support the circumvention of sanctions. It's been demonstrated that sanctioned states resist calls for improved domestic human rights by circumventing trade restrictions through illegal trade networks (Chyzh, 2016). These indirect trade flows are less

[27] For example, in 2003 the United Nations Department of Economic and Social Affairs began publicly releasing UN Comtrade data. The Comtrade data contain trade records dating back to 1962, recording the trade flows by country and harmonized system (HS) code.

efficient but allow the sanctioned state to more easily resist policy change by mitigating the impact of sanctions.

Arms trade studies find similar patterns of indirect trade allowing restricted states to resist external pressures. Scholars note arms exporting states exert outsized influence on the states who import their weapons, since advanced weapon systems rely on specialized components with few alternative suppliers (Kinsella, 1998; Krause, 1992; Pamp et al., 2021). If states lose access to legitimate arms procurement, they must decide between a potentially costly conversion of military systems to other arms suppliers or identify methods to indirectly acquire arms from their original suppliers (Krause, 1992). When arms embargoes restrict a states' ability to openly procure weapons, it's been observed that nearby countries are more likely to increase the amount of arms imports (Bove & Böhmelt, 2021). It's suspected that the increase in arms imports is caused by an increase in the demand by the recently embargoed neighboring state.

While no quantitative network analysis of dual-use proliferation has been published, there is some related literature on illicit small arms transfers. Sparse quantitative network studies mapped the illicit arms trade, but with narrow geographic and temporal scope. Kinsella's analysis of the small arms and light weapons (SALW) black market in Africa resulted in a network consisting of 74 states (37 African states and 37 states from outside of Africa) with a total of 209 edges (Kinsella, 2006). Despite its limited regional scope and purely descriptive nature, Kinsella's work demonstrates the potential utility of network analysis in visualizing the complex illicit networks underlying many different fields within the international relations discipline.[28]

[28] Note that Kinsella's paper predates the development of relevant inferential network models such as the exponential random graph model (ERGM).

Borrowing from these previous studies, I expect network analysis to provide novel glimpses into nonproliferation. If restrictions like sanctions and arms embargoes create networks of conduits and end destinations, it's reasonable to expect a similar pattern of circumvention applies to dual-use export restrictions. The global dual-use proliferation network is often discussed within the literature, but frequently accompanied by lamenting the lack of quantitative data (Kinsella & Montgomery, 2017). The interconnected and globalized nature of manufacturers, distributors, freight forwarders, brokers, and consumers create a natural network pattern that can obfuscate illegal activities (Bunn & Potter, 2018; Dunnicliff & Izewicz, 2015; Koch, 2019; Russell & Wirtz, 2008).

Considering the popular notion of dual-use proliferation networks, supply-side nonproliferation scholarship should consider adopting methods that account for interdependence between observations. Social network analysis explicitly models structural dependencies, allowing research designs to better reflect the complexity of which states serve as conduits and end destinations for illicit dual-use exports.

The "Hidden Population" Problem

Quantitative analysis requires sufficient observations to properly test hypotheses. Other areas, such as global commercial trade or arms trade, often rely on international organizations' published data such as the UN Comtrade data or the Stockholm International Peace Research Institute's Trend Indicator Value, respectively.

Unfortunately, the study of illicit activity is inherently more difficult to observe and measure. Any attempts to investigate illicit proliferation of dual-use goods must find a workable solution to the "hidden population" problem. The concept of a "hidden population" problem is common across other disciplines interested in events that are difficult to measure, such as the prevalence of human trafficking (Scullion 2015) and ecological studies of tiger populations (Karanth et al., 2006). For the hidden population of illicit dual-use exports, quantification challenges arise from a variety of factors such as: states' legal frameworks, states' capabilities to detect violations, and states' capacity to successfully prosecute violators.

In the context of human trafficking, states' legal definitions of what constitutes "human tracking" varies. This variation complicates efforts to compare the prevalence of trafficking within the international system. Likewise for dual-use goods, states' control lists and licensing requirements differ from country to country even though many base these requirements off of UNSCR 1540 or the multilateral regimes. Even states with nearly identical controls list may have different licensing requirements, which means an export of a dual-use good from State A may require prior approval whereas the exact export from State B may not require any prior authorization. Even among states with similar legislative frameworks, the ability to detect dual-use export violations varies from country to country (Bauer & Bromley, 2019; Crail, 2006). States with limited resources or expertise may struggle to develop strategies for identifying shipments of concern among the vast global flow of goods entering and exiting ports of entry. As mentioned during the discussion on commercial trade networks, UN Comtrade data is reported by HS codes. These import classifications are the primary language of trade. For example, HS codes determine

applicable tariffs and other trade barriers such as quotas. Unfortunately, there is little correlation between dual-use goods' export classifications and their HS code classifications (Chatelus & Heine, 2016). This disconnect between HS codes and export classifications complicates governments' ability to sift through vast trade data to identify shipments of likely dual-use proliferation.

Dual-use goods can be visually similar to standard commercial counterparts that are subject to less stringent controls. Differentiating dual-use from commercial items poses another significant detection challenge for state authorities. For example, certain equipment used in pharmaceutical research may also be used in biological weapons programs. Shipping paperwork may mislead authorities regarding the true end user and/or end destination in order to avoid scrutiny or licensing requirements. Depending on the item, it can be difficult to discern a dual-use item from a commercial equivalent that is not enumerated on any multilateral control list.[29] This is a unique problem with detecting illicit dual-use shipments.

Difficulties in successfully enforcing export controls continue to exacerbate the hidden population problem. Similar to issues with detecting illicit exports, states with similar legislative frameworks may experience different challenges in successfully enforcing the export control regulations (Bauer & Bromley, 2019). Bauer and Bromley (2019) describe how European states have faced challenges prosecuting alleged violators. Some states' requirements for criminal charges include willful intent to violate export control regulations, which has proven difficult in

[29] For example, a stainless steel valve will unlikely fall under of the multilateral export control regimes' control lists. If a similar stainless steel valve is lined with a corrosion-resistant material, such as a fluoropolymers, then the valve is likely enumerated on export control lists. Both valves would appear externally identical, making detection difficult if exporters falsely declared the corrosion-resistant valves as standard stainless steel valves.

some cases. Other times, enforcement is hampered due to the complicated nature of pursuing an export control case in a court of law. Sometimes juries and judges may not understand the regulations sufficiently. Other times, prosecutors may not bring a case to court due to a lack of evidence or uncertainty in convincing a jury and judge that a particular item met control criteria (which often requires bringing in a technical SME that may not translate well in court).

