Downstream carbon leakage from upstream carbon tariffs: Evidence from trade tariffs

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Abstract

Pricing the carbon content of imports, or *carbon tariffs*, is being considered as a solution to policy-induced carbon leakage. However, the unilateral implementation of carbon tariffs could have unintended consequences, such as further emission reshuffling or costly trade retaliation. This is particularly the case as proposed carbon tariffs will target emissions from upstream products. This paper estimates how upstream carbon tariffs will affect carbon leakage by exploiting variation in export tariffs. Using a two-country model, I show first show that an upstream carbon tariff can lead to emission leakage down the supply chain. Empirically, I estimate the upstream and downstream foreign emission effects of export tariffs using plausibly exogenous increases in export tariffs during the 2018-2019 trade war for US manufacturing facilities, while controlling for other tariff changes. While I find evidence that US greenhouse gas emitting facilities respond to export tariffs on their outputs by reducing their emissions, I also find evidence of increased emissions from downstream facilities through input-output linkages. In the case of the US manufacturing industries that faced export tariff increases during the trade war, emission increases from input users could offset the emission reductions from facilities in upstream targeted industries. Results in this paper highlight the importance of input-output linkages for the net emission effect of incomplete carbon tariffs.

Keywords: climate policy, carbon leakage, carbon tariffs, trade policy

JEL Codes: F18, Q54, Q56, Q58

Code and data availability

The code and the underlying data to reproduce the figures, and tables are accessible here.

Disclosure statement

The author declares no competing interests.

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1 Introduction

After three decades of multilateral negotiations, countries have failed to deliver a binding and cooperative global solution for climate change mitigation. Global greenhouse gas (GHG) emissions continue to rise (NOAA, 2022), prompting some countries like those in the European Union to implement varying domestic policies to mitigate climate change, such as carbon trading markets. United Nations Climate Change Conferences are continuing to lay the foundations of an international carbon market to link domestic carbon markets, and to ensure cost-effective emission reductions (Simmons et al., 2021).

One problem with this patchwork of country-level climate policies is carbon leakage, where emission reductions from regulated countries are offset by emission increases in unregulated countries. Carbon leakage undermines the global benefits of country-level or unilateral climate policies by countering their GHG reductions. As a response to potential carbon leakage, countries with carbon prices are considering imposing carbon tariffs on trading partners without equivalent climate policies. Carbon tariffs price the carbon content of imports. Beyond reducing carbon leakage, Nordhaus (2015) demonstrates that targeted tariffs could also provide an incentive for unregulated countries to implement climate policies. This paper asks: Do carbon tariffs reduce carbon leakage? I follow the carbon leakage definition of Fowlie and Reguant (2018) which is the foreign emission response to unilateral domestic carbon pricing policy.

The unilateral implementation of country-level climate policies can lead to carbon leakage. Computable general equilibrium models find that carbon emissions from unregulated countries can increase by 10 to 30% compared to the emissions reductions in the regulated country, whereas more detailed models have found higher leakage rates and in excess of 100% (Fowlie and Reguant, 2022). Aichele and Felbermayr (2015) empirically estimate that the Kyoto Protocol led to an 8% increase in imported carbon emissions. A proposed policy solution to reduce carbon leakage and incentivize climate policy adoption in unregulated countries is imposing carbon tariffs (Markusen, 1975; Drake, 2018; Nordhaus, 2015).

To counter the carbon leakage risks from its domestic carbon market, the European Union (EU) plans to implement carbon tariffs in 2026 under its Carbon Border Adjustment Mechanism (CBAM). In the US, carbon tariffs were part of the failed Waxman-Markey Bill, and are part of the proposed Clean Competition Act (Clausing and Wolfram, 2023).[1] However, carbon tariffs could have important unintended consequences. For example, a country's imposition of carbon tariffs on trading partners could further reshuffle carbon emissions or lead to costly trade retaliations. Emission reshuffling refers to emission leakage as a response to a carbon tariff where a targeted foreign supplier exports their products, and their emissions, to a third country, thereby unchanging the initial carbon leakage (Fowlie, Petersen and Reguant, 2021).[2]

