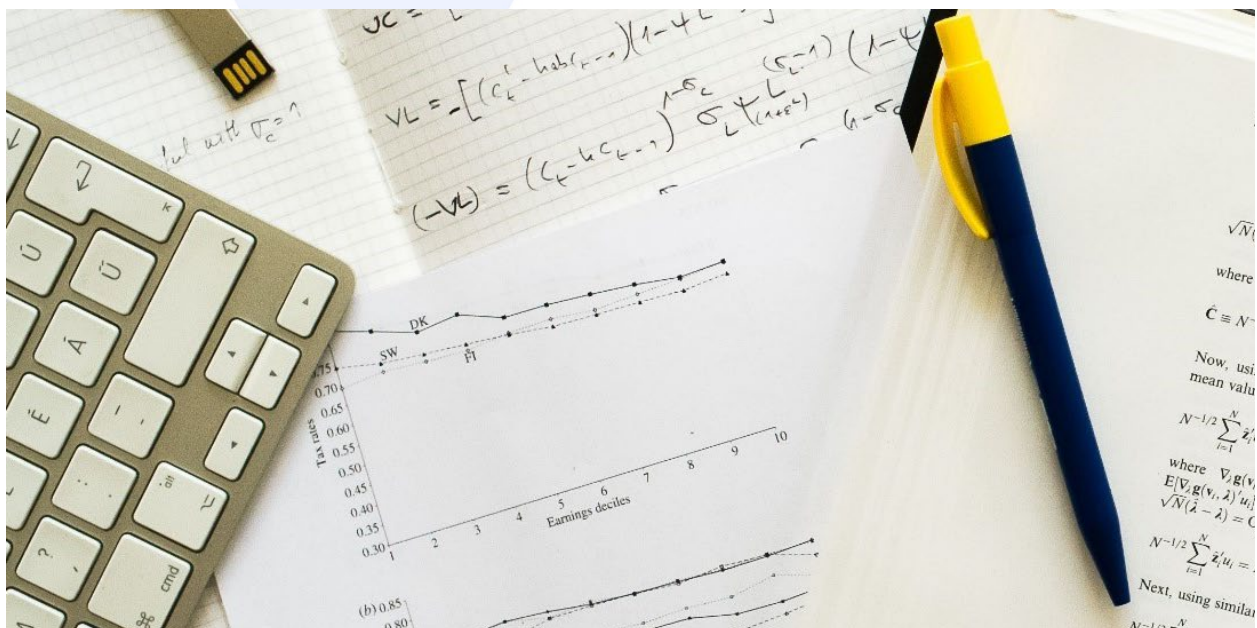


Throwing sand in the chips: unintended effects of export controls

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Abstract

Export controls play a prominent role in the ongoing technological race between the United States and China. This study investigates the short-term direct effects of US export controls on US exports as well as the indirect effects of these measures on the exports of third countries. We collect data on unilateral US measures targeting all exports to China of specific products in the semiconductor production chain, and merge it with monthly trade data on exports of the same products from countries participating to the production chain. First, we find a negative direct effect on US exports of chips. Second, results show positive, significant, effects on the exports of equipment for the manufacturing of semiconductors from the EU, Japan, and Singapore. This evidence is not only suggestive of a limited indirect enforcement of US policies on foreign jurisdictions, but also of the unintended effects such a unilateral policy can trigger.

Keywords: Export Controls, Semiconductors, Trade Policy.

JEL Codes: F14, F13, L52.

1 Introduction

Trade policy has once again captured the spotlight as governments of the major economies strive to safeguard their economic security (Fajgelbaum and Khandelwal, 2022; Amiti et al., 2019). In addition to subsidies and domestic support programs, governments are increasingly turning to trade measures as complementary instruments of industrial policy, with the aim of redefining the global landscape of strategic production chains (Goldberg et al., 2024). Within the ongoing technological rivalry between the United States and China, export controls have emerged as one of the most significant non-tariff trade-policy tools (Bown and Wang, 2024).

These measures restrict, and in some cases prohibit, the transfer of sensitive technologies and materials to protect national security interests.¹ The United States' Export Control Reform Act of August 2018 marked the beginning of a new phase in the use of export control measures. Since then, a series of unilateral measures have targeted products within the semiconductor production chain, bypassing the multilateral framework of the Wassenaar Arrangement on dual-use items.² Despite their growing relevance, we have limited empirical evidence on how unilateral export controls affect trade flows — both for directly targeted products and for countries indirectly exposed through global production chains.

This paper investigates the causal short-term effects of the unilateral tightening in US export controls targeting China on both US exports and the exports of third jurisdictions operating in the semiconductor production chain. The semiconductor industry offers a particularly salient setting to study these effects. As of December 2024, the combined market capitalization of the ten largest global chip producers exceeded USD 6.5 trillion³, reflecting the central role of this industry in advanced economies. Yet, this production chain is highly fragmented across the globe; no single country holds leadership positions across all segments of the chain, creating strong inter-dependencies between countries (Ciani and Nardo, 2022). We consider four waves of US export controls measures introducing additional restrictions to *all* export flows of specific semiconductors and semiconductor-related products directed to China between 2020 and 2023.⁴

Our findings show that US exports of chips decrease after the introduction of export controls, while there are sizable, heterogeneous, adjustments across third countries and segments of the production chain. In particular, results show positive causal effects of unilateral US export control measures on the exports of equipment for the manufacturing of semiconductors from third jurisdictions. This evidence is suggestive of the unintended indirect effects such a unilateral policy can trigger.

US export controls on semiconductors aimed first at restricting the access of Chinese companies to advanced chips with applications in space and defense, and later to the equipment needed to manufacture such chips.⁵ These measures did not target legacy (mature) chips⁶, which are widely used in a set

¹ The list of products targeted by controls and the affected jurisdictions made publicly available when updated; exporting companies apply for a license to export products subject to the measures to the targeted jurisdictions, the administration implementing the export control measure may grant or not the permit to export.

² Since 1996, the Wassenaar Arrangement regulates trade flows of specific items, including some categories of semiconductors, which can have both civil and military applications.

³ Refer to this [Report](#).

⁴ The first wave of US measures targeting Huawei mostly affected specific Chinese entities rather than all export transactions with China. The aim of this study is to look at restrictions targeting *all shipments* to Chinese importers of specific products.

⁵ Details on the different policy waves are included below. Advanced chips can be broadly defined as those in the ultra-small node size (i.e. below 7 nanometers) or in the high-power, high-frequency domain. These chips are crucial for power computing, AI applications, as well as encrypted communication.

⁶ Legacy chips, often called mature-node or foundational chips, are older semiconductor technologies, generally produced with 28-nanometer (nm) nodes or larger, according to the Semiconductor Industry Association (SIA). Node sizes in the range 7–28 nanometers are considered “mainstream”.

of downstream industries such as automotive, aerospace, industrial automation, and consumer electronics. Consequently, the production of these non-sensitive, high-demand semiconductors remains largely outside the scope of these restrictions. In the meanwhile, China was pursuing its industrial policy strategy, promoting an increase in the production of chips for the domestic market, and incentivizing the manufacture of advanced chips in mainland China. The National Integrated Circuit plan and the Made in China 2025 initiative were the most visible industrial-policy actions channeling sizable public resources into the industry.

While US export controls are expected to directly reduce exports of advanced chips from US firms to China, the effect on US exports of manufacturing equipment is not clear-cut, and their impact on exports to China from other countries integrated into the semiconductor value chain is also ambiguous. These measures can generate both intended and unintended effects on third-country exports through distinct mechanisms. The intended effects operate through the Foreign Direct Product Rule (FDPR) and the *de minimis* rule, which extend the reach of US export controls beyond the national jurisdiction. Non-US firms that incorporate US technology, components, or know-how into their production processes must comply with these regulations, potentially constraining their own exports to China. To make these restrictions more binding, the US administration may also lobby for its allies to introduce similar export controls on their domestic companies.⁷ These channels imply a negative effect of US export controls on third-country trade. The unintended effects might work in the opposite direction. Trade restrictions on US exports may prompt adjustments of trade flows along the global production network. Chinese firms might increase imports from alternative suppliers to continue obtaining products needed to pursue their industrial-policy goals. Given the opposing forces of these mechanisms, which cannot be separately disentangled, the net effect of US export controls on third-country exports is ultimately an empirical question. Such an assessment requires granular trade data and a disaggregated analysis along the different segments of the semiconductor production chain.

To empirically investigate the short-term net effect of US export controls, we compile a novel dataset combining detailed information on policy measures targeting China with high-frequency trade data along the production chain. Monthly bilateral export data from January 2017 to August 2024 are obtained from UN Comtrade for key economies, namely the United States (US), the European Union (EU), Taiwan, Japan, Malaysia, Singapore, and South Korea. We focus on 32 HS 6-digit product codes representative of different stages of the production chain.⁸ Information on the timing and scope of US export control measures is drawn from the Global Trade Alert (GTA) database, which allows to match specific unilateral policy actions targeting China to affected semiconductor-related products.⁹

We identify four main waves of US export control interventions. The first, issued by the Bureau of Industry and Security (BIS) in June 2020, restricted exports of high-tech goods for military end-use to China, Russia, and Venezuela, broadening licensing requirements for integrated circuits. In August 2022, the United States imposed additional controls on AI-related chips — particularly affecting Nvidia's exports to China and Russia — to prevent potential military applications. The third wave, in October 2022, introduced new export controls on advanced computing and semiconductor manufacturing equipment and expanded the Export Administration Regulations (EAR), extending the Foreign Direct Product Rule (FDPR) and requiring US persons engaged in certain semiconductor activities to obtain export licenses. Finally, in November 2023, the BIS further tightened restrictions on advanced semiconductors, manufacturing equipment, and

⁷ During 2023, in agreement with the US administration, the Japanese and the Dutch governments introduced controls on the export of specific equipment for the manufacturing of semiconductors. Refer to the [column](#).

⁸ In their studies on the EU semiconductor value chain, ([Ciani and Nardo, 2022](#)) and ([Bonnet and Ciani, 2023](#)) provide a list of trade codes at the HS-6-digit level related to the different types of chips, as well as to manufacturing equipment, wafers, raw materials, and other inputs.

⁹ Refer to [GTA website](#) for detailed information.

supercomputing technologies, while extending licensing requirements to additional equipment and software.

To estimate the impact of these measures on trade flows, we rely on a difference-in-differences setup. Separate regressions are estimated for US exports (to capture *direct effects*) and for third countries (to capture *indirect effects*). The high-dimensionality of our dataset allows us to include a rich set of fixed effects to control for unobserved heterogeneity: origin–destination–month effects absorb time-varying bilateral shocks; origin–destination–product effects capture product-specific bilateral factors constant over time; and origin–product–month effects account for supply-side conditions varying by exporter, product, and time. To study both the intensive and extensive margins of trade, we estimate specifications using the Poisson pseudo-maximum likelihood (PPML) estimator on different dependent variables. The sequential nature of policy implementation leads us to apply a staggered difference-in-differences design, comparing changes in exports of products affected by US controls with unaffected product–destination pairs.¹⁰

Our results indicate that US export controls effectively reduced US exports of chips to China, leading to a 21% reduction over the period under investigation and therefore reaching the objective of the policy. By contrast, the analysis does not find any (statistically) significant effects on US exports of equipment. However, the evidence points to indirect effects for the third jurisdictions, which experienced an average increase in equipment export of 66.2%, corresponding roughly to an 11.45 Bn USD increase compared to the pre-policy annual average. These findings suggest that China adjusted its import strategy in response to possible tighter restrictions. This reaction reflects its strong reliance on foreign equipment, which is a segment of the supply chain where China has not yet obtained a technological leadership as opposed to the EU, the US, and Japan (Bown and Wang, 2024).¹¹ Heterogeneity in these effects is substantial: EU and Japanese exports of equipment to China increase by 139 percent and 65 percent, respectively. Notably, Taiwan is the only third country exhibiting a contraction in exports of chips and equipment following US measures, reflecting its deep integration with the US semiconductor ecosystem. We also find modest but positive effects on third-country chip exports at the extensive margin, indicating partial substitution away from US suppliers. To benchmark the magnitude of export controls, we translate estimated effects into export-tax equivalents (ETEs) and results show that the reduction in US semiconductor exports is economically comparable to a moderate ad-valorem export tax of roughly 4–7%, while the increase in export of equipment for third countries is akin to an export subsidy between 4% and 13%.

When we distinguish across policy waves, our estimates show that these effects are primarily driven by the most recent measures, i.e. those introduced in October 2022 and November 2023. In particular, the October 2022 measures are associated with a 28 percent increase in equipment exports, while the November 2023 measures correspond to a considerably larger increase of 74.2 percent. Looking at effects over time, the positive effect on equipment exports from third countries becomes evident after approximately eight months and remains persistent thereafter. In contrast, third-country exports of chips initially rise but turn negative after a similar lag, consistent with a temporary sizable adjustment of Chinese imports.¹² We also provide evidence on the Chinese market using data on production, aggregate imports and exports to check what happened in China in the period under consideration. If anything, production capacity expanded, likely supported by long-planned industrial-policy strategies. In addition, we

¹⁰ We use the estimator proposed by (Nagengast and Yotov, 2025), which accounts for heterogeneous treatment effects in a PPML setting with high-dimensional fixed effects which builds on the Wooldridge estimator.

¹¹ The interested reader can refer to this [column](#), which appeared on the Financial Times in August, 2023.

¹² This change in the sign of the staggered coefficients is consistent with the non-significant average effect on chips' exports of third countries found in the PPML specifications.

run several robustness checks, that confirm the validity of our baseline results when extending the sample to all products and other affected jurisdictions, and testing for potential re-routing of trade flows.

Overall, our results highlight that unilateral trade measures such as US export controls can generate unintended effects on third countries, shaping trade patterns well beyond their intended targets. This suggests that multilateral coordination may be a more effective approach for achieving economic security and industrial objectives in complex, globally integrated, production networks such as the semiconductor value chain.

1.1 Contribution to the literature

This paper contributes to several strands of literature. First, it is broadly related to the extensive literature examining the effects of protectionist measures on trade flows, with a focus on the US–China trade war (Fajgelbaum and Khandelwal, 2022; Amiti et al., 2019). This body of work primarily studies the impact of *import* tariffs on trade and welfare. We contribute by shifting the focus to *export* restrictions — a policy instrument that has gained significant relevance over the last decade but remains underexplored empirically — and by quantifying both the direct and indirect effects of these measures on trade flows of targeted products across the semiconductor production chain. By translating our estimates into export-tax equivalents, we provide a quantitative bridge between the stream of research on tariff-based and the one on non-tariff trade policy.¹³ Recent studies investigate the trade effects of economic sanctions (Afesorgbor, 2019), with an emphasis on trade restrictions imposed on Iran in 2010, (Haidar, 2017) and Russia in 2014 (Crozet and Hinz, 2020), finding that trade deflection attenuates the negative effects on the sanctioned country. Our study brings evidence related to this literature, as it focuses on the short-term effects of a unilateral measure restricting trade to targeted countries, such as export controls. Our findings confirm that miscoordination in policy implementation can lead to indirect effects on third countries' exports that were likely unintended by the government implementing the policy.