Lastly, even cases that are successfully detected and prosecuted must be published publicly to make the information readily available. Currently, on the United States' Bureau of Industry and Security routinely publishes export violation cases. In the past, it was rare for other countries to publish detailed accounts of export violations. For example, the United Kingdom's Export Control Joint Unit (ECJU) published a list of export violations that were settled between January and March 2024 (Export Control Joint Unit, 2024).[30] The published notice did not specify the companies, commodities, or destinations involved in any of the violations. The ECJU's notice only contained the financial penalty and the related export regulation that was violated. This lack of published details inhibits scholars' efforts to understand global proliferation patterns and how they may vary from source state to another source.

The lack of detected, prosecuted, and published violations of dual-use exports continues to create a hidden population problem. The result of these "hidden population" challenges is a lack of easily observed data, which until now have left large-*n* quantitative analysis out of reach. Because of these complications, nonproliferation scholars have been unable to assess how well the sample data represent the true global population of dual-use export violations. Lacking a

[30] Refer to the appendix for a screenshot of the ECJU notice to exporters.

clear picture of the population of illicit trade, a large sample size of the available data must serve as proxy.

Benefits of Innovative Supply-Side Proliferation Research Approaches

Considering other international relations subfields' common themes of indirect and clandestine trade to avoid restrictions, it's reasonable to expect similar behavior within a WMD proliferation context. Until now, there have not been usable data to identify how often restricted end destinations rely on networks to procure strategic goods. To date, no proliferation scholarship has quantitatively investigated the actual pathways that facilitate the transfer of WMD technology despite commonly-held assumptions that modern proliferation programs are international in scope.

States often seek to purchase dual-use equipment from abroad rather than devote time and resources to develop a domestic production capability (Bunn & Potter, 2018; Debs & Monteiro, 2017). As Bunn and Potter (2018, p.13) point out, "[e]very state that has attempted to get nuclear weapons in the last three decades has sought to buy critical technologies from abroad." This tendency to rely on external sources creates a valuable opportunity for international relations scholarship. Modern WMD programs are built using advanced components from across the world that are often illegally procured. These illicit procurement channels create observable networks, provided states publish enough details about illegal dual-use exports that have been successfully detected and enforced.

The Strategic Export Violation (SEV) dataset attempts to provide a glimpse into the hidden population of proliferation by recording 1397 observations of illicit exports from the USA between 2008-2022. The term "strategic" encompasses items with both conventional military technology and dual-use applications; the latter having applications in both peaceful uses and WMD programs. The SEV data come from publicly available case documents published by the U.S. Department of Commerce's BIS. The BIS documents primarily detail violations of goods and technologies enumerated on the Commerce Control List (the USA's amalgamation of multilateral regime control lists and other unilateral controls), but some cases involve either military or purely commercial goods.[31] Distinct patterns emerges when the SEV data are subset into military, dual-use and commercial networks. These different network structures likely reflect how proliferators' attempts to balance transaction costs and security vary depending on the type of commodity they are trying to smuggle. This paper will focus on illicit dual-use proliferation, since the nonproliferation literature is primarily concerned with WMD-related technologies and rarely concerns itself with conventional military or commercial goods.

Limiting the SEV data to only illicit dual-use exports, 826 cases remain that include 110 different states. Due to limited explanatory variable data, 10 states must be dropped from the dataset, which removes 40 cases.[32] The remaining 100 states and 786 cases results in a network containing 1,039 observations of an illicit dual-use export. Converting the states into nodes and

[31] Some cases involve military equipment under the Department of State's jurisdiction, typically when BIS suspends the perpetrator's ability to send and/or receive U.S. goods for a period of time in conjunction with the party's violations of the U.S. arms export regulations. Other cases concern purely commercial goods (e.g., wooden pallets, scrap metal, electronics, petri dishes, and chemical production software) that were exported to prohibited destinations or particular entities on restriction party lists such as the BIS Entity List (15 CFR 744.16).
[32] Afghanistan, the Bahamas, Barbados, Democratic Republic of Congo, Hong Kong, Iraq, Isle of Man, Malta, Monaco, North Korea, and Turks and Caicos were removed from the data due to missing values for either 2008 KOF Globalization Index or 2008 POLITY V scores.

observations into edge weights creates a network graph (Figure 29 below). Within the network graph, each node has been color-coded based on its role as either a source, conduit, or end destination. Due to limitations with available data, the SEV data are entirely sourced from the U.S. Department of Commerce published export violation cases. Because of the limited data, each observation has the U.S. acting as the source state which has been color-coded as green. States are labelled as conduits if they more often serve as intermediaries than final locations. Alternatively, states are labelled end destinations if they are more often the final point in a proliferation pathway. In the event that a state appears equally as often as a conduit or end destination, the state will be depicted as an end destination. In the following network graphs, red circles represent end destinations while yellow circles represent conduits.

Any network can be visualized by different methods, but the following network graph is based on the Fruchterman-Reingold algorithm that's ideally suited for large networks. The initial graph, using the Fructerman-Reingold algorithm, was difficult to interpret because of the number of nodes in the center of the graph. The congestion hampered interpretability of the overall network structure, specifically the connections between the most prominent conduits and end destinations. To improve the cleanliness of the network graph, the *tkplot* command from the *igraph* R package was used to customize node placement (v.2.1.0.9003; Csardi & Nepusz, 2006).