Proposed carbon tariffs also target upstream manufactured goods, such as cement, fertilizers, aluminum, and iron and steel. Therefore, these tariffs might also have unintended effects on the emissions from downstream polluting industries using these goods as inputs. Since no carbon tariffs are currently in place but are being proposed, the goal of this paper is to empirically estimate the effect of carbon tariffs on carbon leakage by looking at the emission change of facilities in industries facing increased export tariffs on their output or inputs. Import tariffs in this paper are defined as tariffs imposed by a country on imports from trading partners, whereas export tariffs are tariffs imposed by trading partners on a country's exports. Therefore, from the perspective of a country facing carbon tariffs, the relevant trade policy equivalent are

[1] Without first a domestic carbon price, Brunel and Levinson (2024) show that a carbon tariff alone is not a climate policy, as it is equivalent to a carbon consumption tax combined with a subsidy on carbon emissions.

[2] Emission reshuffling can be seen at the carbon leakage equivalent of trade diversion. Using a simulation model, Fowlie, Petersen and Reguant (2021) show the potential leakage from emission reshuffling from California's unilateral carbon tariffs on GHG emissions from electricity imports.

export tariffs.

I first develop a simple general equilibrium two-country model to study whether upstream carbon tariffs reduce carbon leakage. Since there are currently no carbon tariffs in place, I also use the conceptual model to show that trade tariffs can be used to proxy the effect of carbon tariffs on carbon leakage. Even if current trade policy has been shown to implicitly subsidize the carbon content of traded goods (Shapiro, 2021), it is not evident that trade tariff variation can inform the emission effects of carbon tariffs.

As a response to introduction of a upstream carbon tariff, the model predicts a reduction in foreign emissions from the upstream industries. However, through downward pressure on the price of the upstream good, downstream customers of the tariffed good benefit from input cost reductions and increase their emissions. Emission leakage simply moves down the supply chain from the directly targeted upstream good to the unregulated downstream sector. In the case where carbon tariffs are imposed according to an industry-level average carbon intensity, the model also show that trade tariffs and carbon tariffs have the same upstream and downstream emission effects.

Empirically, I exploit increases in export tariffs faced by US industrial facilities during the 2018-2019 trade war to proxy the effect of carbon tariffs on trading partner GHG emissions. Similarly to proposed carbon tariffs, such as the EU CBAM, the 2018-2019 trade war exports tariffs targeted specific upstream products which affected downstream customers. However, the trade war tariffs targeted a different set of products than the EU CBAM, and also targeted some downstream products. I document that for GHG emitting US industries, about 3/4 of upstream targeted CBAM industries were also targeted by the trade war, and that they both affect nearly all the same set of downstream emitting facilities through supply chain linkages. This imperfect overlap of targeted products is a limitation of the study. Also, while the empirical setting is in the US, the paper is not a predictive exercise of the potential impact of EU CBAM on US emissions, but rather a quasi-natural experiment to inform the design of carbon tariffs.

I use difference-in-differences models to estimate the GHG emission response of US manufacturing facilities to facing increases in export tariffs. Importantly, I account for the emission consequences of supply-chain linkages where emissions of downstream industrial facilities are affected by the use of the outputs from directly tariffed industries as inputs. In terms of expected effects, export tariffs on the output of a facility restrict their foreign market access and hence should lead to emission reductions. The use of those products facing export tariffs as inputs will have a counteracting emission effect by lowering the cost of domestic inputs for those producers. Since US facilities were also simultaneously protected by import tariff measures applied to foreign trading partners, I also control for the emission effects of these import tariff increases. By reducing import competition, import tariffs should increase emissions. The increased cost of the use of tariffed inputs should reduce emissions of downstream facilities.

I find evidence that export tariffs imposed on the output of US facilities reduced GHG emissions. I estimate that GHG emissions of US facilities facing export tariff increases on their output fall by about 3% for each 1 percentage point (pp) increase in export tariffs. However, I also find that emissions increase for downstream facilities that use as outputs from facilities targeted by the export tariffs as inputs. For each 1 pp increase in export tariffs, downstream facility emissions increase by 4%. Using these estimated semi-elasticities and the emission scale of upstream and downstream producers, I find that it cannot be statistically rejected that the emission reductions of targeted industries are offset by the emission increase from downstream users. Such results are consistent with other empirical studies on tariff changes from the North American Free Trade Agreement (NAFTA), the 2018-2019 trade war, and the 2002-2003 US steel tariffs. They also find evidence of offsetting effects of tariffs from downstream input users (Cherniwchan, 2017; Flaaen and Pierce, 2024; Cox, 2023).