Second, our empirical results contribute to the recent body of work on the effects of non-tariff policy tools — and in particular export controls — on trade flows. Ando et al. (2024) analyze the effect of US export controls on Japanese exports to China, focusing on the entry of Huawei into the US Entity List. Their findings show that exports of high-end semiconductors from Japan to China decreased significantly after the introduction of the restriction. Crosignani et al. (2026) show that, once Chinese customers of US companies are subject to export controls, US suppliers are more likely to terminate relations with them; however, Chinese firms reconfigure their production chains, while US companies report negative effects on profitability, market capitalization, and employment. Relatedly, anwarexport find that targeted Chinese companies reliant on US imports experience positive effects on innovation, while US suppliers of targeted products see negative effects on innovation. Our paper provides the first comprehensive cross-country assessment of how general export controls — rather than entity-specific measures — reshape trade flows across distinct segments of the semiconductor value chain.

Lastly, our study speaks to the literature on the economics of the semiconductor industry and the role of trade and industrial policy in shaping its evolution. Early contributions documented how trade policies — including tariffs and voluntary export restraints — have historically been used to alter competitive dynamics in this sector (Irwin, 1996). More recently, Bown (2020) traces the escalation of US trade policy toward China's semiconductor sector, while Bown and Wang (2024) provide a comprehensive account of how modern industrial policy is reshaping the global semiconductor landscape through a combination

¹³ Several studies investigate the effects of political tensions involving China, including (Fuchs and Klann, 2013), and (Heilmann, 2016) which focuses on the effects of consumer boycotts. (Du et al., 2017)) find that political shocks involving the two largest global economies have a short lived effect on trade flows between China and the US.

of subsidies, trade restrictions, and strategic investments. [Goldberg et al. \(2024\)](#) offer a broader analytical framework for industrial policy in the semiconductor sector, examining how governments balance efficiency and security considerations. On the theoretical side, a nascent literature in geoeconomics formalizes the strategic rationale for such policies. [Clayton et al. \(2024\)](#) argues that export controls may be optimal for the hegemonic country even if they destroy value for domestic firms, while [Liu et al. \(2024\)](#) employs a calibrated model with technology transfers to show that comprehensive restrictions on semiconductors could raise domestic welfare. We contribute to this literature by providing causal evidence on how unilateral export controls — a specific and increasingly prominent policy tool — reshape trade flows across the semiconductor production chain, documenting both intended direct effects and unintended indirect effects on third countries that prior work has largely discussed qualitatively or modeled without quantifying.

This manuscript unfolds as follows. In section 2, we describe the policy context and the database; section 3 illustrates the empirical strategy. Estimation results are reported in section 4. Section 5 discusses adjustments in the Chinese market, while robustness checks are reported in section 6. Section 7 concludes.

2 Background and Data

2.1 Background on US Export Control Policies

Before the recent wave of export controls issued, trade flows of strategically sensitive items were regulated by multilateral agreements. These agreements had the objective to limit exports of items that could be employed both in civil and military applications (i.e. dual use items), which included, among others, products from the semiconductor supply chain, such as integrated circuits. The Wassenaar Arrangement has been the first of these voluntary, multilateral export control regimes. Established in 1996, it “contributes to regional and international security and stability by promoting transparency and greater responsibility among participating states, which coordinate their national policies to ensure certain technologies are not transferred or otherwise diverted to countries that undermine these goals.”¹⁴

In recent years, the effectiveness of such multilateral arrangements has weakened, due in part to geopolitical tensions and difficulties in reaching consensus. This has led to a growing reliance on unilateral export controls by single countries, particularly in relation to emerging and advanced technologies, marking a gradual shift away from multilateralism toward more nationally driven approaches. Notably, the United States have adopted a particularly assertive unilateral strategy which included four major waves of unilateral export controls targeting China’s semiconductor sector between 2020 and 2023. The main objective moved from national security considerations to economic and geopolitical motivations in the context of the technological race between the US and China. Preventing the use of the most advanced products was meant to slow down the Chinese technological advancement.¹⁵

The first episode of unilateral tightening of export controls on trade flows of specific products by the US administration took place in June 2020, when the Bureau of Industry and Security (BIS) imposed new restrictions on high-technology goods — particularly integrated circuits — destined for military end-use in China, Russia, and Venezuela. The measure expanded licensing requirements, broadened the definition of military end-use, and extended the list of controlled items, targeting exports to *all* entities operating in the three countries. In August 2022, new controls targeted high-performance AI chips (particularly Nvidia’s A100 and H100) exported to China, Hong Kong, and Russia, establishing performance thresholds that would automatically subject future chips of similar capability to the same licensing requirements. Controls extended to technologies used to develop or enhance these chips.

Later, in October 2022, the BIS issued comprehensive restrictions on advanced computing chips and semiconductor manufacturing equipment. This measure leveraged US leadership in production equipment to create supply chain choke-points, expanded the Foreign Direct Product Rule (FDPR) to cover foreign-produced items, and prohibited US persons from supporting the development of specific advanced integrated circuits in China without a license. A temporary general license permitted continued manufacturing in China of certain products destined for non-Chinese markets. Last, in November 2023, the BIS introduced an additional tightening of restrictions on advanced semiconductors, semiconductor manufacturing

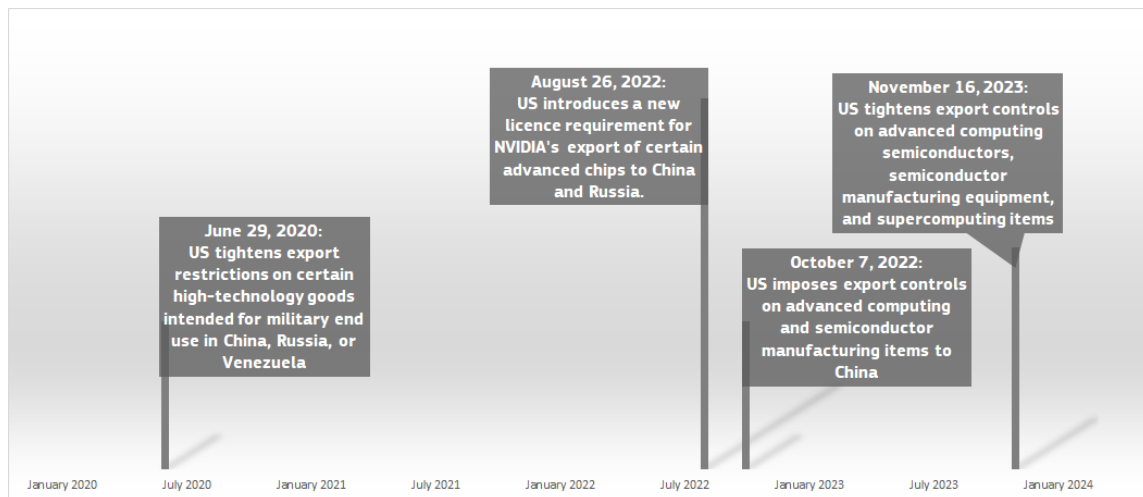
¹⁴ 42 countries, spanning over six continents, participate to the Wassenaar Arrangement: Argentina, Australia, Austria, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, India (since 2017), Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Republic of Korea, Romania, Russian Federation, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Türkiye, Ukraine, United Kingdom and United States. In addition to the participating countries, the Wassenaar Arrangement also has associate members that are not full members but participate in the regime’s activities and implement its control lists: Israel, Singapore, Taiwan. The Wassenaar Arrangement also has guest countries that participate in its meetings and activities but are not full members or associate members: Brazil, Chile, China, Egypt, Indonesia, Kazakhstan, Malaysia, Pakistan, Philippines, Saudi Arabia, Thailand, United Arab Emirates. Check this [link](#) for more details.

¹⁵ The interested reader can refer to this [column](#).

equipment, and supercomputing items. A key goal was to further restrict China’s capability to produce advanced chips with potential military, artificial-intelligence, or high-performance computing applications.¹⁶ Key additions included controls on high-bandwidth memory (HBM) chips, the addition of approximately 140 Chinese firms to the Entity List, and regulatory refinements to strengthen enforcement of existing controls.

Figure 1 reports the timeline — with the exact implementation date — of the four semiconductor-related policies potentially impacting exports of semiconductors to *all* Chinese entities.

Figure 1: Timeline of Semiconductor-Related US Policies Affecting Exports to All Chinese Companies (with Implementation Dates).



Notes: The timing and description of the US export control policies are derived from the Global Trade Alert (GTA) database.

Source: GTA, analysis by authors.

¹⁶ One of the factors behind this tightening episode has been the announcement by the Chinese company SMIC of being capable of manufacturing advanced semiconductors despite the US export controls.

2.2 Data

We construct a dataset combining monthly bilateral export data with detailed information on US export control policies. Trade data covering seven major semiconductor-producing economies — the United States, European Union, Japan, Malaysia, Singapore, South Korea, and Taiwan — from January 2017 to August 2024, is obtained from UN Comtrade.¹⁷ Information on US export control policies comes from the Global Trade Alert (GTA) database,¹⁸ which systematically tracks information on unilateral state interventions likely to affect international trade, such as subsidies, export-related measures, tariffs, or protective measures, since 2008. Each GTA entry records the policy timing (announcement, publication, and implementation dates), implementing and affected jurisdictions, intervention type, and affected products at the HS 6-digit level, with links to official documentation. We select policies meeting three criteria: (i) classified as “Export bans” or “Export Licensing Requirements” under UN MAST Chapter P3,¹⁹ (ii) implemented by the United States with China as an affected destination, and (iii) targeting at least one semiconductor-related product.

We use the implementation date to define policy timing, assigning events to the nearest full month (using the 15th as cutoff). This process originally identifies approximately 25 semiconductor-related export control policies implemented by the US and affecting exports to China of semiconductors or of technology related to semiconductors. However, we distinguish between policies mandating the addition of foreign companies to the US Commerce Department Entity List (*firm-specific policies*) and policies potentially affecting all foreign companies (*general policies*). General interventions in principle affect all exports to an affected destination, e.g. China, while firm-specific policies only affect exports to the blacklisted companies listed in the Entity List. We do not include the latter in our analysis. While export controls targeting exports to Huawei would not be part of this study, the restriction of all exports of NVIDIA chips to China and Russia would. We identify semiconductor-related products using the classifications from (Bonnet and Ciani, 2023) and (Bonnet et al., 2025), which map HS codes at 6-digit level to specific segments of the semiconductor value chain.²⁰ Our analysis focuses on three segments: semiconductor manufacturing equipment, wafers, and final products — analog, discrete, logic, micro chips, and memories.

¹⁷ Data on the European Union refer to the Union of 27 member states. Monthly data for Taiwan are available through a specific agreement between Eurostat and the Taiwan Customs Office. Interestingly, Taiwan exports in this database account for 98.9% of exports recorded under “Other Asia” in standard UN Comtrade. Due to data publications constraints, we have shorter time series for Singapore (up to March 2024), Korea (December 2023), and Taiwan (June 2024). China includes Hong Kong and Macao.

¹⁸ Available [here](#).

¹⁹ The UN Mast Chapter P3 overall includes export licenses, export quotas, export prohibitions and other restrictions other than sanitary and phyto-sanitary or technical barriers to trade. Export bans prohibit exports of certain products, while export licensing requirements mandate government approval before exporting. These correspond to UNCTAD MAST classifications P31 and P33, respectively. More details can be found [here](#).

²⁰ Chips and integrated circuits are primarily under HS headings 8541–8542; manufacturing equipment under 8486; wafers and chemical inputs under 3818, 3824. Some specialized equipment (e.g., optical inspection) appears under headings 9011, 9030–9031.

This yields 32 HS 6-digit product codes in the semiconductor production chain (see Appendix A for the list of product codes and related descriptions).²¹

2.2.1 Descriptive Statistics

To motivate our empirical approach and provide context for our empirical investigation, we first describe the structure of our sample, the scope of US export control measures across product segments, and the geographic distribution of semiconductor trade.

Table 1 summarizes the export structure of semiconductor-related products across the seven economies in our sample. Countries in our sample export an average of 22 products to 107 destinations. China, together with the US and the EU, are the geographical entities exporting the largest amount of products to the highest number of destinations (23–24 products reaching 128–137 destinations), while Malaysia shows the narrowest footprint (19 products to 58 destinations). Taiwan and South Korea seem to have a similar export structure as they export 20 products across 75 and 76 destinations, respectively.

Table 1: Number of exported products and destinations reached by product

	CN	EU	JP	KR	MY	SG	TW	US	Total
N. of 6-digit Products	23	24	20	19	19	21	20	24	22
N. of Destinations	137	135	84	75	58	76	76	128	107

Notes: Summary statistics on the estimation sample for the period January, 2017 – August, 2024.

Source: GTA, analysis by authors.

Table 2 documents the product coverage of each policy wave. The October 2022 and November 2023 measures were broader in scope, affecting 5 equipment codes and 11 chip codes each. Earlier policies targeted fewer products: June 2020 affected only 1 chip code, while August 2022 controlled 5 chip codes. Notably, wafer products remained unrestricted throughout the period.²²

Table 2: Number of products affected by US export controls

Segment of Value Chain	N. of 6-digit Products	N. of 6-digit Products affected by the policy			
		Jun. 2020	Aug. 2022	Oct. 2022	Nov. 2023
Wafers	2	0	0	0	0
Equipment	17	0	0	5	5
Final Products	13	1	5	11	11

Notes: Summary statistics on the estimation sample for the period January, 2017 – August, 2024.

Source: GTA, analysis by authors.

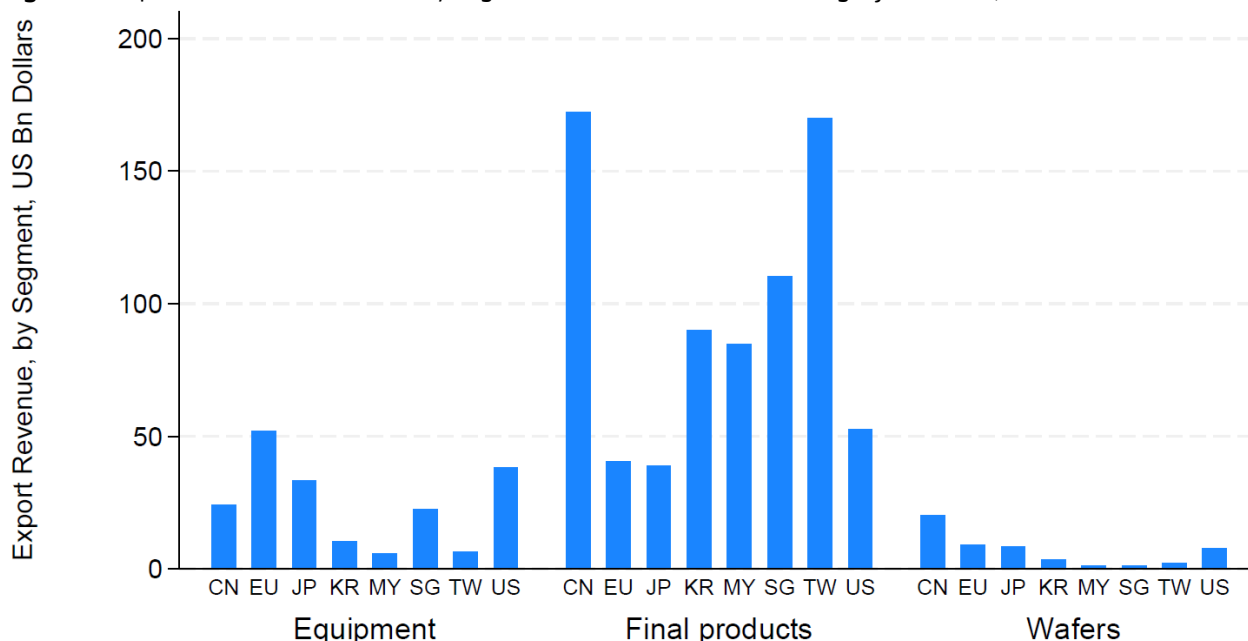
Figure 2 illustrates the geographic distribution of semiconductor exports by value chain segment in 2023. Three patterns emerge confirming the distribution of production stages across the global supply chain of semiconductors. Final products dominate trade flows, with China and Taiwan as leading exporters. China specializes in analog and discrete devices, while Taiwan leads in advanced logic and memory (Ciani and Nardo, 2022). South Korea and Singapore are also major exporters. Equipment exports are concentrated

²¹ In the period under investigation, the US administration did not introduce export control measures directly affecting raw-materials and other inputs for the production of semiconductors. Moreover, these items are traded also along other production chains, thus hampering causal identification of US policies on semiconductors. Please refer to this [website](#) to track export controls on raw materials Worldwide.