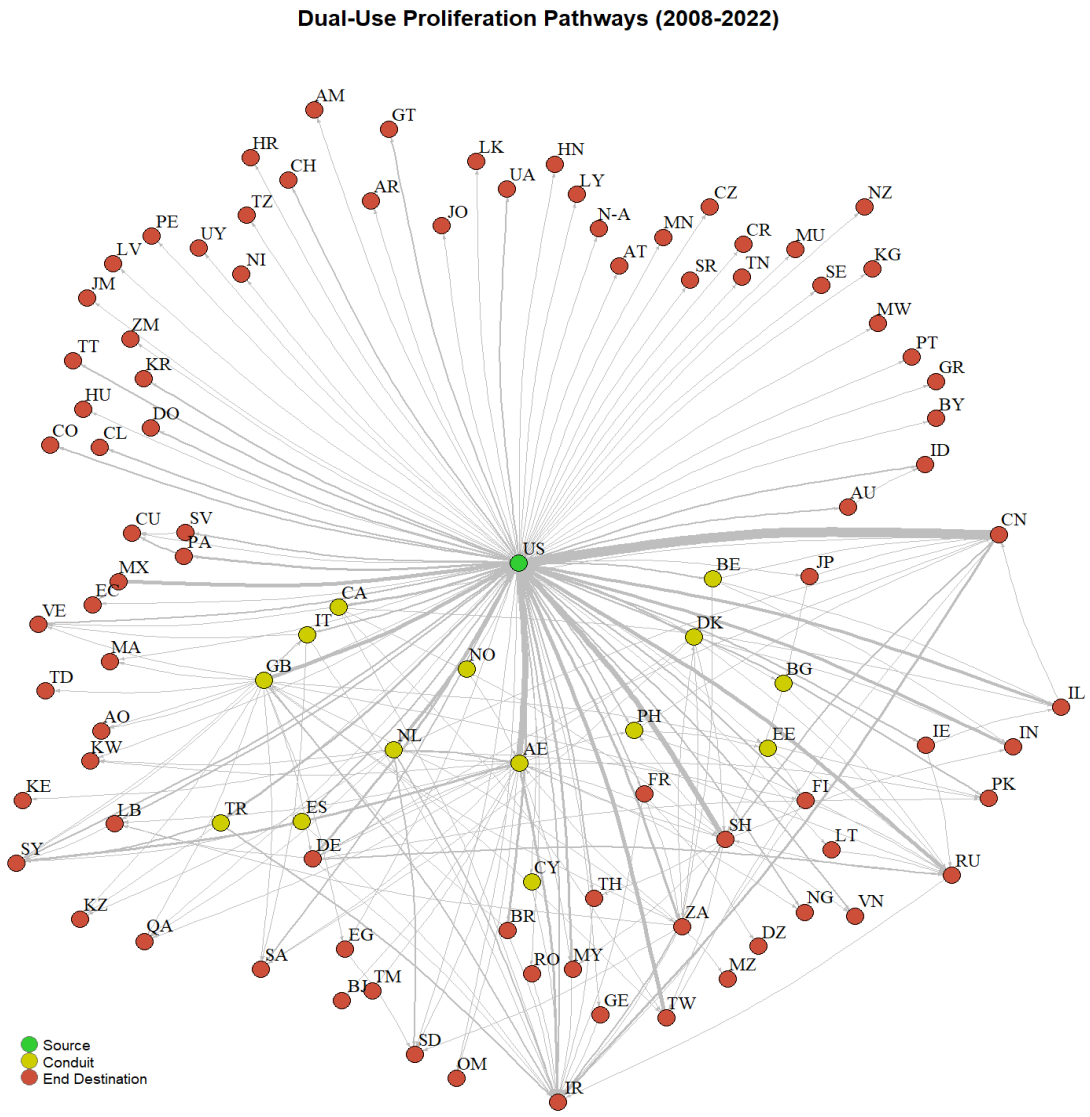

Figure 29: The network of dual-use export violations originating from the United States from 2008-2022. The network contains 100 states (nodes) and 1,039 observations represented by the edge weights connecting different nodes. These data were extracted from export violation cases published by the U.S. Department of Commerce.

Qualitative studies often lament the lack of quantitative data, arguing that efforts "to further raise illicit WMD-related trade from the realms of 'invisible crime' are necessary, including further conceptual research on illicit trade" (Salisbury, 2017, p.301). Others have echoed similar sentiments of the difficulties in measuring intrinsically hidden activities, how those challenges continue to constrain scholarship, and the need for developing alternative methods to measure

illicit trade (Bove & Böhmelt, 2021; Bunn & Potter, 2018; Fuhrmann, 2008; Kinsella & Montgomery, 2017). By quantifying a sample of the "hidden population" of illicit dual-use trade, the SEV data serve as a valuable contribution to nonproliferation scholarship.

Data Generation & Inferences

The SEV data rely entirely on violations published by the United States' Department of Commerce. Currently, no other state publicly releases as thorough information on the frequency or content of dual-use export violations. While the SEV data are a novel contribution, providing a glimpse into the hidden population of illicit dual-use trade, the data generation process may impact models' inferences.

The SEV dataset consists primarily of tangible exports of finished hardware, components, raw materials, or equipment used to produce or test dual-use goods. Intangible exports of software and technology account for roughly 5% of the SEV dataset's total observations. The extremely skewed distribution of tangible export violations is likely a reflection of the relative difficultly in detecting illicit intangible technology transfers compared to tangible items (Heau & Brockmann, 2024). It's possible that the intangible exports more often involve direct transfers from the United States to the end destination, since electronic transmission eliminates the need to spend resources diverting through conduit states. As a result, the observed network likely undercounts the proliferation pathways of intangible export violations.

There were no observed proliferation pathways that involved more than two conduit states. This could suggest that proliferators only rely on at most two diversion points when they feel like

prioritizing secrecy over efficiency. However, it's also possible that some proliferators rely on three or more conduits in hopes of more thoroughly evading scruntiny from export enforcement authorities. Without a full picture of the true population of illicit dual-use exports, it's possible that the SEV network undercounts the frequency and complexity of conduits' roles in proliferation pathways.

Lastly, the SEV's reliance on only cases originating from the United States limits the ability to confidently extrapolate findings to other potential source countries. Because no other country publishes dual-use export violation cases as frequently or as thoroughly, the available data are inherently USA-centric. Other countries with domestic dual-use industries may experience different proliferation attempts, with either more or less reliance on conduit states to facilitate illicit dual-use exports. Until other countries' export violation cases are publicly available for comparison, we are limited to inferences based on the United States.

Methods

Given the common assumptions surrounding how proliferators attempt to procure dual-use equipment from across the globe, it is unsurprising that scholars often speak about proliferation in network terms (Albright & Stricker, 2018; Bunn & Potter, 2018; Kinsella & Montgomery, 2017; Montgomery, 2008). This tendency to write using network terminology and suggest interdependent qualities of proliferation patterns creates concerns that traditional regression models will fit poorly. The typical regression models assume conditional independence of observations, which is unlikely to reflect the international system of illicit strategic goods proliferation. End destination ties are likely impacted by conduits' ties; restricted destinations are

going to form ties with states who can better access prohibited goods and services (Bove & Böhmelt, 2021; Chyzh, 2016). If an end destination's likelihood to form a tie with another state is dependent on the other state's access to US-origin goods, then we cannot assume independence among network ties. Therefore, this kind of interdependent, dyadic international relations data cannot be properly analyzed with traditional logistic regression methods (Cranmer & Desmarais, 2011; Thurner et al., 2019).

Network analysis offers the ideal methodological tool for investigating the dual-use proliferation networks- the exponential random graph model (ERGM). ERGMs assess the conditional probability of a tie between two nodes, given the rest of the network (Wasserman & Pattison, 1996). This means ERGMs treat the observed network as a single pull from a multivariate distribution of networks. By treating the observed network as a part of a larger distribution, the ERGM does not need to rely on assumptions about independence of actors or ties within the network (Cranmer & Desmarais, 2011). Phrased differently, because ERGMs consider network *Y* (the observed network) as a single instance from a multivariate distribution of networks, the independence assumption can be relaxed (Cranmer et al., 2017; Krivitsky, 2012). Relaxing the need for assuming independence between observations, ERGMs are left with only two assumptions (Cranmer & Desmarais, 2011; Cranmer et al., 2017). The first assumption states that there is an equal probability of observing any two networks with the same descriptive statistics' values included in the specification (e.g., centralization or density). Since the observed network is often the only network that is possibly observed, it's typically scholars' best available representation of all possible values. ERGMs' second assumption is that the observed network has the average value of the descriptive statistics over the other networks within the multivariate

distribution that could have been observed. Network scholars are quick to point that this assumption is required to identify network parameters, and it's no different in practice from the usual assumption that an inferential model is correctly specified (Cranmer & Desmarais, 2011; Krivitsky, 2012).