Proposed carbon tariffs by the EU are incomplete as they are restricted to emissions from upstream products (Titievskaia, Simões and Dobreva, 2022). Results in this paper highlight the importance of considering the downstream emission effects of incomplete carbon tariffs. In the case of the set of industries covered by the 2018-2019 trade war, it cannot be rejected that the emission rebound from downstream producers offsets the emission reductions from producers directly targeted by the export tariffs. In this study, I estimate the impact of carbon tariffs on foreign emissions. In the case where the imposing country, such as the EU, has a cap-and-trade policy, then domestic emissions should not rebound. In that case, the foreign emission effect equals the global emission effect. If the country imposing carbon tariffs instead has a carbon tax, then domestic emissions can increase as a response to carbon tariffs. In this case, it still matters to study foreign emission responses to domestic climate policies, as national emissions are centerpieces of current climate negotiation processes under the United Nations Framework Convention on Climate Change.

I also estimate event-study models to test for differences in pre-trends, and conduct several robustness checks. To explore potential heterogeneity driving this main result, I interact the tariff changes with industry measures of trade and GHG intensity. I find some evidence that facilities in trade-intensive industries reduced their emissions more in response to export tariffs, and that less trade-intensive downstream users increased their emissions by more. This result suggests less trade-intensive downstream users benefited more from the domestic reductions in the price of affected products used in their production. I also find some evidence of more important emission changes for upstream and downstream facilities in GHG-intensive industries. If tariffs are leading to similar average output changes across industries of different GHG intensities, then we would expect more emission intensive industries to see greater emission changes.

I build on the empirical trade literature which uses tariff changes as quasi-experimental variation to study numerous outcomes. Researchers have estimated the effect of the 2018-2019 trade war tariff changes on US consumption, elections, employment, prices, and output (Amiti, Redding and Weinstein, 2019; Blanchard, Bown and Chor, 2019; Goswami, 2019; Waugh, 2019; Fajgelbaum et al., 2020; Flaaen and Pierce, 2024; Autor et al., 2024). More closely related to this study, studies in the trade and the environment literature have also leveraged tariff variation to empirically identify the effect of trade on local air pollution. Using a triple-difference research design, Cherniwchan (2017) finds that trade liberalization under NAFTA leads to air pollution reduction in US manufacturing plants through access to cheaper inputs from Mexico. Using a shift-share research design, Bombardini and Li (2020) exploit changes in export tariffs faced by Chinese producers from 1982 to 2010 to study the effect of trade on pollution and mortality in China.

The paper makes a contribution to the empirical trade literature by studying the effects of tariffs on global air pollution, namely GHG emissions, as opposed to local air pollution. Indeed, since the marginal damages from local air pollution are heterogeneous, is it not clear ex-ante whether reallocating air pollution across trading partners causes more or less environmental damage. However, since GHG emissions are a uniformly mixed global pollutant, any reductions of carbon leakage leads to environmental benefits. A second contribution is to consider both the downstream effect of not only import but also export tariffs. Indeed, previous papers have typically restricted the supply chain linkage analysis to the indirect effect from import tariffs. Only recently have empirical trade papers considered all channels.[3] Indeed, Autor et al. (2024) consider the direct and indirect effect of the trade war import and retaliatory tariffs on employment. In this paper, I also extend the potential supply chain effects by considering the effect on input cost of import and export tariffs, which had not been done in the trade and the environment literature.

[3]See Flaaen and Pierce (2024) for a historical discussion of the literature on the supply chain effects of tariffs.

There exists also a theoretical, numerical, and structural literature studying the effects of carbon tariffs. Studies have found that a large enough country or group of countries can reduce the foreign production of a polluting good through the use of an import tariff (Markusen, 1975; Fowlie, Reguant and Ryan, 2016; Böhringer, Carbone and Rutherford, 2018; Hsiao, 2020; Brunel and Levinson, 2024).[4] This study contributes to this literature chiefly by providing empirical evidence of the effect of carbon tariffs.

Recent studies have also developed and calibrated quantitative trade models to study global carbon emission reductions from optimal carbon tariff policies (Farrokhi and Lashkaripour, 2021; Kortum and Weisbach, 2021; Weisbach et al., 2023). These studies generally find that optimal carbon border taxes are ineffective at cutting global emissions relative to other policies such as climate clubs or optimal multilateral carbon taxes. This study aims to complement these models by highlighting the potential importance of input-output linkages in the manufacturing sector when considering proposed incomplete carbon tariffs.