²² We include these items in our sample as they are a crucial intermediate product of chips' manufacturing whose trade flows are closely linked to dynamics affecting chips' demand and supply.

in the US, EU, and Japan — economies with strong capital goods manufacturing. China’s equipment exports remain minimal, highlighting its dependence on foreign suppliers. Wafer exports show a different pattern: China leads, followed by the EU, Japan, and US. This reflects the relatively mature and geographically dispersed nature of wafer production.

Figure 2: Export revenue (in Billion \$) by segment of the value chain and origin jurisdiction, 2023.



Notes: Export values for the different segments of the value chains, reported by exporting country.
Source: UN Comtrade, analysis by authors.

2.3 Motivating Evidence

To motivate our econometric analysis, we first present graphical evidence on how semiconductor trade patterns evolved around the introduction of US export controls. In particular, we examine whether export patterns diverged between the United States (the implementing country) and major third-jurisdictions across the two main segments of the semiconductor value chain — manufacturing equipment and chips.

Focusing on exports of equipment to China (Figure 3a), EU exports to China increased sharply beginning in early 2023, following the introduction of the first US export controls affecting the segment in October 2022. In contrast, US exports declined mildly immediately after the controls took effect, recovering only modestly in the second half of 2023 and early 2024. These patterns appear to be China-specific and not synchronized with global trends, as shown in Figure 3c. Indeed, exports of equipment to the rest of the world (excluding China) for both regions began declining in the second half of 2022, interrupting the upward post-pandemic trajectory. A similar increase in equipment exports to China is observed for other key suppliers, such as Japan and Singapore (Figure S1). Figure S3 further shows that suppliers experiencing this acceleration in exports to China — including the EU — also increased their market penetration in China (by around 8% for the EU) in 2023 and 2024, whereas the United States lost market share over the same period.

Turning to chip exports to China (Figure 3b), it is more difficult to identify clear shifts in export flows from the United States and the EU around the introduction of the four US policy measures affecting this segment. Exports of chips from both the EU and the United States to China did not decline following the controls introduced in 2020. Instead, they continued on an upward trajectory until the second half of 2021,

a pattern that is also visible in their exports to the rest of the world (Figure 3d), likely reflecting strong global demand and adjustments in response to the chip shortages that emerged during the Covid-19 pandemic.

Exports from both regions began to decline in the second half of 2021 and continued falling throughout 2022, thus preceding the wave of export controls introduced in the second half of 2022. A recovery becomes visible only in the second half of 2023. Nevertheless, despite this lack of synchronization with policy timing, this decline is not mirrored in exports to the rest of the world, which remained relatively stable over the same period, as shown in Figure 3d. Moreover, the contraction in chip exports to China appears more pronounced for the United States, the country implementing the export controls, and milder for the EU (Figure 3b).

Interestingly, a more pronounced decline in chip exports to China following the controls introduced in the fall of 2022 is observed for Taiwan, a major global semiconductor exporter (Figure S2), which holds a substantially larger market share in China (Figure S4) than the EU and the United States. Indeed, Figure S4 shows a slight decrease in Taiwan's share of the Chinese import market (which accounted for around 38% of China's chip imports in 2024). Overall, however, China's import shares for key suppliers of final products remained relatively stable over the period, in contrast to the pronounced market-share reallocation observed in the equipment segment.

A related question is whether the diverging export patterns observed across major suppliers after the October 2022 and November 2023 export controls translated into net changes in China's overall semiconductor imports, thereby shedding light on domestic market mechanisms. Figure 4 reports year-on-year growth rates of Chinese imports of semiconductor equipment and final products.

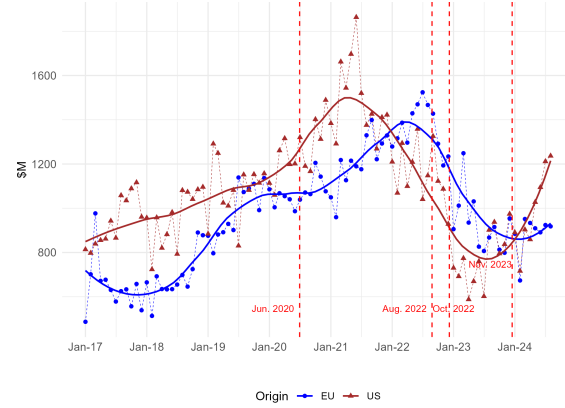
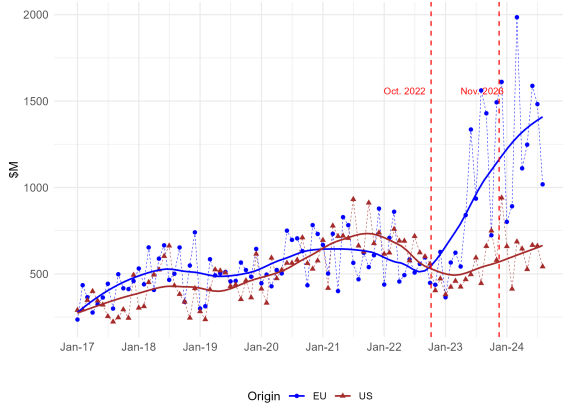
Total Chinese imports of equipment from all partners rose sharply beginning in late 2023 and through the first half of 2024, nearly doubling in December 2023 relative to a year earlier, before easing during 2024. This surge suggests that restrictions coincided with a substantial expansion in Chinese demand for semiconductor manufacturing equipment, rather than merely a reshuffling of suppliers. Combined with the previous evidence on exports to China by key suppliers, this increase in purchases appears to be concentrated among the EU, Japan, and Singapore, to the detriment of the United States.

By contrast, starting in 2023, imports of chips — the final products targeted by the policy — diverged from equipment trends. While the two segments had displayed broadly synchronized dynamics prior to 2022, chip imports declined in 2023 and recovered only modestly in early 2024. These contrasting patterns — strong growth in equipment imports versus weaker dynamics in final products — point to distinct adjustment mechanisms across segments, with the equipment sector exhibiting the most pronounced import expansion during the period of US export controls.

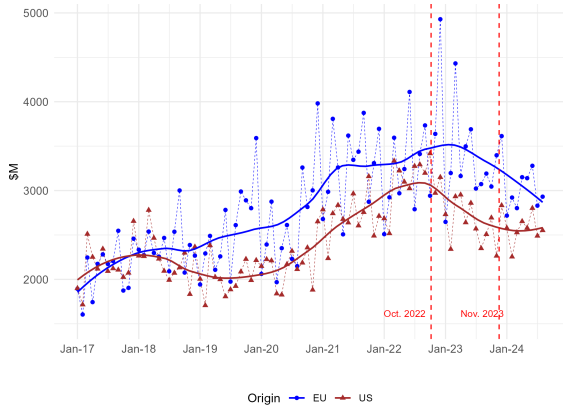
These descriptive patterns reveal key features that motivate our empirical approach. First, US and third-country export patterns to China diverge sharply for equipment after October 2022 — the US remains stable while the EU and other jurisdictions surge. This suggests potential indirect effects of US restrictions on third-country exporters, accelerating purchases of chip-making equipment from suppliers different from the US. Second, equipment and final products show divergent patterns (equipment imports surge while chips' imports decline), suggesting US export controls affected different segments through different mechanisms — possibly reflecting the upstream position of equipment in the value chain and its limited substitutability in the short run.

While suggestive, these descriptive patterns cannot establish causality. The observed trends may reflect demand-side factors (e.g. Chinese industrial policy) or supply-side factors (e.g. technological determinants) unrelated to US export controls. In the following section, we develop an empirical strategy to ac-

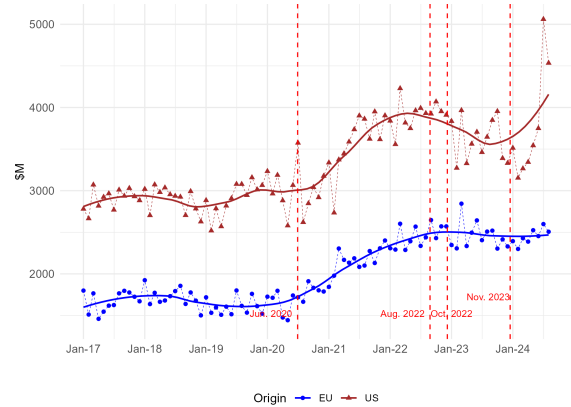
Figure 3: Export values (\$M) to the World and China: equipment and chips.



(a) Export values (\$M) to China, equipment segment



(b) Export values (\$M) to China, chips segment



(c) Export values (\$M) to the world (excluding China), equipment segment

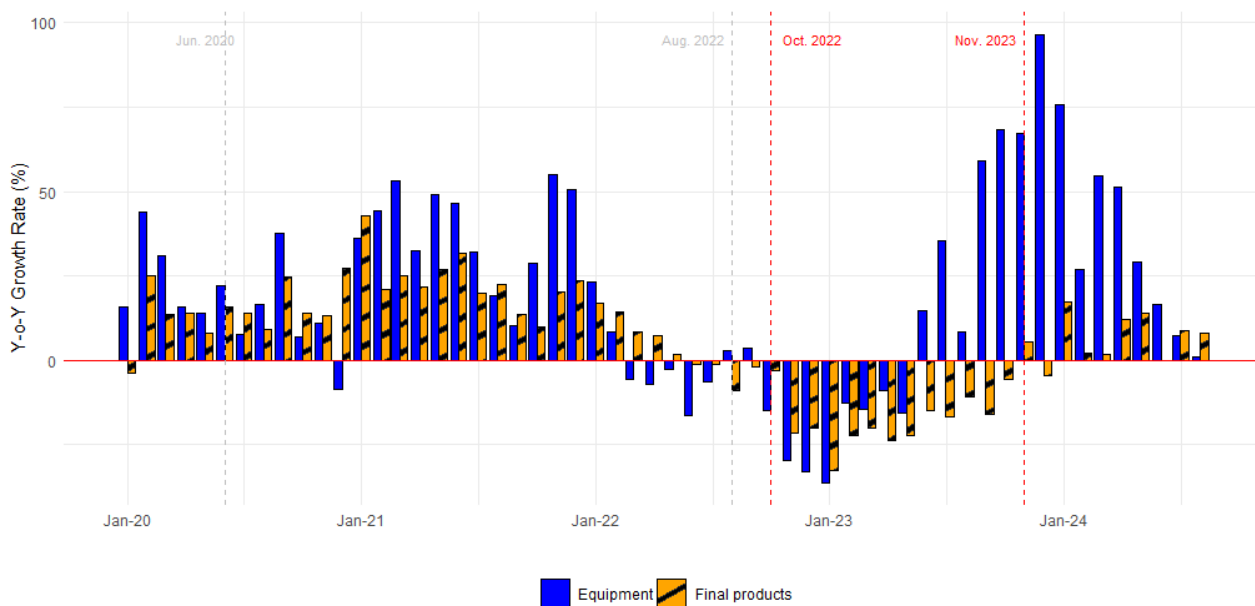
(d) Export values (\$M) to the world (excluding China), chips segment

Notes: Dashed lines show the monthly trade flows from UN Comtrade, the bold ones show the loess smoother using local regressions (smoothing parameter = 0.4). The vertical red line shows the implementation date of the US export controls on advanced computing and semiconductor manufacturing items to the People's Republic of China (PRC) (Oct. 2022) as obtained from the Global Trade Alert (GTA) Database.

Source: UN Comtrade, GTA, analysis by authors.

count for these confounding factors and isolate the causal impact of US export controls on export flows to China from the US and from jurisdictions indirectly affected by these policies.

Figure 4: Chinese semiconductor-related imports: year-on-year growth rates



Notes: Chinese import data from all countries for products in the equipment and chip sector of the semiconductor supply chain. Author’s elaboration on UN Comtrade data. The vertical lines show the implementation date of the US export controls — where the grey dashed lines correspond to the first two waves targeting chips only, while the dashed red lines included also equipment as targeted product. Information on the export control policies are derived from the Global Trade Alert (GTA) Database. *Source:* UN Comtrade, GTA, analysis by authors.

3 Empirical Strategy

Our empirical strategy exploits variation across three dimensions: products (targeted vs. non-targeted by export controls), destinations (China vs. other countries), and time (before vs. after policy implementation). We employ a triple difference-in-differences framework that compares export flows of products affected by US export controls to China with a control group consisting of: the same products exported to other destinations, and non-targeted semiconductor products exported to China. This triple-difference approach allows us to isolate the policy effect while controlling for product-specific supply shocks, destination-specific demand shocks, and global semiconductor market trends.

We estimate two sets of regressions to capture direct and indirect effects. Direct effects are identified from US export flows, while indirect effects are identified from exports of other major semiconductor-producing countries (EU, Japan, South Korea, Taiwan, Malaysia, Singapore) — so-called *third countries*. Our baseline specification restricts the sample to the 32 semiconductor-related products. In Section 6, we broaden the scope of the analysis to all traded products.

The baseline estimating equation is given by:

$$Y_{odpt} = \beta Post_t \times CHN_d \times TargetSEMIC_p + \alpha_{odp} + \alpha_{opt} + \alpha_{odt} + \varepsilon_{odpt} \quad (3.1)$$

where Y_{odpt} denotes our variable of interest, the export flows (in values) from origin o to destination d for product p at time t , where $o \in \{US, EU, JP, KR, MY, SG, TW\}$. The triple interaction includes the binary variable for the introduction of the policy ($Post_t$), another binary variable indicating China as target of the export controls (CHN_d) among destination countries and a third dummy ($TargetSEMIC_p$) equal to one when the product is a semiconductor, subject to the policy. Our coefficient of interest, β , captures the triple-difference: the change in exports of targeted products to China after policy implementation, relative to: (i) non-targeted products to China, (ii) targeted products to other destinations, and (iii) the pre-policy period.