This flexible modeling approach enables ERGMs to perform typical hypothesis testing regarding dependent network structure, in additional to conventional covariates node (state) or edge (dyad) levels (Cranmer & Desmarais, 2011; Krivitsky, 2012). For our purposes, the ERGM's ability to incorporate network measures like out-degrees provide substantial appeal when compared to other modeling options that would only include covariates pertaining to states (e.g., participation in multilateral export control regimes) or dyads (political system similarity). Using network measures and typical covariates, ERGMs find its parameters by maximizing the probability of an observed network over the networks with the same number of vertices that could have been observed (Cranmer et al., 2017). In order to compare the observed network to similarly-sized networks, ERGMs rely on Markov Chain Monte Carlo maximum likelihood estimation (MCMC-MLE). Because of their additional complexity when compared to traditional ERGM models, Count ERGM models typically have higher risks of degeneracy, which is when the observed and simulated networks fail to sufficiently converge during the MCMC-MLE process (Krivitsky, 2012).

The ERGM was initially only capable of handling single networks of undirected, binary ties. Networks with directed or valued data were either unable to use the ERGM or had to "flatten" their data in order fit the ERGM's constraints. These flattened research designs lost the full

context of the data and risked the introduction of bias into the ERGM model" (Caimo & Gollini, 2023; Krivitsky, 2012).

Cranmer and Desmaris (2011) and Krivitsky (2012) further refined the ERGM, expanding the model to "count" valued edges. This version of the ERGM, later further refined by Krivitsky et al. (2024) is referred to as the "Count ERGM." This expansion from the original ERGM's binary edge restriction represented an important growth in the nature of network analytical tools, which is ideal for the directed, valued network of dual-use proliferation (Desmarais & Cranmer, 2012). This paper represents the likely first use of the Count ERGM for nonproliferation scholarship.

Variables and Operationalization

The dependent variable is a count of illegal dual-use exports from one state to another state. The data come from the Strategic Export Violation dataset. The SEV dataset converts published export violation cases into a novel unit of analysis called a "proliferation pathway" that differentiates when multiple items and/or multiple shipping routes are involved in published export violation case. Often some cases involve the export of multiple items with different dual-use classifications, as well as different conduit and/or end destinations. Straightforward conversion of those cases to only one observation from the source country to end destination would omit valuable information on the types of commodities being smuggled and any conduits involved.

For example, consider a published case involving an American company illegally exporting dual-use electronics to Russia.[33] The American company initially exports the electronics to Estonia to avoid scruntiny, and later has the electronics shipped from Estonia to Russia directly. Other times, the electronics are sent from Estonia onto Finland before arriving in Russia. Later, the American company ships the electronics directly to Finland for re-export to Russia. If the SEV dataset followed a straightforward unit of analysis, then this case would only result in one observation (Figure 30 below) that contains the source country sending electronics to the end destination.

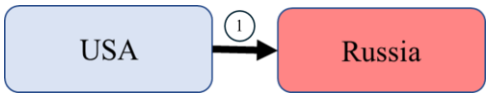

Figure 30: This straightforward approach only captures the source and final destination countries, resulting in a single observation of an edge connecting the USA to Russia.

The SEV data's operationalization of a proliferation pathway more accurately captures the nature of each violation's complexity because it accounts for different items exported along the same route or any involved conduit states. As shown in Figure 31 (below), the example case of electronics destined for Russia now results in three different proliferation pathways that measure Estonia's and Finland's roles as conduits. Now, these three distinct pathways generate seven different observations to reflect the frequency of each state's involvement.

[33] Cases 800–802 in the SEV data.

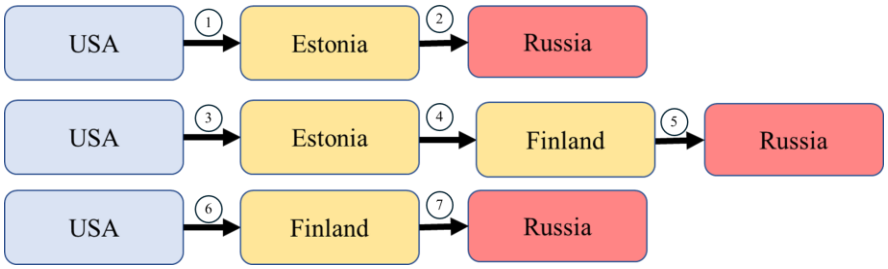

Figure 31: Proliferation Pathway's approach better captures the use of Estonia and Finland as conduits, resulting in three different proliferation pathways that create seven observations of illicit dual-use exports.

The SEV dataset contains additional observations related to illicit military and commercial transfers, but this model will focus solely on the dual-use proliferation pathways. The count ERGM is intended to find likely drivers behind why some nodes form ties to others and fail to form ties with other nodes. Those ties of interest are the network representation of the observed proliferation pathways. The frequency is measured as a count variables between a given directed dyad, representing how many times an illegal dual-use export was observed between the sending node (exporter) and the receiving node (importer).

Due to limitations regarding temporal accuracy of the export violations, the model will rely on explanatory variables from 2008. The data begin in 2008 and end in 2022, but often the original source documents do not provide sufficient detail to place a given observation within a particular year. Other cases involve activities that continue for multiple years with unclear periods of activity.[34]

ERGM model covariates include network structures, nodal attributes (state-specific traits), and edge attributes (dyadic traits). The network structure of interest is the out-degree. Out-degree

[34] The lack of clear temporal information within the data also prohibits the use of the Temporal Exponential Random Graph Model (TERGM).

scores represent directed edges from a particular node to multiple receiving nodes. Out-degree configurations capture states who most often export, such as the source and conduits. Measures of outdegrees are often used to determine if nodes less frequently form edges than expected on average and if those nodes send edges to fewer other nodes on average. ERGM models often opt for the geometrically down-weighting network statistics in order to avoid degeneracy problems, which is a higher concern for Count ERGMs (Hunter & Handcock, 2006; Thurner et al., 2019). Our model will set the threshold of out-degrees at 1, meaning the out-degree term will differentiate only between states with no outbound ties versus nodes with at least one outbound tie. For the models, a negative out-degree parameter effect will provide evidence that the network contains fewer states that export at all, and even fewer who export to many importers.