While the impact of supply-chain linkage emission consequences of incomplete carbon tariffs has been discussed conceptually in Clausing and Wolfram (2023), and estimated with an empirically calibrated quantitative trade model in Campolmi et al. (2023), they have not been estimated using quasi-experimental models. This study provides empirical evidence of the importance of the downstream emission effect of upstream carbon tariffs.

This paper has several limitations. The empirical setting of the trade war is potentially a poor proxy to study the effect of proposed carbon tariffs, since different products are targeted, and at different rates. This suggests viewing cautiously the external validity of the results presented. In the paper, I more formally describe this potential overlap. Furthermore, the 2018-2019 trade war also involved both protectionist and retaliatory tariffs, multiples waves of tariffs, as well as relief programs and bilateral purchase agreements to attempt to solve the trade war. I attempt to econometrically control for and disentangle these effects. The analysis also ignores the potential indirect upstream effect on suppliers of downstream customers being directly targeted by tariffs. This restriction is common in the trade war literature, as the analysis focuses on the manufacturing sector and most directly targeted industries are already upstream sectors.

The rest of the paper has the following structure. Section 2 provides background on the 2018-2019 trade war and the proposed EU carbon tariffs. Section 3 presents a conceptual framework to think about the emission effects of carbon tariffs, and trade tariffs. Section 4 discusses the data. Section 5 presents the empirical framework. Section 6 presents and discusses the results. Section 7 concludes the paper. Appendix A, B, and C offer additional theoretical derivations, figures and tables.

2 Background

2.1 The 2018-2019 trade war

Through 2018 and 2019, the US raised import tariffs on major trading partners, and trading partners retaliated with export tariffs. This trade war was characterized by new tariffs applied on thousands of traded goods, and most changes ranged from 5 to 25 percentage point increases in ad valorem tariff rates (Fajgelbaum et al., 2020). Important manufacturing industries output protected by US import tariffs include iron and steel products, aluminum, washing machines and solar panels. Major retaliatory partners to the US import tariffs include China, the EU, Canada, Mexico, India, Russia, and Turkey. Targeted US products by

[4] In the case of a group of countries, Hsiao (2020) highlights the importance of coordination and commitment between the countries' policy stringency and timeline to effectively reduce carbon leakage.

export tariffs include agricultural products, aluminum, and iron and steel products. Retaliatory or export tariffs on US GHG reporting manufacturing industries imposed by China, Canada, the EU, and Mexico affected respectively about 5%, 2%, and both 1% of the total value of US exports. Tariffs imposed by India, Russia, and Turkey account for less than 0.1% each. Tariffs between the US, and Canada and Mexico were lifted in 2019, and in 2021 with the EU. Import and export tariffs between the US and the other trading partners, such as with China, remained in place (Flaaen and Pierce, 2024).

2.2 The European Union's Carbon Border Adjustment Mechanism

In 2026, the EU will require importers (or exporters to the EU) to pay a carbon tariff on the embedded GHG emission content of their goods (Titievskaia, Simões and Dobreva, 2022). The policy is called the Carbon Border Adjustment Mechanism (CBAM). In practice, the CBAM will require importers to purchase GHG permits priced at the prevailing EU Emissions Trading System price. The CBAM will apply to a subset of upstream traded products: cement, electricity, fertilizers, iron, steel, and aluminum. The emissions of downstream products using these tariffed upstream products will not be covered. For example, the embedded GHG emissions in imported rolled steel would face a carbon tariff, but not the emissions embedded in the steel content of imported automobiles. To determine the carbon content of imports, the CBAM will have a hybrid structure. Importers can either report their verified emissions to pay the price of the actual embedded emissions in their products or pay based on a default emission intensity. Default values by exporting country and good will be set at an average emission intensity.

Given that the 2018-2019 trade war covered some of the same products targeted by the upcoming CBAM, namely the iron, steel, and aluminum products, learning the GHG emission effect of the trade war on these industries could inform the effect of proposed carbon tariffs. Section 4 provides a more explicit analysis of the overlap of upstream and downstream coverage of the trade war and CBAM tariffs. The next section develops a stylized model to show the effects of carbon tariffs on upstream and downstream emissions, and that trade tariffs have the same emission effects as proposed carbon tariffs based on average emission intensity.