Our approach identifies the causal effect of export controls under the assumption that, absent the policy, export flows of targeted products to China would have evolved parallel to the control group (same products to other destinations, and non-targeted products to China). This parallel trends assumption could be violated for different reasons. First, China-specific demand shocks might differentially affect targeted vs. non-targeted semiconductor products (e.g., if Chinese industrial policy simultaneously shifts demand toward the products targeted by US controls). Second, there might be product-specific supply shocks differentially affecting exports to China vs. other destinations (e.g., if production capacity for targeted products expands precisely when controls are introduced). Last, the existence of anticipation effects could lead to pre-treatment adjustments in trade flows.

We address these threats through a rich set of fixed effects and validate our identification assumption using event studies as illustrated with Equation 3.2. We introduce three sets of high-dimensional fixed effects. We include origin–destination–product fixed effects (α_{odp}) to control for time-invariant bilateral trade relationships at the product level. These absorb factors such as: established supplier relationships, product-specific quality differences across origins, and persistent policy barriers (e.g., pre-existing tariffs, standards). Origin–product–month fixed effects (α_{opt}) absorb supply-side shocks varying by exporter, product, and time. Examples include production capacity changes or technological improvement for specific products, common for all destination countries but depending on the inherent features of the exporting country. Origin–destination–month fixed effects (α_{odt}) account for time-varying bilateral factors af-

fecting all products, such as macroeconomic conditions, or bilateral trade policy changes.²³ We estimate Equation 3.1 using three complementary specifications to capture different adjustment margins. First, we rely on a PPML specification which is our preferred baseline because it handles zero trade flows without dropping observations, provides consistent estimates in the presence of heteroskedasticity common in trade data (Silva and Tenreyro, 2006), and captures adjustments on both intensive (i.e. how much to export) and extensive (i.e. whether to export) margins. Second, OLS used with log exports isolates the intensive margin by conditioning on positive trade flows. The coefficient β in this specification can be interpreted as the percentage change in export values for continuing exporters. Third, we adopt a linear probability model to examine whether export controls affect the probability of exporting (market entry). The dependent variable equals 1 if exports of a specific product from a given origin are positive, 0 otherwise.

We further split the policy variable to distinguish between different segments of the semiconductor supply chain actually affected, i.e. equipment and chips. As previously documented (see Table 2), wafers were not targeted by any US export control measure during our sample period. Standard errors are clustered at the origin–destination–product level. This clustering addresses two concerns: serial correlation within the same export relationship over time (as trade flows exhibit persistence), and heteroskedasticity across different trade relationships.

Given the sequential nature of policy implementation with US export controls being implemented in four waves between June 2020 and November 2023, with different products entering treatment at different times, we also apply a staggered difference-in-differences design. Recent econometric literature demonstrates that standard two-way fixed effects estimators can produce misleading results under staggered treatment timing, particularly when treatment effects are heterogeneous across cohorts or over time. We estimate an event study version of equation 3.1 that allows effects to vary flexibly over time:

$$Y_{odpt} = \sum_{l=-T}^{T-1} \beta_l \times I_{t=l} \times CHN_d \times TargetSEMIC_p + \alpha_{odp} + \alpha_{opt} + \alpha_{odt} + \varepsilon_{odpt} \quad (3.2)$$

where $I_{t=l}$ are time-specific dummy variables equal to 1 l periods before/after the introduction of US export control policies on a given product p , and 0 otherwise. Coefficients β_l trace out the dynamic response before and after the policy shock.²⁴ We use the estimator proposed by (Nagengast and Yotov, 2025), which accounts for heterogeneous treatment effects in a PPML setting with high-dimensional fixed effects, generalizing the linear setting from (Wooldridge, 2021).²⁵

The staggered design compares products entering treatment at each wave with (i) products never targeted during the sample period, and (ii) products not yet targeted. This approach uses only valid comparisons and avoids the contamination from “forbidden comparisons” that can bias standard two-way fixed effects estimators. Moreover, this setting allows for pre-trend validation: coefficients for $l \leq -1$ (pre-treatment periods) should be close to zero and statistically insignificant if the control group provides a valid counterfactual.

²³ We cannot include destination–product–month fixed effects, which would control for destination-specific demand for each product over time, because our policy shock varies at the destination–product–time level but is common across all exporters. Including these fixed effects would result in perfect multicollinearity with the treatment variable.

²⁴ Coefficients are normalized to zero in the month before the introduction of the policy.

²⁵ The extended two-way fixed effect estimator presented in (Wooldridge, 2021) maintains the general structure of the basic two-way fixed effect regression, but it also allows for treatment effect heterogeneity by additionally introducing suitable cohort (i.e., all units treated in a particular year) and year interactions.

4 Results

This section presents our main findings on the causal effects of US export controls. We begin by reporting baseline difference-in-differences estimates for direct effects on US exports and indirect effects on third countries (Section 4.1). We then examine heterogeneity across countries and policy waves before presenting dynamic evidence from our event study analysis in Section 4.2. Finally, Section 5 examines how Chinese production and trade patterns responded to these restrictions.

4.1 Baseline Results

Tables 3 and 4 present baseline estimates for the effects of US export controls on export flows. As discussed in the previous section, all specifications include an extensive set of fixed effects to address confounding factors that may bias identification. In Table 3, which examines the direct effects on US exports, we include destination–product, product–month, and destination–month fixed effects. In Table 4, focusing on third countries, we include origin–destination–product, origin–product–month, and origin–destination–month fixed effects to absorb origin-specific determinants of exports. In both tables, Panel (A) reports results pooling all semiconductor and semiconductor-related products, while Panel (B) distinguishes between chips and semiconductor manufacturing equipment.

Direct effects on US exports. Table 3 summarizes the direct impact of US export controls on US exports of targeted products. We interpret results across three specifications jointly. PPML (Column 1) captures the overall effect including both intensive and extensive margins. OLS with log exports (Column 2) isolates the intensive margin by conditioning on positive trade flows, with coefficients interpretable as percentage changes for continuing exporters. The linear probability model (Column 3) examines market entry and exit decisions. The aggregate estimates in Panel (A) indicate that the decline in US exports is driven primarily by adjustments along the intensive margin. The PPML coefficient in Column (1) is not statistically significant, while the OLS estimate in Column (2) implies that the introduction of US export controls reduced US exports to China by approximately 25.4 percent.²⁶

Panel (B) disaggregates effects by value chain segment, revealing that the aggregate results in Panel (A) mask important heterogeneity. Equipment exports show no significant response, while chip exports drive the overall decline. For chips, PPML estimates in column (1) indicate a mildly significant reduction, while OLS estimates (see column (2)) point to a larger and, more precisely estimated, decline, suggesting that US chip exports to China fell by between 21.6 and 36 percent after the introduction of export controls. Column (3) shows no evidence of an increased probability of zero trade flows, indicating that US exporters did not exit product–destination markets. Overall, these findings indicate that US export controls primarily reduced the volume of existing export relationships rather than inducing market exit, pointing to an adjustment predominantly along the intensive margin.

Indirect effects on other exporting countries. Table 4 examines how US export controls affected exports to China from other major participants in the semiconductor value chain. Panel (A) shows that, on average, the introduction of US controls led to an increase in exports to China from third countries. The PPML estimate in Column (1) suggests a positive effect of 13.5 percent, significant at the 10 percent level. This aggregate positive effect contrasts sharply with the negative direct effect on US exports documented in Table 3, providing prima facie evidence of trade adjustments as Chinese importers increase flows from non-US suppliers.

However, this aggregate effect masks substantial heterogeneity across product segments, as Panel (B) reveals; the aggregate positive effect is driven entirely by semiconductor manufacturing equipment. The

²⁶ The magnitude of estimated coefficients is obtained using the formula: $100 * (e^{\hat{\beta}} - 1)$.

Table 3: Direct Effects on US Exports

Dep. Var.:	PPML <i>Exports</i> (1)	OLS $\ln(\text{Exports})$ (2)	OLS <i>ExportDummy</i> (3)
Panel A:			
$Post_t \times CHN_d \times TargetSEMIC_p$	-0.132 (0.119)	-0.293* (0.155)	0.007 (0.006)
Panel B:			
$Post_t \times CHN_d \times TargetSEMIC_p^{equip}$	0.174 (0.116)	0.093 (0.239)	0.003 (0.011)
$Post_t \times CHN_d \times TargetSEMIC_p^{chips}$	-0.243* (0.125)	-0.448*** (0.166)	0.009 (0.007)
destination-product FE	Y	Y	Y
product-month FE	Y	Y	Y
destination-month FE	Y	Y	Y
Observations	419,625	197,850	458,988
Adjusted R-squared		0.851	0.662
Pseudo R-squared	0.979		

Notes: Robust standard errors in parentheses, clustered by destination-product.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Source: UN Comtrade, GTA, analysis by authors.

PPML coefficient of 0.508 implies a 66.2 percent increase in equipment exports to China from third countries.²⁷ This large effect operates primarily through the intensive margin: the OLS coefficient of 0.205 indicates that continuing exporters increased their shipment values by 22.7 percent on average. The absence of a significant extensive margin effect (Column 3) indicates this adjustment reflects expanded sales by existing exporters rather than their entry in new product-destination markets.

For chips, in contrast to equipment, we find no significant aggregate effect in PPML or OLS specifications (Columns 1–2). However, Column (3) uncovers a modest but statistically significant extensive-margin effect: the probability of positive chip exports to China increased by 1.2 percentage points for third countries. This pattern — insignificant intensive margin but positive extensive margin — suggests US export controls facilitated market entry by alternative suppliers without substantially changing volumes for continuing exporters.

The contrasting patterns across segments align with their different positions in the value chain. Equipment represents upstream production capability that is difficult for China to substitute domestically in the short run, generating strong demand for imports from any available source. Chips, by contrast, face more elastic supply as multiple countries possess production capacity (Figure 2), and China's expanding domestic production (Section 5) may offset import reductions from the US.

Tables 3 and 4 together reveal asymmetric effects of US export controls. US chip exports declined by 21–36 percent, while equipment exports from the EU, Japan, and other third countries surged by 23–66 percent. These opposing movements suggest US restrictions successfully reduced US market presence in

²⁷ This result is robust to a more conservative specification that includes destination–HS4 product–month fixed effects. While destination–HS6 product–month fixed effects cannot be included due to perfect collinearity with the policy shock, aggregating to HS4 allows us to capture broader demand shocks. Under this stricter specification, the PPML coefficient decreases to 0.313 but remains significant at the 1 percent level.

Table 4: Indirect Effects on Other Countries

Dep. Var.:	PPML <i>Exports</i> (1)	OLS $\ln(\textit{Exports})$ (2)	OLS <i>ExportDummy</i> (3)
Panel A:			
$Post_t \times CHN_d \times TargetSEMIC_p$	0.127* (0.075)	0.087 (0.062)	0.005 (0.006)
Panel B:			
$Post_t \times CHN_d \times TargetSEMIC_p^{equip}$	0.508*** (0.094)	0.205** (0.102)	-0.012 (0.008)
$Post_t \times CHN_d \times TargetSEMIC_p^{chips}$	0.002 (0.065)	0.041 (0.067)	0.012* (0.007)
origin-destination-product FE	Y	Y	Y
origin-product-month FE	Y	Y	Y
origin-destination-month FE	Y	Y	Y
Observations	1,461,494	658,104	1,690,526
Adjusted R-squared		0.858	0.675
Pseudo R-squared	0.989		

Notes: Robust standard errors in parentheses, clustered by origin-destination-product.

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Source: UN Comtrade, GTA, analysis by authors.

China but generated substantial unintended indirect effects that partially undermine the policy's effectiveness. We next examine how these effects vary across individual exporting countries and policy waves.

4.2 Heterogeneous Effects

Heterogeneity across third countries. The aggregate indirect effects in Table 4 conceal substantial heterogeneity across individual countries. Figure 5 decomposes these effects by export origin, revealing that positive effects on equipment concentrate mainly in the EU, Japan, and Singapore. This is consistent with each country's comparative advantage in the supply chain, as all three are major producers of equipment for chip manufacturing. While the EU and Japan specialize in the production of advanced machines, Singapore fabricates less sophisticated models. Notably, Singapore presents a slightly distinct pattern: beyond a large increase in equipment exports to China (94 percent), it also experiences a significant rise in chip exports (36.7 percent), reflecting its dual role as both a machinery producer and a major regional trade hub with substantial assembly capacity. Anecdotal evidence supports these findings. The Dutch firm ASML, the world's largest producer of high-end semiconductor manufacturing equipment, received a higher number of orders for its deep ultraviolet (DUV) and extreme ultraviolet (EUV) machines from China following the adoption of US controls. Chinese customers unable to purchase advanced EUV or the most sophisticated DUV machines reportedly increased purchases of remaining DUV models still available for export.²⁸

In contrast, Taiwan exhibits sharp declines in exports of both equipment (−37.7 percent) and chips (−25.8 percent) to China, making it the only third country showing negative effects across both segments. This unique pattern reflects Taiwan's singular position in the global semiconductor ecosystem and its close alignment with the US. Taiwan Semiconductor Manufacturing Corporation (TSMC) is the leader in the production of advanced chips (Ciani and Nardo, 2022), serving as a key supplier to major US firms such as

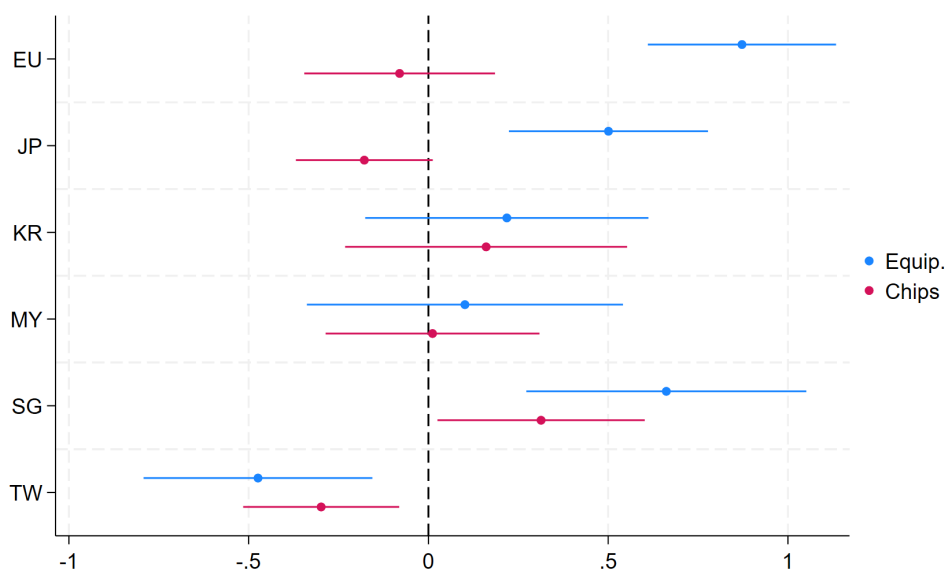
²⁸ While our data do not allow us to distinguish machine types, we observe an aggregate increase consistent with this pattern. More details can be found in the following [ISPI publication](#).

Nvidia, Apple, Broadcom, and Qualcomm (Miller, 2022). This deep integration with the US semiconductor industry — whereby American companies design chips that TSMC produces, while US firms like Intel and Texas Instruments maintain significant investments in Taiwanese facilities — makes Taiwan particularly responsive to US export control policies, resulting in a sharp contraction of its semiconductor exports to China.