Nodal attributes include economic globalization, economic strength, nonproliferation regime participation, and industrial capability. The ability for a state to send or receive dual-use goods may be enhanced by an economy that is more connected to the globalized marketplace. The KOF Globalization Index (KOFGI) serves as the measure of globalization that accounts for economic, social, and political dimensions. Of particular interest for the SEV network, the KOFGI considers transportation and communications technology as primary traits of a globalized economy (Dreher et al., 2008). Accounting for transportation and logistical capacity is intended to account for the "Rotterdam Effect," in which major transshipment countries (e.g., Netherlands and Belgium) prominence within trade networks is increased due to the high volumes of through-trade flowing onto other states (De Benedictis et al., 2014).The KOFGI contains annual measurements for over 120 countries starting in 1970. The measure uses a continuous scale that ranges from 0.00 to 100.00.

Many scholars have discussed the idea of how states may prepare for WMD program development by building up their industrial and technical capabilities (Debs & Monteiro, 2017; Narang, 2022). For example, a state must have sufficient industrial capabilities to continuously develop and maintain complex systems related to WMD programs. As a proxy for national power, I will rely on widely used Correlates of War's (COW) Composite Index of National Capabilities (CINC) scores (Singer, 1988). The CINC scores account for various measures of national power, such as military expenditure, military personnel, energy consumption, iron and steel production, urban population, and total population. The most recent CINC scores are from Version 6.0 that include data from 1816-2016.

States' membership in the four multilateral export control regimes suggests some domestic implementation of strategic trade controls that should impact how dual-use goods are managed and reduce the likelihood of proliferation (Crail, 2006; Koch, 2019). For this paper, we've tallied each states' membership status within the four multilateral regimes as of 2008: the Australia Group, the Missile Technology Control Regime, the Nuclear Suppliers Group, and the Wassenaar Arrangement. States who are formal members of the regime receive a score of 1, while non-members receive a score of zero. These scores are combined to form an index of multilateral export control regime membership called the "MECR Membership Index." The resulting measure is an ordinal variable that ranges from 0 (no regime membership) to 4 (membership in each regime).

An alternative model specification breaks the MECR Index into four dichotomous measures to indicate a state's membership in each regime as of 2008. States who are members of a particular export control regime are coded as 1, while non-members are coded as 0.

Since developing WMD programs may be resource-intensive, the model will control for economic strength. Oftentimes specialized equipment needs to be sourced from abroad, which can be financially costly and less efficient (Chyzh, 2016). Jang and Yang (2022) demonstrate that strong economies are more likely to import nuclear and related goods, which likely holds true for states seeking illicit suppliers. Economic strength will be measured using the natural log of the World Bank's 2008 data on gross domestic product (GDP) per capita.[35]

Edge attributes include regime similarity and minimum distance between two states' capitals. Previous studies have found evidence that exports of dual-use items are influenced by security and political considerations more so than economic (Fuhrmann, 2008; Kroenig, 2009). As a proxy for diplomatic relations within a given dyad, the model will account for how similar the two states' political system are to each other. Regime similarity will be measured by the absolute difference in Polity V scores between two states in 2008. The 21-point Polity V scores measure a state's regime authority, with a minimum score of -10 indicating a severely autocratic government and a +10 score indicating a strong democratic government. Dyads with large differences suggest political dissimilarity that could contribute to additional political disagreements and trade restrictions. Dyads with low differences indicate similar political structures, which could enable greater trade facilitation and reduced restrictions.

[35] The World Bank does not provide Taiwan's GDP/capita. The IMF data was used instead (source: https://www.imf.org/external/datamapper/NGDPDPC@WEO/TWN?zoom=TWN&highlight=TWN_

Since geographic proximity has been found to contribute to suspected illicit arms transfers, it's possible that a similar effect is found in illicit dual-use proliferation patterns (Bove & Böhmelt, 2021). Given the potential natural impact on geographic distance on smuggling, the model will account for distance between states using the distance between a dyad's capitals using Gleditsch's Distance Between Capital Cities data set (http://ksgleditsch.com/data-5.html).

Hypotheses

Similar to the literatures in the arms trade and nuclear trade, I assume the drivers of illicit dual-use proliferation will more closely reflect political traits rather than economic ones. As such, the number of states acting as conduits and end destinations will be low, with a handful of states representing the majority of illicit proliferation. Dual-use export control restrictions are largely borne out of a combination of international commitments from the multilateral regimes and geopolitical interests. Economic considerations, such as industrial capacity or degree of globalization, are also likely to impact dual-use proliferation patterns.

Exporting states (conduits) are unlikely to be chosen at random. Conduits states that re-export to end destinations are likely appealing pathways for multiple end destinations. Given that only certain states will possess the traits necessary to be a preferred conduit, I expect that the relatively few states who export even once will represent a large concentration of all illicit exports. Thurner et al. (2019) refer to this as the "exporter effect," which suggests that states who export at all are likely to export often. Since this will result in a small number of nodes generating the majority of outbound edges, most states will not have illicit exports (outdegrees) at all.

Hypothesis 1 (outdegree effect): States have, on average, fewer outdegrees than expected at random

Scholars have theorized the proliferation occurs more frequently around states with advanced commercial infrastructure (Kinsella & Montgomery, 2017). Improved infrastructure such as ports, airports, and free trade zones all may facilitate increase illicit trade by reducing transaction costs or allowing the high volume of goods to hide illegal shipments. Using the KOFGI scores as a proxy for economic globalization, I expect higher measures to correlate with a higher likelihood of forming ties.

Hypothesis 2 (economic globalization): As economic globalization scores increase, states have, on average, more ties than expected at random

Given the theorized positive impact of domestic industrial and technical capabilities in developing WMD programs, it's possible that as a country's approximate national power increase then the possibility of proliferation increases (Debs & Monteiro, 2017; Narang, 2022). Therefore, I expect higher CINC scores to correlate with a higher likelihood of forming ties.

Hypothesis 3 (national capability): As a state's national capability increases, they should have more ties than expected at random

Considering the role of the multilateral regimes, formal members are likely to have access to dual-use goods. These countries may be appealing sources or conduits for end destinations, but they should also have stronger trade control regulations to prevent illicit exports. As others have noted, formal regime participation represents a commitment to nonproliferation that typically entails enhanced detection and enforcement mechanisms (Enia, 2020; Koch, 2019; Kroenig, 2009). Thus, states who formally participate in more multilateral regimes should be less frequently observed in the dual-use proliferation network.

Hypothesis 4 (multilateral regime membership): As a state's number of memberships in the four regimes increases (MECR Regime Index score), they should have fewer ties than expected at random

Since trade restrictions are more frequent between states with policy disagreements, dyads with similar domestic political regimes are less likely to impose such barriers. Similar political interests have been shown to increase bilateral dual-use trade (Fuhrmann, 2008; Kroenig, 2009). Directed dyads with fewer export licensing requirements are more likely to have legitimate trade, since it is more efficient than illicit networks that rely on rent-seeking intermediaries (Blanton et al., 2018; Chyzh, 2016).