3 A simple theory of upstream and downstream carbon leakage

I turn to a simple two-country, two-good, general equilibrium model to fix ideas about the effect of carbon tariffs on upstream and downstream foreign emissions. While I am interested in the emission effects of upstream carbon tariffs, empirically I only observe trade tariffs. I therefore also consider the comparison of the emission effects of trade tariffs and carbon tariffs. The model draws heavily from Phaneuf and Requate (2016) and Fowlie and Reguant (2022), who develop theoretical models to study unilateral climate policies in international settings.

3.1 Set-up

Consider two countries, home and foreign, each with a perfectly competitive upstream or supplier industry with a representative firm $i \in (h[\text{ome}], f[\text{oreign}])$ that is a price taker in the input and output markets. Each firm produces a homogenous polluting good (q_h, q_f) with convex cost function $(C_h(q_h), C_f(q_f))$. Emissions of the upstream producers are defined by constant GHG emission rates per unit of production (e_h^u, e_f^u), such that upstream GHG emissions are $E_i^u = e_i^u q_i$. The profit functions for each upstream firm is:

$$\pi(q_i) = p_i q_i - C_i(q_i) \tag{1}$$

Downstream consumption of the domestic or imported upstream good in each country is defined by the inverse demand functions ($P_h(c_h)$, $P_f(c_f)$). While the production process of downstream customers are not explicitly defined, in the context of this model, we can think of downstream consumptions as firms using outputs from the upstream industry as inputs. GHG emissions from downstream customers are emitted with constant rate (e_h^d, e_f^d), and downstream GHG emissions are $E_i^d = e_i^d c_i$.

In an unregulated world, the open-trade competitive equilibrium is defined by the following set of equations. Domestic or foreign customers of the upstream good set their respective demand equal to their domestic price:

$$P_i(c_i) = p_i \tag{2}$$

Profit maximization by upstream producers is represented by:

$$\frac{\partial C_i}{\partial q_i} = p_i \tag{3}$$

Open trade between the countries generates a global price such that:

$$p_h = p_f \tag{4}$$

Finally, market clearing requires that global demand be equal to global supply:

$$c_h + c_f = q_h + q_f \tag{5}$$

Equations (2) to (5) define a system of six endogenous variables (c_h, c_f, q_h, q_f, p_h, p_f) and six equations. I am interested in assessing changes in upstream and downstream foreign emission under different trade policy measures, namely a trade tariff and a carbon tariff. Specifically, I want to sign the effect of different trade policy interventions on dE_f^u and dE_f^d. Since in this stylized model emission rates are constant, the upstream and downstream emission effect will be proportional to the respective production and consumption responses. More precisely, changes in upstream or downstream emissions are equal to the change in upstream production or downstream consumptions times their constant emission rate. For example, for any change in policy τ, $\frac{dE_i^u}{d\tau} = \frac{dq_i^u}{d\tau} e_i^u$ or $\frac{dE_i^d}{d\tau} = \frac{dc_i}{d\tau} e_i^d$.

3.2 Policy interventions

Below I compare changes in upstream and downstream foreign emissions for different trade policy interventions. I compare foreign emission changes from carbon tariffs to the empirical context in my data, namely trade tariffs. I first start by establishing the presence of carbon leakage in the upstream industry when the home country imposes a carbon price on emissions.

3.2.1 Home carbon price

I first establish that my stylized model can have carbon leakage from the home country imposing a unilateral carbon price on GHG emissions. Considering first the introduction of a domestic carbon price matters since a carbon tariff on its own is not a climate policy. Indeed, Brunel and Levinson (2024) show that alone, a carbon tariff is equivalent to a domestic carbon consumption tax combined with a domestic carbon pollution subsidy. A carbon tariff is potentially a useful climate policy to target carbon leakage caused by a domestic unilateral carbon price.

For simplicity, I only consider carbon leakage from upstream producers. This follows from the observation that while carbon pricing policies typically cover all industrial emissions, suggested carbon tariffs aim to reduce carbon leakage from a subset of industries covered by domestic carbon prices. Because of this policy feature, I will expand the analysis to upstream and downstream emissions when considering the impact of upstream carbon tariffs. I consider the case where the home policy maker prices domestic GHG emissions using a carbon price τ. Relative to the unregulated set-up, imposing the carbon price changes equation (3) for the home firms to $\frac{\partial C_h}{\partial q_h} + \tau e_h = p_h$, which introduces a home carbon regulation cost wedge between foreign and home marginal costs.