The sizable increases in equipment exports from the EU (139 percent) and Japan (65 percent) likely reflect a reconfiguration of Chinese supply chains toward unrestricted suppliers. This holds true even if, during 2023, the Dutch and the Japanese Governments introduced export controls on exports of equipment from their respective countries to China. Starting in early 2023, Chinese firms reportedly accelerated purchases of equipment from these sources, driven by three concurrent factors: direct restraints on US equipment exports, the extraterritorial reach of US controls through the Foreign Direct Product Rule (FDPR) and the *de minimis* rule — which restrict non-US companies relying on US inputs or software in their manufacturing processes — and the anticipation of future restrictions from European and Japanese authorities, which the US government was actively lobbying to adopt.²⁹

Taken together, these country-level patterns reveal that indirect effects are far from uniform and are shaped by each country’s position in the semiconductor value chain and its degree of alignment with the US. The EU and Japan — countries with advanced equipment manufacturing capabilities but less direct US policy influence than Taiwan — captured the largest market share gains in China, driven by a reconfiguration of Chinese procurement toward unrestricted suppliers. Taiwan, despite its enormous semiconductor capacity, exhibits negative indirect effects consistent with its deep integration with the US industry. These patterns underscore the complex, differentiated impacts of unilateral export controls in globalized production networks.

Figure 5: Heterogeneous Effects Across Third Countries



Notes: Coefficients obtained using PPML estimation. 95% confidence intervals are based on standard errors clustered at the origin-destination-product level. Table S2 in Appendix D reports the numerical coefficients of the estimation.

Source: UN Comtrade, GTA, analysis by authors.

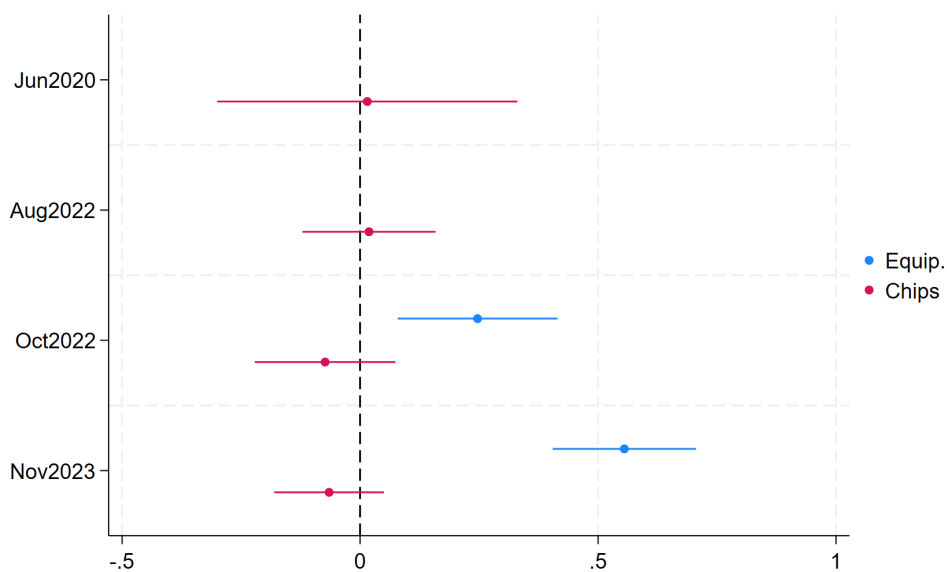
²⁹ See Financial Times reporting on the redirection of Chinese equipment purchases in this [article](#), which notes a surge of approximately 70 percent in Chinese imports of equipment from third countries over this period.

Heterogeneity across policy waves. As documented in Section 2.1, US export controls were implemented in four distinct waves between June 2020 and November 2023, varying in scope and stringency. To understand which policies drove the aggregate effects for the third countries documented above, we estimate separate coefficients for each policy wave distinguishing between chips and equipment. This decomposition reveals whether effects accumulated gradually or concentrated in specific episodes. We rely on PPML estimates, which appropriately account for adjustments along both the intensive and extensive margins and handle zero trade flows in a consistent manner, and we focus on countries indirectly affected by US policies.

Figure 6 summarizes the results. There is no clear evidence that any of the four policy episodes had a systematic positive or negative effect on chip exports from third countries. By contrast, policies introduced in October 2022 and November 2023 generated substantial increases in exports of semiconductor manufacturing equipment to China. The October 2022 measures are associated with a 28 percent increase in equipment exports, while the November 2023 measures correspond to a considerably larger increase of 74.2 percent.

The substantially larger coefficient for November 2023 likely reflects two factors. First, the November 2023 measures expanded the product scope and tightened enforcement mechanisms relative to October 2022, potentially fueling the shift in trade from other producers. Second, fears of further tightening of export control policies by Western governments, including the Netherlands and Japan — which in 2023 began aligning with the US strategy to restrict China’s access to critical technologies through national export controls targeting chip-making equipment — likely accelerated the purchases by Chinese firms to secure supplies and avoid disruptions. The first two policy waves, which were more narrowly targeted measures on chips (June 2020, August 2022), had no significant impact on aggregate trade flows from third countries. This pattern, consistent with the average estimates reported in Table 3, suggests that the US policies were not effective in restraining exports of chips from these third countries and, if anything, had unintended effects on the supply of equipment, a segment in which these countries already had a comparative advantage. Figure S5 in the Appendix presents the corresponding PPML estimates for the direct impact of each policy on US exports.

Figure 6: Heterogeneous Effects Across Policies for Third Countries



Notes: Coefficients are obtained using PPML estimation. 95% confidence intervals are based on standard errors clustered at the origin-destination-product level. Table S3 in Appendix D reports the numerical coefficients of the estimation.

Source: UN Comtrade, GTA, analysis by authors.

Heterogeneous effects over time. The baseline difference-in-differences estimates in Tables 3–4 impose a restriction: they assume that effects are constant over time after the policy implementation. However, export controls may generate dynamic responses as firms adjust their supply chains. To examine these dynamics, we estimate an event study specification that allows effects to vary flexibly before and after each policy wave. This analysis serves two purposes. First, it validates our identification assumption by testing for pre-existing trends in treated vs. control export flows. Second, it reveals the temporal evolution of policy effects, distinguishing short- from longer-run adjustments.

We compare the evolution of third countries' exports over time for products subject to US export control measures targeting China with those of products and destinations unaffected throughout the sample period. More precisely, we use the estimator proposed by (Nagengast and Yotov, 2025), which accounts for heterogeneous treatment effects in a PPML setting with high-dimensional fixed effects.

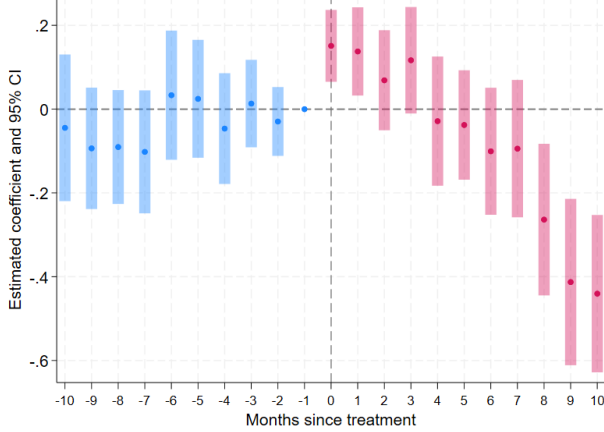
Estimates reported in Figure 7 confirm that the pre-trend assumption is not violated for products in both segments of the value chain.³⁰ None of the pre-treatment coefficients are statistically significant at conventional levels. This pattern supports our identification assumption: absent the export controls, treated and control exports were following parallel trajectories. Moreover, the effect on exports of equipment is relatively small in the months right after the introduction of the policy but it builds up stronger after eight months. The fact that effects build over time rather than declining suggests that we may be observing a sustained reconfiguration of supply relationships. Exports of chips report mild increases in the first months after the introduction of the policies, but suffer sizable and significant reductions after seven months.

These dynamic patterns have important implications. First, static difference-in-differences estimates provide useful summary measures but obscure any temporal heterogeneity. Second, the 8-month lag for

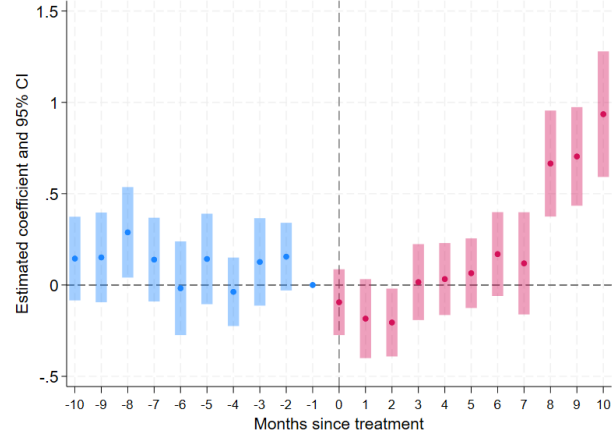
³⁰ Exact estimates are reported in Tables S4 and S5.

Figure 7: Staggered Difference-in-Differences for the Indirect Effects

Panel (a): Chips



Panel (b): Equipment



Notes: This figure plots estimates from a PPML estimation of equation 3.2. Panel (a) shows results for export controls targeting chips, while panel (b) focuses on equipment. 95% confidence intervals are based on standard errors clustered at the origin-destination-product level.

Source: UN Comtrade, GTA, analysis by authors.

equipment suggests that estimates based on shorter post-treatment windows would substantially understate indirect effects. Third, the chips pattern (an initial increase followed by decline) suggests the net effect of export controls evolves as Chinese production capacity adjusts, with longer-run data needed to assess ultimate impacts.

4.3 Export Controls as Export-Tax Equivalents

While the percentage changes reported in previous sections provide direct interpretations of policy effects, translating these estimates into export-tax equivalents (ETEs) helps benchmark their magnitude against familiar trade policy instruments. Export controls are non-tariff regulatory measures, but their impact on trade flows can be expressed in terms of an equivalent ad valorem export tax that would generate the same proportional change in exports. This metric facilitates comparison with studies of tariff-based trade policies and aids policy evaluation. In a standard gravity framework, an export tax τ generates a proportional change in exports according to:

$$\frac{\Delta X}{X} = -\varepsilon \cdot \tau \quad (4.1)$$

where ε denotes the trade elasticity. Rearranging yields the export-tax equivalent:

$$\tau = -\frac{\Delta X/X}{\varepsilon} \quad (4.2)$$

We use the proportional changes in exports ($\Delta X/X$) from our PPML and OLS estimates (Tables 3–4), combined with trade elasticity benchmarks from the literature. Following [Caliendo and Parro \(2015\)](#) and [Costinot and Rodríguez-Clare \(2014\)](#), we adopt $\varepsilon = 5$ as our baseline elasticity, a standard value for differentiated manufactured goods. We also report results for ε equal to 3 or 7 to assess sensitivity to this assumption. Advanced chips with few substitutes may have lower elasticities ($\varepsilon < 5$), implying larger ETEs, while commodity chips with many suppliers may have higher elasticities ($\varepsilon > 5$), implying smaller ETEs. For PPML coefficients, we compute proportional changes as $\Delta X/X = \exp(\beta) - 1$, and for consistency we use the same transformation also for OLS coefficients.

Direct Effects on US Exports. Table 5 reports export-tax equivalents for the direct effects of US export controls on US chip exports to China (from Table 3, Panel B).

Table 5: Export-Tax Equivalents for Direct Effects on US Chip Exports

Specification	Coeff. (β)	Std. Error	Proportional Change (%)	Export-Tax Equivalent		
				$\varepsilon = 3$	$\varepsilon = 5$	$\varepsilon = 7$
PPML	-0.243*	0.125	-21.6%	7.2%	4.3%	3.1%
OLS	-0.448***	0.166	-36.1%	12.0%	7.2%	5.2%

Notes: Proportional changes computed as $\exp(\beta) - 1$. Export-tax equivalents (ETEs) computed as $\tau = -(\Delta X/X)/\varepsilon$. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Source: UN Comtrade, GTA, analysis by authors.

The reduction in US chip exports to China following export controls is economically comparable to an export tax ranging from 4.3% to 7.2% (using the baseline elasticity $\varepsilon = 5$), depending on the specification. The PPML estimate, our preferred specification, implies an ETE of 4.3% — a moderate but meaningful trade friction. The OLS estimate yields a higher ETE of 7.2%, reflecting the larger estimated effect on the intensive margin. Under a more elastic demand scenario ($\varepsilon = 7$), the implied export tax would be lower (3.1–5.2%), while under less elastic demand ($\varepsilon = 3$), it would be higher (7.2–12.0%). We do not compute ETEs for US equipment exports because Table 3, Panel B shows no significant effect on this segment.

Indirect Effects on Third-Country Equipment Exports. Table 6 reports export-tax equivalents for indirect effects on equipment exports from third countries to China (from Table 4, Panel B). The increase in equipment exports from third countries to China is economically equivalent to an implicit export subsidy ranging from 4.5% to 13.2% (using $\varepsilon = 5$), depending on specification. The PPML estimate implies an ETE of -13.2% — a substantial implicit subsidy. The negative sign indicates that third countries experienced export increases equivalent to what would result from a 13.2% reduction in export costs. We do not compute ETEs for third countries' chip exports because Table 4, Panel B shows no significant average effect.

Table 6: Export-Tax Equivalents for Indirect Effects on Equipment Exports

Specification	Coeff. (β)	Std. Error	Proportional Change (%)	Export-Tax Equivalent		
				$\varepsilon = 3$	$\varepsilon = 5$	$\varepsilon = 7$
PPML	0.508***	0.094	+66.2%	-22.1%	-13.2%	-9.5%
OLS	0.205**	0.102	+22.7%	-7.6%	-4.5%	-3.2%

Notes: Proportional changes computed as $\exp(\beta) - 1$. Export-tax equivalents (ETEs) computed as $\tau = -(\Delta X/X)/\varepsilon$. Negative ETEs indicate implicit export subsidies. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Source: UN Comtrade, GTA, analysis by authors.

Translating our estimates into export-tax equivalents reveals that US semiconductor export controls generated moderate trade frictions for US exporters (equivalent to a 4–7% export tax) but large implicit subsidies for competitors (equivalent to 13–28% export subsidies for equipment). This asymmetry highlights the challenge of unilateral export controls in globalized industries: restrictions on domestic firms may be partially offset by trade re-routing to foreign competitors, limiting policy effectiveness while imposing costs on domestic industry.