Hypothesis 5 (political regime similarity): As dyadic political regime similarity increases dyads share, on average, fewer ties than expected at random

As others have identified, geographic proximity remains an important factor in both legitimate and illicit trade networks (Bove & Böhmelt, 2021; Thurner et al., 2019). I expect dyads that are more geographically close will have higher observations of illicit transactions due to reduced logistical complexities and potentially fewer risks of detection from various trade enforcement authorities.

Hypothesis 6 (geographic proximity): As geographic distance between capitals increases, dyads share, on average, fewer ties than expected at random

Statistical Models

I estimate two models for the dual-use network using the Count ERGM made available in the *ergm.count* package in R statistical software (Krivitsky et al., 2024). Model 1 consists of the above network, nodal, and edge attributes.

Model 2 mirrors the first model, but with one difference; the second model splits the effect of the MECR Index into two components: the likelihood of receiving a tie (in-degree) and the likelihood of sending a tie (out-degree). Splitting the MECR Index effect this way allows a better probe into the effects of regime membership. It's possible MECR membership affects the likelihood of sending illicit dual-use goods is different from the likelihood of receiving them. I also compare both models to a null ERGM model in order to provide a baseline for validation; null models are ERGMs that consist of just an edge term which counts the number of edges within a network. Without other explanatory variables, the null model reflects the probability of forming a tie based on the number of nodes and edges within a network.

Reviewing model diagnostics, I find no evidence of multicollinearity or degeneracy issues. Using the *ergMargins* package, I find the highest variance inflation factor (VIF) in either model is below 3.2 (Duxbury, 2024). Regarding MCMC diagnostics, both models converge at stationary distributions. Neither model suffers from degeneracy problems that would indicate the simulated networks are either full (every node is connected to every other node) or empty (no connections between nodes).[36]

Model Results

The models' results are displayed in Table 7 below. In ERGM models, the coefficient indicates the effect of the covariate on the likelihood of a tie forming between two nodes. The outdegree effects reflect strong support for our first hypothesis that a small number of states will account for much of the exports (out-degrees). The negative and statistically significant effect of *Out-Degree* indicates that the observed network has fewer out-degrees than would expected at random. This suggests that the observed network, outdegree distribution are heavily skewed due to the majority of observations involving a relatively exporting states.

Surprisingly, both models support that *global economic integration* has a statistically significant and negative effect on the likelihood of forming a tie. These results refute Hypothesis 2, which expected higher degrees of economic integration to lead to involvement in illicit dual-use trade. This suggests that states with more globally integrated economies are less likely to serve as either conduits or end destinations for illicit dual-use trade. It's possible that states with higher

[36] Appendix B provides more details and MCMC diagnostic plots of both models. There were no degenerate models, suggesting correct model specification.

global economic integration also have more robust detection systems devoted to scrutinizing international trade, such as automated risk-assessment software and well-resourced Customs authorities. These enhanced detection systems could result in stronger enforcement capabilities that create less attractive conduits for proliferators.

Model 1 and Model 2 result in different findings for Hypothesis 3 (national power). The effect did not have a statistically significant effect in the first model, while Model 2 found a positive, statistically significant effect. As a state's national power increases, Model 2 expects an increased likelihood of being involved in an illegal dual-use export.

Hypothesis 4 (multilateral regime membership) found no statistically significant support in Model 1, which included a term for the effect of multilateral regime membership that estimated the effect for both in-degrees (imports) and out-degrees. Model 2 replaces the single, combined term with two different terms. Each term estimates the effect of membership on either in-degrees or out-degrees. Model 2 finds a positive, statistically significant effect of increased regime membership on the likelihood of forming in-degrees. There was no significant effect of regime membership on the likelihood of forming out-degrees. This suggests that as a state becomes a member of more multilateral export control regimes, its likelihood of receiving an illicit transaction increases. This finding is likely driven by the conduit states that received illegal shipments, but who were also often members of multiple regimes.

Neither model found support for Hypothesis 5. Political similarity had no statistically significant effect on an illicit dual-use transaction between a given dyad.

Both models support Hypothesis 6, finding evidence that geographic proximity has a statistically significant and negative effect on observing illegal dual-use trade between two states. As the distance between capitals increases, there is a decreasing likelihood of either country sending an illegal export to the other.

Lastly, the AIC (Akaike information criterion) and Bayesian information criterion (BIC) for Model 1 and Model 2 are both lower than the null model's values. Therefore, each model does a better job than assigning ties at random. Between the two models, Model 1 has a higher AIC than Model 2 but a lower BIC. This is likely driven by Model 2's additional covariate, which is penalized more heavily in BIC calculation.

	Null Model	Model 1 (Base Model)	Model 2 (Directed MECR Model)
edges	-3.808***	-1.643***	-1.813***
	(0.069)	(0.458)	(0.456)
Out-Degree		-4.803***	-4.773***
		(0.244)	(0.246)
Economic Globalization		-0.012***	-0.012***
		(0.003)	(0.003)
National Power		1.521	1.743*
		(0.779)	(0.801)
MECR Membership Index		0.025	
		(0.023)	
GDP per capita (ln)		0.063	0.068*
		(0.033)	(0.033)
Regime Similarity		0.002	0.000
		(0.008)	(0.007)
Capital Distance		-0.048*	-0.050**
		(0.019)	(0.019)
MECR Membership Index (In-Degree)			0.153***
			(0.042)
MECR Membership Index (Out-Degree)			-0.001
			(0.025)
Num.Obs.	9900	9900	9900
AIC	2074.0	1560.5	1550.3
BIC	2081.2	1618.1	1615.1

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 7: Model 1 (Base Model) and Model 2 (Directed MECR Effect Model) results.

Conclusion

Scholars and policymakers have long hypothesized on what drives dual-use proliferation, but were stymied by a lack of quantitative data. Until now, research has relied on qualitative case study analysis and theoretical work. By using the SEV data and ERGM modeling technique, I find evidence that exporting states are not randomly distributed throughout the network. The significance of *out*-degree effects reflect a small number of states serve as the primary conduit for illicit re-exports of US-origin, dual-use goods. Future qualitative studies could focus on the predominant conduit states within the observed network (e.g., the UAE and Netherlands). Given the conduits' heterogenous nature, a more thorough understanding of the mechanisms that led to these states serving as conduits could enhance future quantitative modeling efforts.

The effects of multilateral regime membership were mixed between models. The second model's more sophisticated modeling terms suggest that as a state joins more multilateral export control regimes, it is more likely to receive illicit dual-use goods. This results is likely driven by certain conduits' participation in the regimes, which typically reduces government scrutiny. Curiously, the effect of regime membership on sending illicit exports is not significant. It appears regime membership has no discernible effect on the likelihood of a particular state to be the origin point for illicit dual-use trade. Scholars and policymakers would likely benefit from future studies investigating the mechanisms explaining how multilateral regime membership affects illicit exports.