In order to examine the effect of the home carbon price on domestic and foreign emissions, the six equations from the system are differentiated with respect to the home emission tax τ, and the resulting system of linear equation is solved. Appendix A presents further algebraic detail. The upstream emission response of the equation system to a change in the home emission tax are: $\frac{dq_h}{d\tau} e_h^u < 0$, $\frac{dq_f}{d\tau} e_f^u > 0$. Through raising the marginal cost of production for domestic producers, output reduces and so do home emissions, which is the intended effect. Reductions at home are however offset by increases in foreign emissionsgvm through trade linkages and the increased price of the foreign good.

3.2.2 Carbon tariff

As a response to domestic carbon price-induced carbon leakage, I now consider the effect of an upstream carbon tariff on upstream and downstream emissions. Specifically, here a carbon tariff taxes the emissions embodied in imports of the foreign good based on an industry average emission intensity e_f^u. The default carbon tariff rate for CBAM is an industry average emission intensity rate, and other carbon tariff rates are most likely going to be industry-level averages given the difficulty in attributing embodied emissions to individual importers (Clausing and Wolfram, 2023). I identify the industry-level carbon tariff intervention with the variable τ_c. To derive the effect of the carbon tariff on foreign emissions, I first extend the model to differentiate between foreign goods sold domestically and exported to the home country, since only upstream exported goods face the carbon tariff. Specifically, q_f now represents domestically sold upstream goods, and q_e upstream exported goods. The foreign representative firm's profit function is now represented by the following equation to separate the cost of the carbon tariff:

$$\pi(q_f, q_e) = p_f q_f + p_h q_e - C_f(q_f + q_e) - \tau_c e_f^u q_e \tag{6}$$

Accordingly, the market clearing equation becomes: $c_h + c_f = q_d + q_f + q_e$. Following Cicala, Hémous and Olsen (2022), since the domestic and international markets are fully integrated, between selling domestically or exporting to the home country, the foreign exporter would face a price $p_h - \tau_c e_f^u$. The difference between that price and the foreign price should be zero, therefore the global price condition becomes $p_f = p_h - \tau_c e_f^u$. By trying to reduce the trade distortion caused from the unilateral home carbon price, the carbon tariff reduces the difference down between the home and foreign production costs. To determine the effect of the carbon tariff on upstream and downstream foreign emissions, I solve the modified system of equation by now differentiating the equations with respect to the carbon tariff τ_c. Appendix A shows the new set of differentiated equations in matrix form.

We are interested in changes in emissions coming from foreign production, $\frac{dq_f}{d\tau_c}e^u_f$, $\frac{dq_e}{d\tau_c}e^u_f$, and emissions from changes to downstream consumptions of the upstream goods, $\frac{dc_f}{d\tau_c}e^d_f$. Solving the system of equations, we get the typical effect of a tariff on home and foreign prices. By protecting home producers, the home price increases $\frac{dp_h}{d\tau_c} > 0$ and by restricting access to home market, the carbon tariff decreases the domestic foreign price $\frac{dp_h}{d\tau_c} < 0$. In turn, these price changes induced by the carbon tariff reduce the production of the foreign good, namely $\frac{dq_f}{d\tau_c} < 0$ and $\frac{dq_e}{d\tau_c} < 0$. Scaled by the foreign emission intensity e^u_f implies that direct emission leakage was reduced by the carbon tariff. However, since the policy ony directly target upstream emissions, downstream domestic customers benefit from the reduced price of the foreign good. Indeed, increased consumption of the upstream good causes downstream emissions to increase or $\frac{dc_f}{d\tau_c}e^d_f > 0$. Hence emission leakage simply moves down the supply chain from the directly targeted upstream good to the unregulated downstream sector. This is a consequence of the incomplete nature of the carbon tariff.