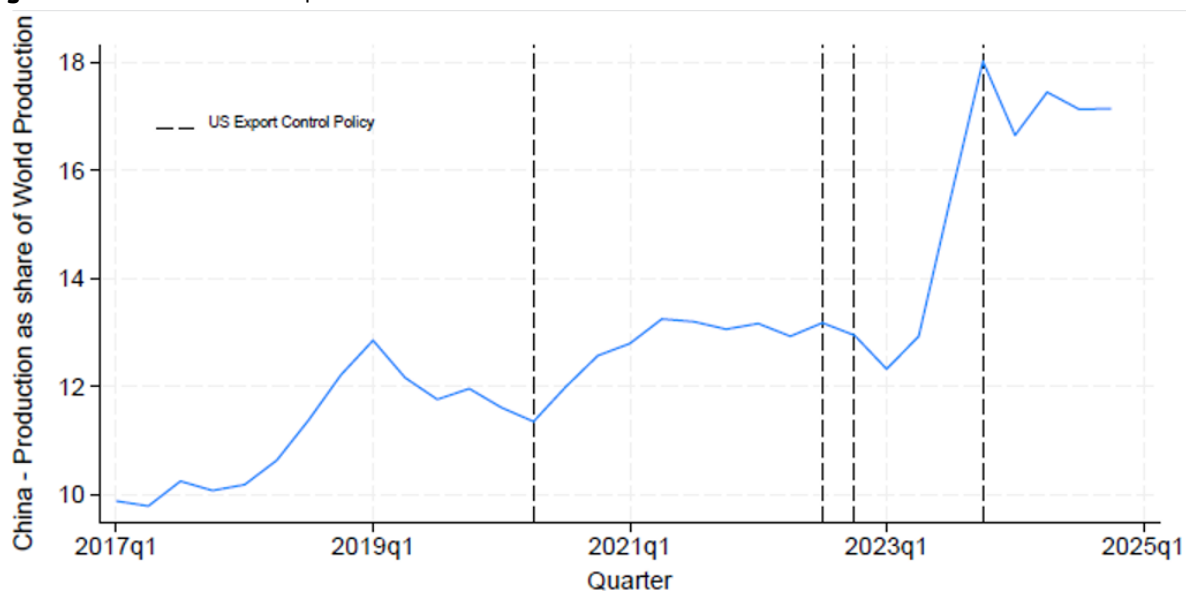
Some drawbacks associated to these calculations shall be considered. Our estimates capture responses over 1–2 years post-policy; trade elasticities typically increase over longer horizons as firms adjust supply chains, suggesting our ETEs likely understate long-run trade frictions (Boehm et al., 2023). Export controls operate through regulatory compliance, licensing delays, and uncertainty rather than explicit prices, and firms may perceive these non-price barriers differently than equivalent taxes, potentially generating larger behavioral responses per unit of trade cost. The ETE calculation assumes other trade flows and prices remain constant (partial equilibrium), while in reality export controls may trigger general equilibrium adjustments that amplify or dampen measured effects. Finally, we report ETEs for broad product categories (chips, equipment), while heterogeneity across specific products (e.g., advanced vs. mature-node chips) likely generates substantial variation in effective tax equivalents not captured by aggregate estimates. These findings contribute to ongoing debates about the appropriate design of export controls. Multilateral coordination — extending restrictions to allied countries — could reduce indirect effects and enhance effectiveness, albeit at the cost of broader economic disruption. Our evaluation of ETEs provides a quantitative foundation for evaluating the net-effect of such tradeoffs.

5 Effects on the Chinese Market

The evidence presented thus far documents substantial trade adjustments: US exports of chips declined, third-country equipment exports surged, while export patterns evolved dynamically. However, a natural question arises: did US export control policies affect semiconductor manufacturing activity within China? This is central to evaluating policy effectiveness: if US export controls reduced Chinese production or technological advancement, they achieved their stated objective. If, however, China maintained or expanded production despite restricted access to foreign technology, the policy's long-run impact may be limited. Fully answering this question requires granular data on production by technology node, innovation metrics such as patents, and firm-level performance, which go beyond the scope of this paper. However, we can provide descriptive evidence on three observable margins: Chinese production levels, Chinese exports, and Chinese imports.

Production. We begin by examining the share of global semiconductor production attributable to China, using data from Techinsights (Figure 8). Following the third and fourth rounds of US restrictions, we observe modest declines in China's production share. These reductions are small, however, and their interpretation is complicated by concurrent developments that cannot be fully disentangled.

Figure 8: US Policies and Chip Production in China



Notes: Production data are retrieved from Techinsights Inc. for the period 2017–2025, while timing of the policies come from Global Trade Alert (GTA) database.

Source: GTA; Techinsights Inc, analysis by authors.

More strikingly, China's share of global semiconductor output increases sharply — by up to 18 percentage points — over the course of 2023. This surge is plausibly linked to the commissioning of new fabrication facilities developed under sustained industrial policy efforts. Over the past decade, the Chinese leadership has channeled substantial resources into building domestic semiconductor capacity. The Made in China 2025 initiative identified semiconductors as a critical sector for the country's economic development and geopolitical standing, setting a target for domestically produced chips to account for 70 percent of the Chinese market by 2025.³¹ Investment has been coordinated through the National Integrated Circuit Industry Investment Fund (the "Big Fund"), which allocated approximately 20 billion dollars in its first phase

³¹ For further discussion: [column](#).

and a further 28 billion dollars in a second phase initiated in 2019, directed primarily toward expanding manufacturing capacity and fostering innovation. Companies such as Semiconductor Manufacturing International Corporation (SMIC) and Huawei have received direct government support to enhance their capabilities in chip design and manufacturing (Miller, 2022). The production gains observed in 2023 are thus consistent with the maturation of these long-planned investments, suggesting that China’s industrial policy may have buffered the impact of US export controls on aggregate production capacity. Overall, the available production data does not suggest that US export controls generated large or persistent declines in China’s share of global semiconductor manufacturing.

Exports. We complement these production patterns with evidence on Chinese exports. Table 7 reports estimates based on Chinese aggregate export data at the product level, testing whether the introduction of US export control measures is associated with changes in Chinese exports of targeted semiconductor products. Across specifications, we find negative and statistically significant effects. This holds both when pooling all targeted semiconductor products (Column 1) and when separating equipment and chips (Column 2).

Table 7: Effects on Chinese Exports

Dep. Var.:	(1)	(2)
	$\ln(Exports)$	$\ln(Exports)$
$Post_t \times TargetSEMIC_p$	-0.464*	
	(0.245)	
$Post_t \times TargetSEMIC_p^{equip}$		-0.634*
		(0.338)
$Post_t \times TargetSEMIC_p^{chips}$		-0.202***
		(0.0444)
Product FE	Y	Y
4-digit chapter-month FE	Y	Y
Observations	2208	2208
Adjusted R^2	0.950	0.950

Notes: Standard errors clustered at the product-level in parentheses.

*

$p < 0.10$, $*p < 0.05$, $**p < 0.01$.

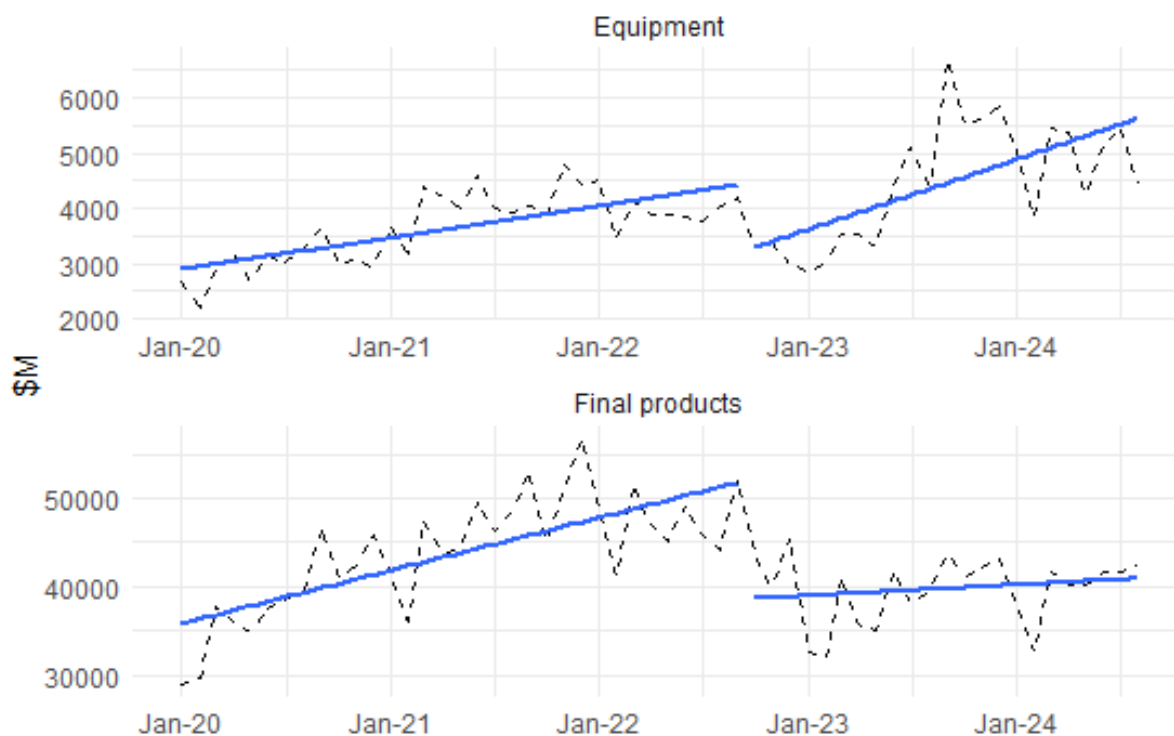
Source: UN Comtrade, GTA, analysis by authors.

Reading these results together with the production evidence yields a coherent picture: the increase in China’s domestic semiconductor production observed during the imposition of US export controls has not fueled Chinese exports but has rather been absorbed by the domestic market. This is consistent with a deepening integration between Chinese semiconductor manufacturers and domestic end-use sectors, and aligns with the import-substitution objectives of China’s industrial policy in this sector.

Imports. Finally, we examine overall Chinese imports of semiconductor manufacturing equipment and chips between January 2020 and the spring of 2024 (Figure 9). The previous section documented a re-configuration of Chinese purchases across suppliers; here we ask whether aggregate import volumes also changed.

For both segments, the data show a clear discontinuity in the second half of 2022, coinciding with the introduction of the third wave of US export control measures. Chinese imports of chips decline sharply and remain subdued through 2024, while imports of equipment display a markedly stronger upward trend over the same period. The divergence between the two segments is notable: the sustained increase in equipment imports is consistent with the supply chain reconfiguration documented in the previous section,

Figure 9: China overall import trends in equipment and chips



Notes: Export data from all countries to China for the period 2020–2025.
Source: UN Comtrade, GTA, analysis by authors.

whereby Chinese manufacturers redirected procurement toward unrestricted EU and Japanese suppliers in anticipation of tightening restrictions. At the aggregate level, therefore, US export controls did not reduce China’s overall access to semiconductor manufacturing equipment — they altered its composition by source.

Overall, the evidence on the Chinese market points toward a nuanced conclusion. Despite substantial disruptive attempts to China’s access to foreign equipment and technology, we do not observe large or persistent negative effects of US export controls on aggregate Chinese semiconductor production; if anything, production capacity expanded, likely supported by long-planned industrial policy investments. At the same time, Chinese exports of semiconductor products declined, suggesting that increased domestic output has been directed inward rather than toward international markets. Meanwhile, aggregate imports of equipment rose, driven by a shift toward unrestricted suppliers at the intensive margin. Further research with more granular data — in particular on production by technology node and firm-level outcomes — would be valuable to better understand the channels behind these patterns and to assess whether US export controls have constrained China’s technological frontier despite the resilience of its aggregate production capacity.

6 Robustness Checks

In this section we perform a series of checks to evaluate the robustness of our estimates.

Alternative sample definitions (all products). As a first robustness check, we run our baseline regressions on all products of the Harmonized System (HS), without restricting to semiconductor-related products only. Table 8 and Table 9 show that results are very similar to those obtained in our baseline regressions reported in Table 3 and Table 4. The only exception concerns export entry effects, reported in column (3) of both tables, which show significantly higher entry rates for countries exporting semiconductors and related products into the Chinese market relative to exporters of other products in the HS nomenclature. Importantly, the magnitude and significance of the positive effect on exports to China of equipment products from other countries (i.e., the indirect effects of export controls) are confirmed. In all the specifications shown in Panel B of these two Tables, we estimate separate effects for product categories related to semiconductors (i.e., equipment and chips) and other products (e.g., radars, advanced electronics) that have also been affected by the different US regulations on export controls and are flagged in the GTA dataset. Results further support conclusions drawn from Tables 3 and 4 on effects at the extensive margin.

Table 8: Direct Effects on US Exports — All HS products in sample

Dep. Var.:	PPML <i>Exports</i> (1)	OLS $\ln(\textit{Exports})$ (2)	OLS <i>ExportDummy</i> (3)
Panel A:			
$Post_t \times CHN_d \times TargetProducts_p$	-0.098 (0.107)	0.038 (0.060)	0.037*** (0.011)
Panel B:			
$Post_t \times CHN_d \times TargetSEMIC_p^{equip}$	0.139 (0.101)	0.173 (0.217)	0.034*** (0.009)
$Post_t \times CHN_d \times TargetSEMIC_p^{chips}$	-0.298** (0.143)	-0.341** (0.167)	0.040*** (0.006)
$Post_t \times CHN_d \times TargetOther_p$	0.057 (0.081)	0.119** (0.059)	0.037*** (0.014)
destination-product FE	Y	Y	Y
product-month FE	Y	Y	Y
destination-month FE	Y	Y	Y
Observations	40,760,024	11,113,514	41,224,740
Adjusted R-squared		0.777	0.574
Pseudo R-squared	0.954		

Notes: Robust standard errors in parentheses, clustered by destination-product. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Source: UN Comtrade, GTA, analysis by authors.

Table 9: Indirect Effects on Other Countries — All HS products in sample

Dep. Var.:	PPML <i>Exports</i> (1)	OLS $\ln(\textit{Exports})$ (2)	OLS <i>ExportDummy</i> (3)
Panel A:			
$Post_t \times CHN_d \times TargetProducts_p$	0.062 (0.052)	0.088*** (0.029)	0.012** (0.005)
Panel B:			
$Post_t \times CHN_d \times TargetSEMIC_p^{equip}$	0.564*** (0.105)	0.225** (0.093)	-0.005 (0.008)
$Post_t \times CHN_d \times TargetSEMIC_p^{chips}$	-0.025 (0.048)	0.076 (0.054)	0.018*** (0.006)
$Post_t \times CHN_d \times TargetOther_p$	-0.015 (0.051)	0.074** (0.035)	0.012** (0.006)
origin-destination-product FE	Y	Y	Y
origin-product-month FE	Y	Y	Y
origin-destination-month FE	Y	Y	Y
Observations	120,929,055	37,708,858	125,258,879
Adjusted R-squared		0.796	0.607
Pseudo R-squared	0.960		

Notes: Robust standard errors in parentheses, clustered by origin-destination-product. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Source: UN Comtrade, GTA, analysis by authors.

Alternative treatment definitions (all affected jurisdictions). Although US export controls analyzed in this study were primarily targeting China, some of these measures also designated additional destination countries as affected jurisdictions, including Russia and a set of other countries subject to US arms embargoes.³² To account for these additional jurisdictions, Table 10 presents a robustness check in which we allow these other affected destinations identified in the GTA database to enter the regressions as separate treated groups, denoted as RUS_d for Russia and $Embargoed_d$ for other embargoed countries.