This paper represents the first use of a count ERGM model applied to nonproliferation scholarship, establishing a starting point for future refinements. The use of illicit transactions as

the dependent variable demonstrates ERGMs utility in other research interested in other types of "hidden populations" across multiple international affairs fields, such as human trafficking or arms trafficking. ERGMs have already been used in measures of the legitimate arms trade, but not yet on illicit arms transfers. The SEV data's military observations were omitted from this study but could be used in future papers to investigate drivers explaining illicit arms trade networks. This use of the newly created SEV data may encourage other scholars to find alternative measurements of illicit activity and expand the possible research designs to explore new opportunities.

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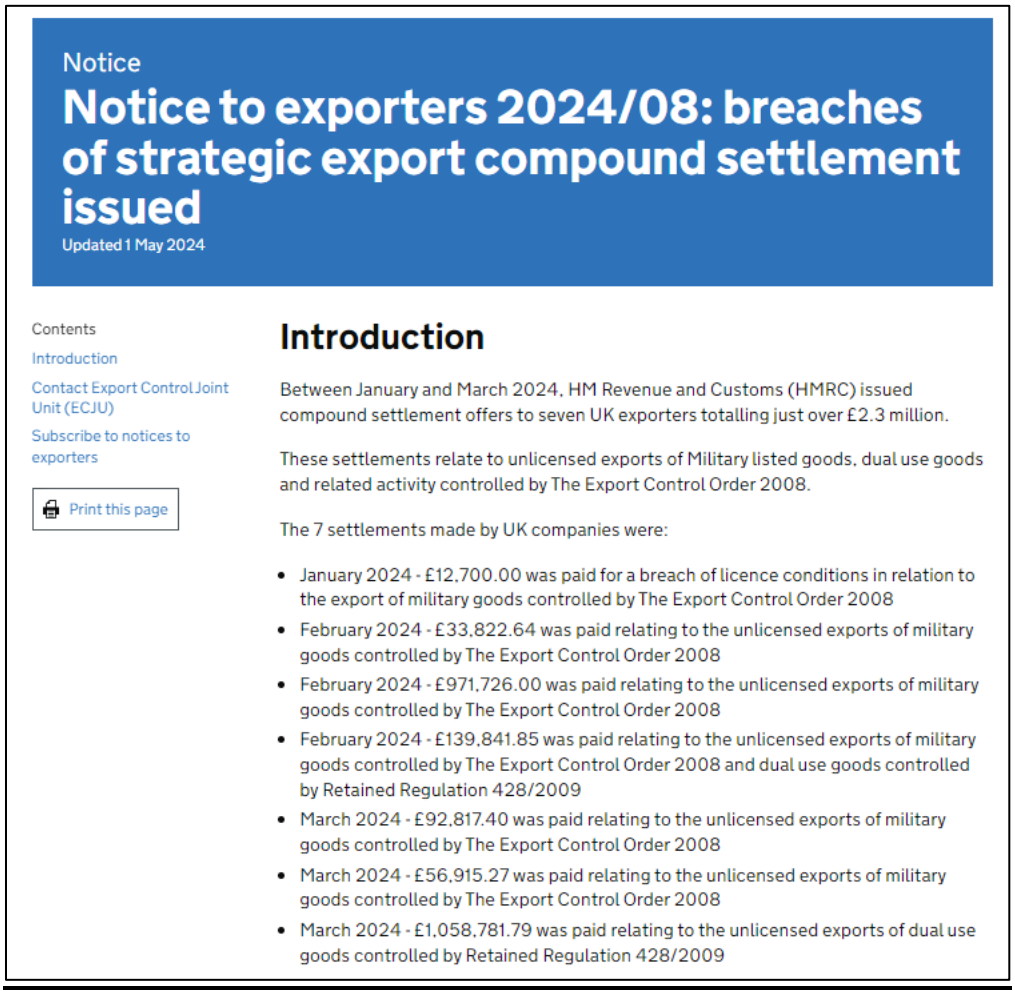
APPENDICES

Appendix A: Example of Insufficient Export Violation Details



Notice

Notice to exporters 2024/08: breaches of strategic export compound settlement issued

Updated 1 May 2024

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Introduction

Between January and March 2024, HM Revenue and Customs (HMRC) issued compound settlement offers to seven UK exporters totalling just over £2.3 million.

These settlements relate to unlicensed exports of Military listed goods, dual use goods and related activity controlled by The Export Control Order 2008.

The 7 settlements made by UK companies were:

- January 2024 - £12,700.00 was paid for a breach of licence conditions in relation to the export of military goods controlled by The Export Control Order 2008
- February 2024 - £33,822.64 was paid relating to the unlicensed exports of military goods controlled by The Export Control Order 2008
- February 2024 - £971,726.00 was paid relating to the unlicensed exports of military goods controlled by The Export Control Order 2008
- February 2024 - £139,841.85 was paid relating to the unlicensed exports of military goods controlled by The Export Control Order 2008 and dual use goods controlled by Retained Regulation 428/2009
- March 2024 - £92,817.40 was paid relating to the unlicensed exports of military goods controlled by The Export Control Order 2008
- March 2024 - £56,915.27 was paid relating to the unlicensed exports of military goods controlled by The Export Control Order 2008
- March 2024 - £1,058,781.79 was paid relating to the unlicensed exports of dual use goods controlled by Retained Regulation 428/2009

Figure 32: Example of the United Kingdom's Export Control Joint Unit published note of settled export violations. The note discloses the financial penalties and related regulations but does not include additional information that would enable a better understanding of global proliferation patterns.

Appendix B: Model Diagnostics

Model 1 MCMC Diagnostics:

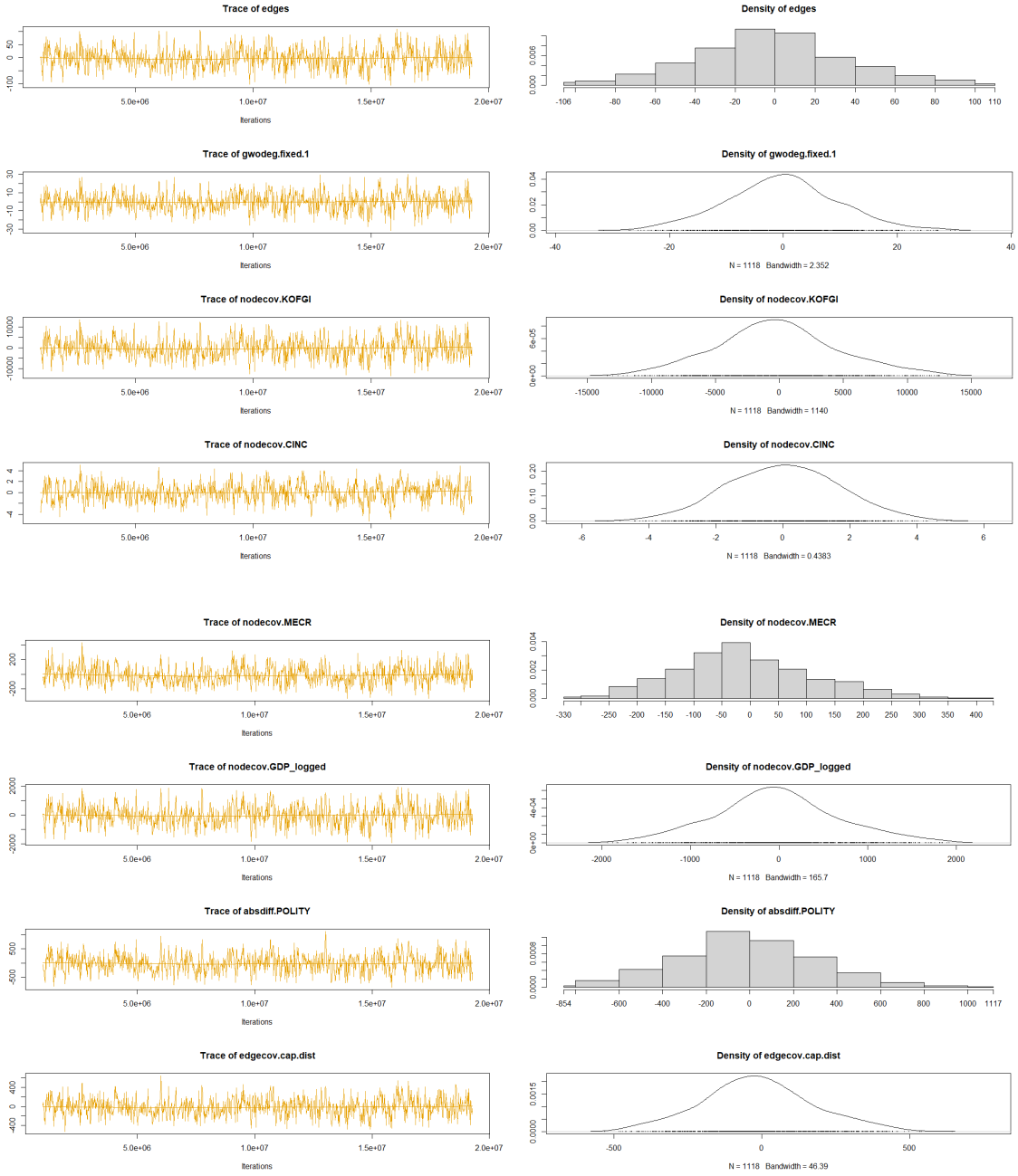

Figure 33: Markov Chain Monte Carlo diagnostic plots for Model 1 (Base Model). The trace plots for all covariates appear well, avoiding any flat portions or prolonged periods of time on the positive or negative sides of the y axis.

Model 2 MCMC Diagnostics:

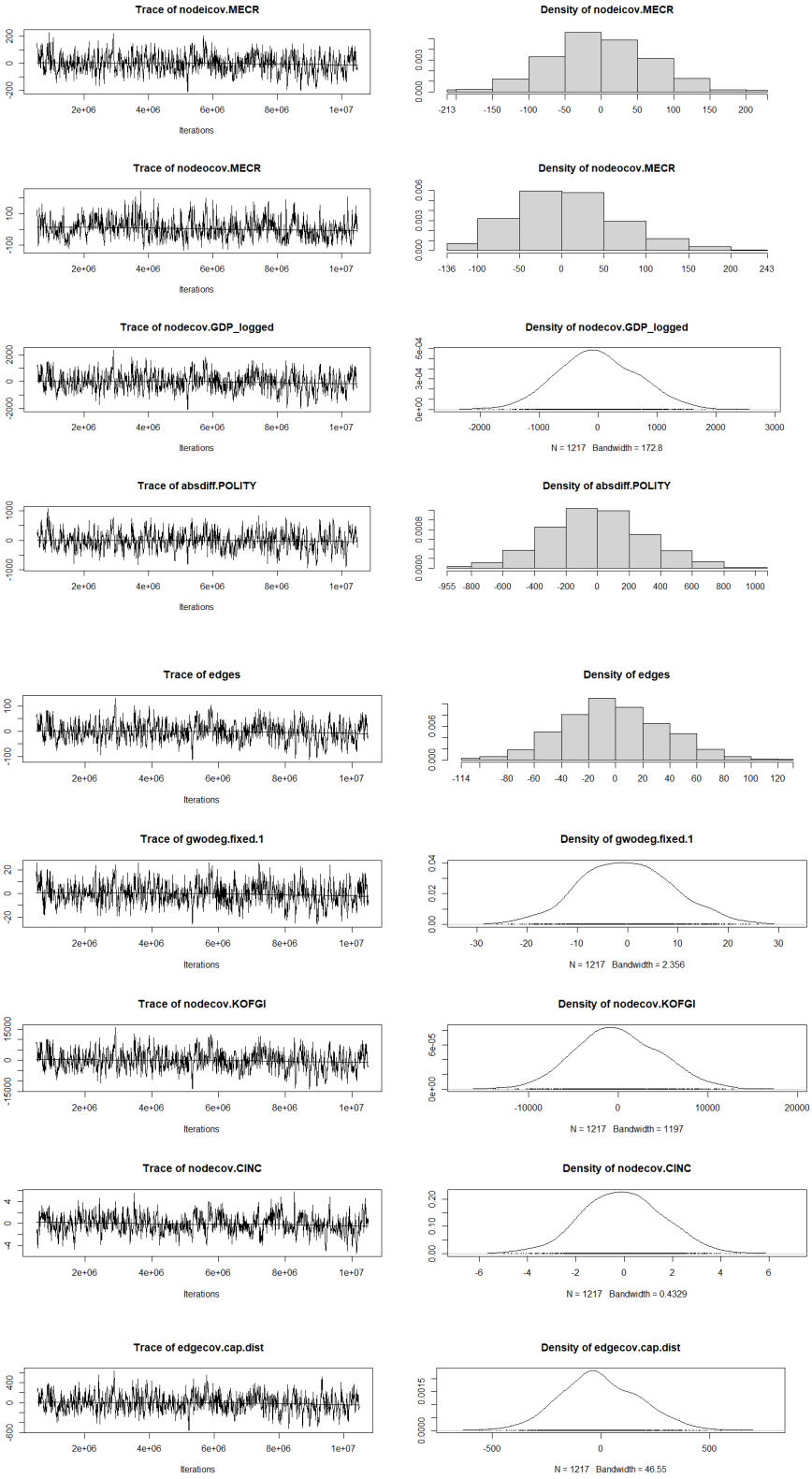

Figure 34: Markov Chain Monte Carlo diagnostic plots for Model 2 (Directed Regime Effect Model). The trace plots for all covariates appear well, avoiding any flat portions or prolonged periods of time on the positive or negative sides of the y axis.