Considering the direct effects of US export controls on US exports in columns (1) and (2), the negative and mildly significant baseline effect on exports of chips to China reported in Table 3 remains unchanged after including this additional group of treated countries. We also do not find significant effects on the exports of chips and equipment to the other affected countries (Column 2).³³ Columns (3) and (4) of Table 10 report the results for third countries. Consistent with our baseline estimates in Table 4, we again find a positive and statistically significant effect on third countries' exports of equipment to China. In addition, we observe a negative and significant effect on the exports of chips and equipment to Russia. However, one should exercise caution when interpreting the potential impacts on Russia. Indeed, this strong drop in exports of semiconductors to Russia might also be attributable to the impacts of other restrictions, such

³² As detailed in Section 2.1, the restrictions on high-technology goods with military applications introduced in June 2020 also applied to Russia and Venezuela. The license requirements for Nvidia chips issued in August 2022 likewise listed Russia among the affected destinations. Moreover, the tightening of export restrictions on advanced semiconductors and semiconductor manufacturing equipment introduced in November 2023 broadened the geographic scope of the October 2022 controls, which had targeted only China. To mitigate circumvention risks, this revision extended export controls to additional countries subject to US arms embargoes, including Belarus, Central African Republic, Cuba, DPR Korea, DR Congo, Eritrea, Iran, Iraq, Lebanon, Libya, Mali, Myanmar, Nicaragua, Republic of the Sudan, Russia, Somalia, South Sudan, Syria, Venezuela, Yemen, Zimbabwe.

³³ The coefficient relative to the US exports of equipment to Russia in column (2) is omitted from the regression results because US export flows of affected semiconductor machinery to Russia were already zero before the introduction of the policy.

as sanctions that Western countries imposed on Russia following its aggression against Ukraine in early 2022, which partially overlaps with the timing of the introduction of US export controls. Nevertheless, this evidence suggests that while export controls may have marginally contributed to restricting access to semiconductors for other sanctioned countries, such as Russia, they did not have a similar intended effect on exports of equipment to China, which further reinforces conclusions drawn from our baseline regressions.

Table 10: Effects on Other Destinations affected by US Export Controls

Dep. Var.:	US		Third countries	
	(1)	(2)	(3)	(4)
			PPML <i>Exports</i>	
$Post_t \times CHN_d \times TargetSEMIC_p$	-0.132 (0.119)		0.124* (0.075)	
$Post_t \times RUS_d \times TargetSEMIC_p$	0.250 (0.312)		-2.596*** (0.581)	
$Post_t \times Embargoed_d \times TargetSEMIC_p$	-0.290 (0.352)		-0.390 (0.355)	
$Post_t \times CHN_d \times TargetSEMIC_p^{equip}$		0.174 (0.116)		0.506*** (0.094)
$Post_t \times CHN_d \times TargetSEMIC_p^{chips}$		-0.243* (0.125)		-0.001 (0.066)
$Post_t \times RUS_d \times TargetSEMIC_p^{equip}$		NA		-5.096*** (0.994)
$Post_t \times RUS_d \times TargetSEMIC_p^{chips}$		0.230 (0.307)		-2.643*** (0.590)
$Post_t \times Embargoed_d \times TargetSEMIC_p^{equip}$		0.001 (0.516)		0.637 (0.809)
$Post_t \times Embargoed_d \times TargetSEMIC_p^{chips}$		-0.319 (0.369)		-0.512 (0.378)
origin-destination-product FE	Y	Y	Y	Y
origin-product-month FE	Y	Y	Y	Y
origin-destination-month FE	Y	Y	Y	Y
Observations	419,625	419,625	1,461,494	1,461,494
Pseudo R-squared	0.978	0.978	0.989	0.989

Notes: Robust standard errors in parentheses, clustered by origin-destination-product.

*** p < 0.01, ** p < 0.05, * p < 0.10.

Source: UN Comtrade, GTA, analysis by authors.

Trade re-routing analysis. The imposition of US export controls on China may have triggered even more complex dynamics in global trade patterns of semiconductors, potentially affecting countries geographically close to China. To this end, we explore whether there are signals of trade re-routing to ASEAN countries such as Vietnam. Shifts in the destination markets of products subject to US export controls could reflect broader trade reallocation in response to the policy, but could also signal potential triangulation, where goods affected by controls are re-routed to China via third countries.³⁴ We conduct a preliminary investigation into whether there are concurrent changes in exports of semiconductor-related products to ASEAN countries³⁵, which are major trading partners of China and could potentially act as trade hubs due to their proximity to this country.

³⁴ For example, a [FT article](#) reports that US authorities have been investigating whether intermediate entities located in countries such as Singapore could have accumulated US Nvidia chips to re-sell to China.

³⁵ This group includes Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, Vietnam.

Table 11 reports difference-in-differences PPML estimates for US exports to ASEAN countries. In columns (1) and (2), we replace the policy-destination interaction in our baseline specification with a binary indicator for ASEAN destinations, excluding exports to China from the sample. Columns (3) and (4) estimate separate coefficients for ASEAN and China destinations. Across all specifications, US exports to ASEAN countries did not exhibit significant changes following the export control policies, regardless of whether we examine chips or equipment.³⁶ This suggests no clear evidence of trade re-routing due to US export controls via ASEAN countries at the aggregate level.

By contrast, Table 12 shows that exports of semiconductor equipment from third countries to ASEAN destinations (columns 2 and 4) increased, albeit at roughly half the magnitude of the effect observed for China. This pattern could indicate that the positive effects on equipment exports to China may be even larger than implied by our baseline difference-in-differences analysis due to the presence of re-routing through third-country hubs. However, these results should not be interpreted as definitive evidence of violations since we do not yet account for trade flows between third-country hubs and China, nor use methods to detect illicit shipments.

Table 11: Effects on Exports of the US to ASEAN Countries

Dep. Var.:	PPML Exports			
	excl. China		incl. China	
	(1)	(2)	(3)	(4)
$Post_t \times ASEAN_d \times TargetSEMIC_p$	-0.083 (0.092)		-0.097 (0.098)	
$Post_t \times ASEAN_d \times TargetSEMIC_p^{equip}$		0.105 (0.174)		0.111 (0.174)
$Post_t \times ASEAN_d \times TargetSEMIC_p^{chips}$		-0.155 (0.111)		-0.174 (0.116)
$Post_t \times CHN_d \times TargetSEMIC_p$			-0.143 (0.121)	
$Post_t \times CHN_d \times TargetSEMIC_p^{equip}$				0.197* (0.116)
$Post_t \times CHN_d \times TargetSEMIC_p^{chips}$				-0.266** (0.127)
destination-product FE	Y	Y	Y	Y
product-month FE	Y	Y	Y	Y
destination-month FE	Y	Y	Y	Y
Observations	416,681	416,681	419,625	419,625
Pseudo R-squared	0.975	0.975	0.978	0.979

Notes: Robust standard errors in parentheses, clustered by destination-product. *** p < 0.01, ** p < 0.05, * p < 0.10.

Source: UN Comtrade, GTA, analysis by authors.

³⁶ We also considered Singapore separately as a destination market and found no significant effect.

Table 12: Effects on Exports of Other Countries to ASEAN Countries

Dep. Var.:	PPML Exports			
	excl. China		incl. China	
	(1)	(2)	(3)	(4)
$Post_t \times ASEAN_d \times TargetSEMIC_p$	0.068 (0.058)		0.100 (0.063)	
$Post_t \times ASEAN_d \times TargetSEMIC_p^{equip}$		0.192** (0.085)		0.306*** (0.096)
$Post_t \times ASEAN_d \times TargetSEMIC_p^{chips}$		0.052 (0.061)		0.022 (0.065)
$Post_t \times CHN_d \times TargetSEMIC_p$			0.150* (0.080)	
$Post_t \times CHN_d \times TargetSEMIC_p^{equip}$				0.550*** (0.094)
$Post_t \times CHN_d \times TargetSEMIC_p^{chips}$				0.001 (0.070)
origin-destination-product FE	Y	Y	Y	Y
origin-product-month FE	Y	Y	Y	Y
origin-destination-month FE	Y	Y	Y	Y
Observations	1,444,559	1,444,559	1,461,494	1,461,494
Pseudo R-squared	0.981	0.981	0.989	0.989

Notes: Robust standard errors in parentheses, clustered by origin-destination-product. *** p < 0.01, ** p < 0.05, * p < 0.10.

Source: UN Comtrade, GTA, analysis by authors.

7 Conclusion

This study provides novel insights into the effects of unilateral export control policies on trade flows along the semiconductor supply chain, a sector that is critical for advanced economies. Our findings suggest that the recent wave of US export controls targeting China has generated asymmetric effects on semiconductor trade of key countries operating within the global production network. The decline in US and Taiwanese chip exports to China is consistent with the intended direct effects of these policies. By contrast, the increase in semiconductor equipment exports to China from the EU, Japan, and Singapore points to potential unintended adjustments induced by US export controls.

On the one hand, the decline in Taiwanese exports of both chips and equipment to China illustrates the intended negative extraterritorial effects of US export controls. These effects are likely driven by the deep technological and commercial ties between the US and Taiwanese semiconductor industries, which make Taiwan subject to compliance with US regulations, including the Foreign Direct Product Rule (FDPR), as well as by strategic political alignment. On the other hand, the positive indirect effects on equipment exports from major producing economies such as the EU, Japan, and Singapore likely reflect a response by Chinese manufacturers seeking to hedge against the risk of further Western restrictions. China's surge in purchases of semiconductor equipment and tools — an area in which it still relies heavily on foreign-made technologies — is consistent with its industrial objectives of achieving greater self-sufficiency in semiconductor production and expanding domestic manufacturing capacity to mitigate the impact of US-led export restrictions.

Turning to heterogeneity across policy waves, our results show that these positive indirect effects on chip-making equipment strengthened across successive US measures, increasing from the initial controls introduced in October 2022 to the more stringent measures implemented in November 2023. Effects intensify after a phase in which other Western governments, notably the Netherlands and Japan, began aligning with the US-led restrictions on critical technologies. The staggered difference-in-differences event study analysis — drawing on recent advances in the econometric literature on treatment effect heterogeneity — provides additional insights into the dynamics of these effects. Specifically, the results suggest that the increase in equipment exports to China from third countries is not immediate but intensifies over the months following the policy shock. At the same time, the absence of pre-trends supports the validity of our identification strategy. A comprehensive set of robustness checks confirms that our findings are robust to alternative sample and treatment definitions and provides preliminary evidence of potential trade triangulation through countries geographically proximate to China.

Findings presented in this study capture the short-term effects associated with the implementation of US export controls, as the phenomenon under study is very recent. With a longer time span and more extended time series data, future research will be able to move beyond short-run impacts and examine long-run adjustments in global supply chains driven by these restrictive policies, which remain unobservable with the current data.

Nevertheless, our results already reveal clear and immediate unintended indirect effects of unilateral trade restrictions that can alter trade patterns in third countries, potentially undermining the effectiveness of the intended policy objectives. These insights highlight the complexities and challenges of enforcing unilateral export controls within globally interconnected supply chains. They carry important implications for policymakers and underscore the importance of policy coordination, particularly in sectors characterized by highly fragmented and internationally dispersed production networks. Multilaterally coordinated frameworks may therefore be more effective in achieving national security goals while limiting unintended economic consequences.

Ultimately, this study contributes to a deeper understanding of the interactions between trade policy, national security, and critical value chains. As technological competition between the United States and China continues to evolve, it is crucial to account for the broader consequences of unilateral export control policies and to consider alternative approaches that balance security concerns with international cooperation. This would allow policymakers to foster a more stable and secure global trade environment while supporting the long-term development of critical industries like semiconductors.

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Annexes

List of HS product codes in the semiconductors' supply chain

Table S1: HS2017 products by code and segment

HS17 code	HS2017 description	Segment
381800	Chemical elements, doped for use in electronics, in the form of discs, wafers or similar forms; chemical compounds doped for use in electronics	Wafers
382499	Chemical products, mixtures and preparations, not elsewhere specified or included, under heading 3824	Wafers
841410	Vacuum pumps	Equipment
841459	Fans, not elsewhere specified or included under subheading 8414.51	Equipment
841490	Parts of air or vacuum pumps, air or other gas compressors, fans, and ventilating or recycling hoods incorporating a fan	Equipment
841950	Heat exchange units, not used for domestic purposes	Equipment
842129	Machinery for filtering or purifying liquids, not elsewhere specified or included	Equipment
842139	Machinery for filtering or purifying gases, other than intake air filters for internal combustion engines	Equipment
842199	Parts of machinery for filtering or purifying liquids or gases	Equipment
844319	Printing machinery used for printing by means of plates, cylinders or other printing components of heading 84.42, not elsewhere specified or included	Equipment
848610	Machines and apparatus used solely or principally for the manufacture of semiconductor boules or wafers	Equipment
848620	Machines and apparatus used solely or principally for the manufacture of semiconductor devices or electronic integrated circuits	Equipment
848640	Machines and apparatus used solely or principally for the manufacture or repair of masks and reticles, assembling semiconductor devices or electronic integrated circuits, or for lifting, handling, loading or unloading items of heading 8486	Equipment

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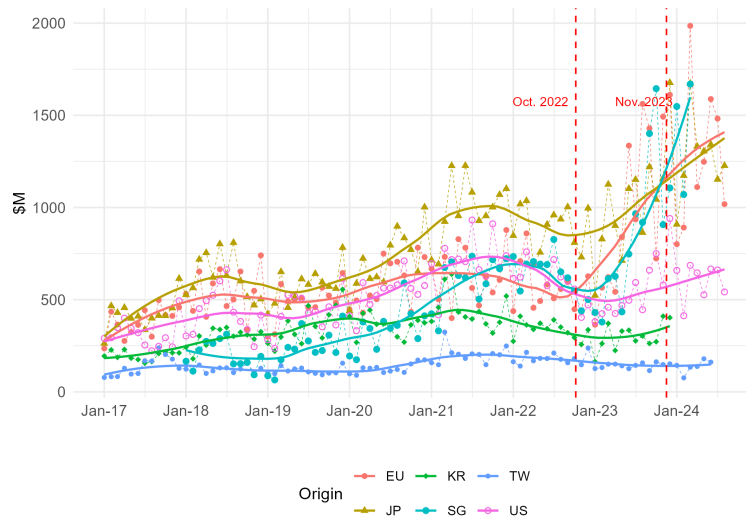
HS17 code	HS2017 description	Segment
848690	Parts and accessories of machines and apparatus of heading 8486	Equipment
901120	Compound optical microscopes for photomicrography, cinephotomicrography or micro-projection	Equipment
903082	Instruments and apparatus for measuring or checking semiconductor wafers or devices	Equipment
903084	Instruments and apparatus, not elsewhere specified or included in heading 9030, with a recording device	Equipment
903089	Instruments and apparatus, not elsewhere specified or included in heading 9030, without a recording device	Equipment
903141	Optical instruments and appliances for inspecting semiconductor wafers or devices, or photomasks or reticles used in manufacturing semiconductor devices, not elsewhere specified or included in chapter 90	Equipment
853650	Electrical switches, not elsewhere specified or included in heading 8536, for a voltage not exceeding 1000 volts	Final products
854110	Diodes, other than photosensitive or light-emitting diodes (LED)	Final products
854121	Transistors, other than photosensitive, with a dissipation rate of less than 1 W	Final products
854129	Transistors, other than photosensitive, with a dissipation rate of 1 W or more	Final products
854130	Thyristors, diacs and triacs, other than photosensitive devices	Final products
854140	Photosensitive semiconductor devices, including photovoltaic cells, whether or not assembled in modules or made up into panels, and light-emitting diodes (LED)	Final products
854190	Parts of diodes, transistors and similar semiconductor devices, and photosensitive semiconductor devices	Final products
854231	Electronic integrated circuits: processors and controllers, whether or not combined with memories, converters, logic circuits, amplifiers, clock and timing circuits, or other circuits	Final products
854232	Electronic integrated circuits: memories	Final products
854233	Electronic integrated circuits: amplifiers	Final products

Continues on next page

HS17 code	HS2017 description	Segment
854239	Electronic integrated circuits, not elsewhere specified or included in heading 8542	Final products
854290	Parts of electronic integrated circuits	Final products
903300	Parts and accessories of machines, appliances, instruments or apparatus of chapter 90, not elsewhere specified or included	Final products

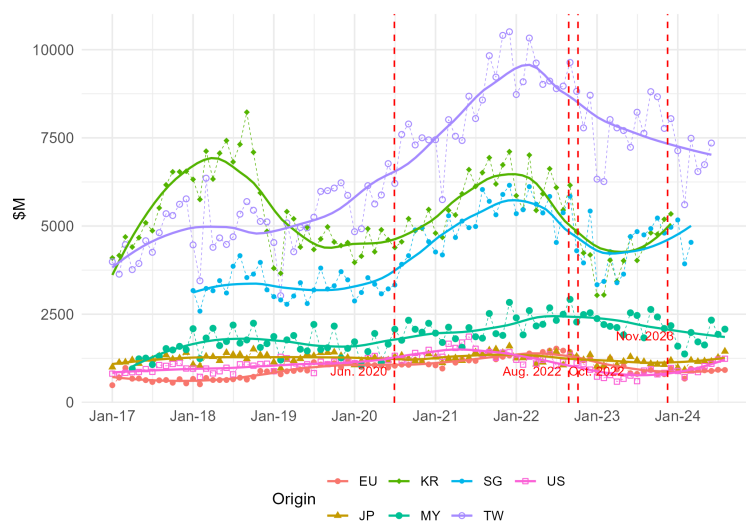
Additional Figures

Figure S1: Export values (\$M) to China from key suppliers, equipment



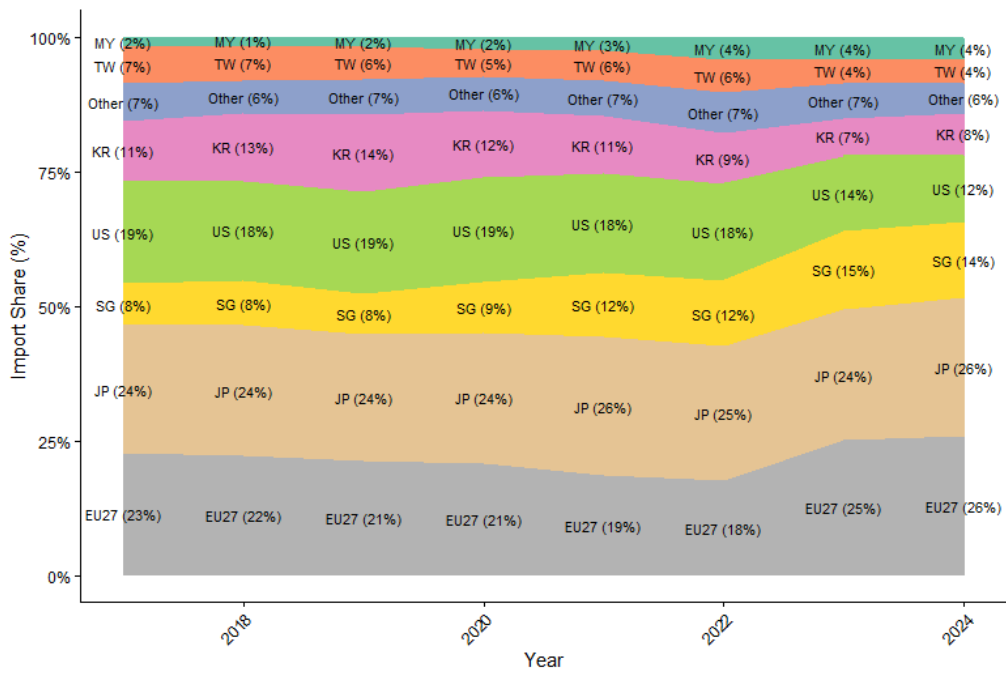
Data Source: UN Comtrade.

Figure S2: Export values (\$M) to China from key suppliers, chips



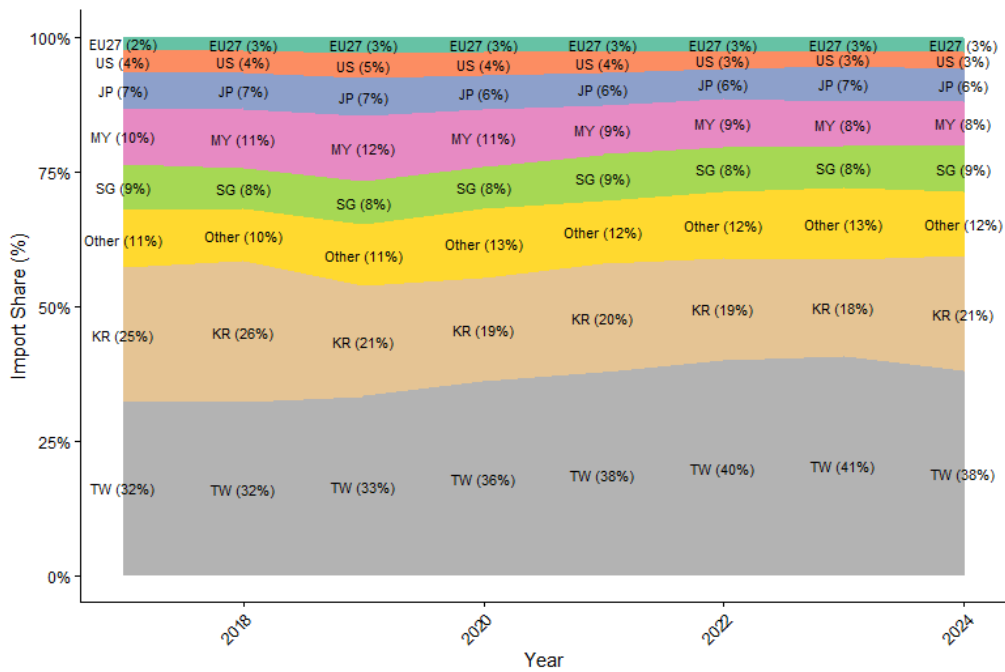
Data Source: UN Comtrade.

Figure S3: China import shares of key suppliers, equipment



Data Source: UN Comtrade.

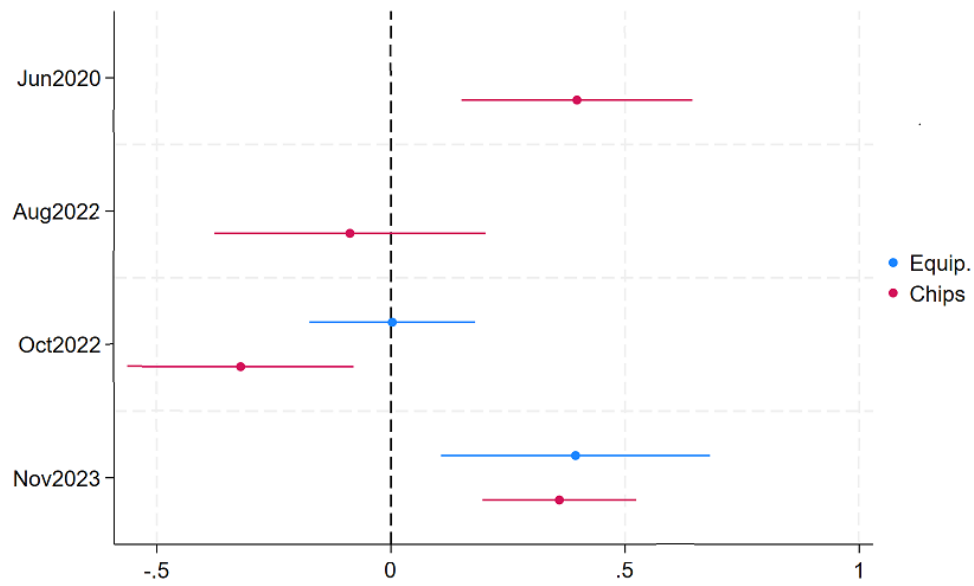
Figure S4: China import shares of key suppliers, chips



Data Source: UN Comtrade.

Direct effects on US exports

Figure S5: Heterogeneous Effects Across Policies for US



Notes: Coefficients are obtained using PPML estimation. 95% confidence intervals are based on standard errors clustered at the origin-destination-product level.

Source: UN Comtrade, GTA, analysis by authors.

Heterogeneous Effects: Tables with coefficients

Table S2: Heterogeneous Effects Across Third Countries

Dep. Var.:	PPML <i>Exports</i>	
	Coeff.	SE
$Post_t \times CHN_d \times TargetSEMIC_p^{equip} \times EU27_o$	0.872***	0.134
$Post_t \times CHN_d \times TargetSEMIC_p^{equip} \times JPN_o$	0.501***	0.141
$Post_t \times CHN_d \times TargetSEMIC_p^{equip} \times KOR_o$	0.218	0.201
$Post_t \times CHN_d \times TargetSEMIC_p^{equip} \times MYS_o$	0.101	0.224
$Post_t \times CHN_d \times TargetSEMIC_p^{equip} \times SGP_o$	0.662***	0.199
$Post_t \times CHN_d \times TargetSEMIC_p^{equip} \times TWN_o$	-0.474***	0.162
$Post_t \times CHN_d \times TargetSEMIC_p^{chips} \times EU27_o$	-0.080	0.135
$Post_t \times CHN_d \times TargetSEMIC_p^{chips} \times JPN_o$	-0.178*	0.097
$Post_t \times CHN_d \times TargetSEMIC_p^{chips} \times KOR_o$	0.160	0.200
$Post_t \times CHN_d \times TargetSEMIC_p^{chips} \times MYS_o$	0.011	0.152
$Post_t \times CHN_d \times TargetSEMIC_p^{chips} \times SGP_o$	0.313**	0.147
$Post_t \times CHN_d \times TargetSEMIC_p^{equip} \times TWN_o$	-0.298***	0.111
origin-destination-product FE	Y	
origin-product-month FE	Y	
origin-destination-month FE	Y	
Observations	1,461,494	
Pseudo R-squared	0.989	

Notes: Coefficients reported here are those displayed graphically in Figure 5. Robust standard errors are clustered by origin-destination-product. *** p < 0.01, ** p < 0.05, * p < 0.10.

Source: UN Comtrade, GTA, analysis by authors.

Table S3: Heterogeneous Effects Across Policies for Third Countries

Dep. Var.:	PPML <i>Exports</i>	
	Coeff.	SE
$PostJun2020_t \times CHN_d \times TargetSEMIC_p^{equip}$	NA	NA
$PostAug2022_t \times CHN_d \times TargetSEMIC_p^{equip}$	NA	NA
$PostOct2022_t \times CHN_d \times TargetSEMIC_p^{equip}$	0.247***	0.086
$PostNov2023_t \times CHN_d \times TargetSEMIC_p^{equip}$	0.555***	0.077
$PostJun2020_t \times CHN_d \times TargetSEMIC_p^{chips}$	0.015	0.161
$PostAug2022_t \times CHN_d \times TargetSEMIC_p^{chips}$	0.019	0.071
$PostOct2022_t \times CHN_d \times TargetSEMIC_p^{chips}$	-0.073	0.075
$PostNov2023_t \times CHN_d \times TargetSEMIC_p^{chips}$	-0.065	0.059
origin-destination-product FE	Y	
origin-product-month FE	Y	
origin-destination-month FE	Y	
Observations	1,461,494	
Pseudo R-squared	0.989	

Notes: Coefficients reported here are those displayed graphically in Figure 6. Robust standard errors are clustered by origin-destination-product. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Source: UN Comtrade, GTA, analysis by authors.

Table S4: Heterogeneous Effects Across Event Time for Third Countries for the Chip segment

	Coefficient	SE	95% Conf. Interval	
			Lower	Upper
Simple Average	-0.08	0.06	-0.19	0.03
Time to Event				
-10	-0.04	0.09	-0.22	0.13
-9	-0.09	0.07	-0.24	0.05
-8	-0.09	0.07	-0.23	0.05
-7	-0.10	0.07	-0.25	0.04
-6	0.03	0.08	-0.12	0.19
-5	0.02	0.07	-0.12	0.17
-4	-0.05	0.07	-0.18	0.09
-3	0.01	0.05	-0.09	0.12
-2	-0.03	0.04	-0.11	0.05
-1	(reference period)			
0	0.15	0.04	0.07	0.24
1	0.14	0.05	0.03	0.24
2	0.07	0.06	-0.05	0.19
3	0.12	0.06	-0.01	0.24
4	-0.03	0.08	-0.18	0.13
5	-0.04	0.07	-0.17	0.09
6	-0.10	0.08	-0.25	0.05
7	-0.09	0.08	-0.26	0.07
8	-0.26	0.09	-0.44	-0.08
9	-0.41	0.10	-0.61	-0.21
10	-0.44	0.10	-0.63	-0.25

Notes: Coefficients reported here are those displayed graphically in Figure 7, Panel (a) Chips. 95% confidence intervals are based on standard errors clustered at the origin-destination-product level.
Source: UN Comtrade, GTA, analysis by authors.

Table S5: Heterogeneous Effects Across Event Time for Third Countries for the Equipment segment

	Coefficient	SE	95% Conf. Interval	
			Lower	Upper
Simple Average	0.20	0.09	0.03	0.38
Time to Event				
-10	0.14	0.12	-0.08	0.37
-9	0.15	0.13	-0.09	0.40
-8	0.29	0.13	0.04	0.54
-7	0.14	0.12	-0.09	0.37
-6	-0.02	0.13	-0.27	0.24
-5	0.14	0.13	-0.10	0.39
-4	-0.04	0.10	-0.22	0.15
-3	0.13	0.12	-0.11	0.37
-2	0.16	0.09	-0.03	0.34
-1	(reference period)			
0	-0.09	0.09	-0.27	0.09
1	-0.18	0.11	-0.40	0.03
2	-0.21	0.09	-0.39	-0.02
3	0.02	0.11	-0.19	0.22
4	0.03	0.10	-0.16	0.23
5	0.06	0.10	-0.13	0.26
6	0.17	0.12	-0.06	0.40
7	0.12	0.14	-0.16	0.40
8	0.67	0.15	0.38	0.95
9	0.70	0.14	0.43	0.97
10	0.94	0.18	0.59	1.28

Notes: Coefficients reported here are those displayed graphically in Figure 7, Panel (b) Equipment. 95% confidence intervals are based on standard errors clustered at the origin-destination-product level.

Source: UN Comtrade, GTA, analysis by authors.

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