An important limitation of this simplified set-up, is that I hold emission intensity fixed. In other words, firms can only respond through reduced output as opposed to emission abatement. For carbon tariffs based on industry-level average emission intensities, this is reasonable as individual firms do not have a direct incentive to abate. However, a firm-level carbon tariff on exports would give a direct incentive for the foreign producer to abate emissions by adjusting their emission intensity. The CBAM carbon tariff proposed by the EU has a voluntary facility-level carbon tariff component, however it is unclear whether the overall foreign emission reduction would be greater or less than under a trade tariff or industry-level carbon tariff. Indeed, further targeting at the firm level could lead to a reshuffling of emissions, where lower emissions plants would export to the carbon tariff imposing country, and the higher emission plants would export to trading partners without carbon tariffs (Fontagné and Schubert, 2023). The emission differences between firm-level carbon tariffs, industry-level carbon tariffs or trade tariffs are left for future work.

3.2.3 Trade tariff

Since I do not empirically observe carbon tariffs in the data, but instead trade tariffs, I now consider whether the upstream and downstream foreign emission effects of the industry-level carbon tariff translate to a trade tariff. Here I model the trade tariff as a specific tariff that directly taxes the foreign good imports at a rate of τ_t per unit. Since there are constant emission rates in this model, the changes in upstream and downstream foreign emissions follow directly from the carbon tariff case. The foreign representative firm's profit function is now represented by the following equation:

$$\pi(q_f, q_e) = p_f q_f + p_h q_e - C_f(q_f + q_e) - \tau_t q_e \tag{7}$$

and the global price condition becomes $p_f = p_h - \tau_t$. The sign of the comparative static exercise for the trade tariff case again follow directly from the industry-level carbon tariff. The upstream trade tariff reduces direct foreign upstream emissions, but by pushing domestic foreign prices down, emission leakage now leaks downstream the supply chain by increasing downstream consumption emissions.

Hence, the foreign emission effect of the trade tariff has the same effect as the industry-level carbon tariff since both interventions do not incentivize changes to emission intensity. Therefore, given the current default baseline carbon tariffs being proposed based on industry-level emission intensity, I view the trade tariff variation from the 2018-2019 trade war as a reasonable source of variation to empirically study the upstream and downstream GHG emission effects of carbon tariffs.

3.3 Connection to estimation

This stylized model highlights the unintended spillover leakage effects of targeting carbon tariffs to upstream goods, such as currently proposed by the EU CBAM. While the tariff reduces direct leakage through a reduction in production and emissions of the upstream producers, the reduction in the upstream good price leads to increased emissions and consumption downstream in the supply chain.

From the data, I will estimate the effect of trade tariff change on upstream emissions, namely $\frac{(dq_f+dq_e)}{d\tau_t}e^u_f$, and the downstream emission change from the same upstream tariff, or $\frac{dc_f}{d\tau_t}e^d_f$. These counteracting effects could differ depending not only on specific emission intensity of each sectors, but the relative size of upstream supply and downstream demand responses.

The model also shows that the foreign emission effects of a trade tariff is the same as an industry-level tariff. The model therefore provides some conceptual support for using the trade tariff increases during the trade war to learn about the upstream and downstream foreign emission effects of proposed carbon tariffs.

4 Data

In order to estimate the upstream and downstream emission effects of the trade war export tariffs on US manufacturing plant emissions, I compile a panel data set of plant-level GHG emissions, tariff changes, and trade and input-output data to aggregate tariffs at the industry level and calculate downstream tariff exposure. Using restricted access US Census of Manufactures data, tariff change exposure could be calculated at the plant-level. However, without such restricted access, I am limited to calculating the tariff increase at the most disaggregated industry level, namely at the NAICS 6-digit level. This section describes the data sources, presents summary statistics of manufacturing industries affected by trade war tariffs, and explores the exposure overlap between the trade war export tariffs and EU CBAM tariffs.

4.1 Trade war tariff data

Commodity or product-level tariffs are used in the analysis to construct industry-level trade tariffs protecting or faced by US manufacturing plants. While the variable of interest is the export tariffs, I need to account for confounding increases in import tariffs. The ad valorem trade war tariff increases for 2018 and 2019 between the US and retaliatory trading partners are taken from Fajgelbaum et al. (2020) and Fajgelbaum et al. (2021).

These data include the US tariffs waves on iron and steel, aluminum, China varieties, washing machines and solar panels, and the retaliatory tariffs from China, Europe, Canada, Mexico, India, Russia and Turkey. Non-manufacturing sectors, such as oil, mining, and agricultural production, were also targeted by the trade war. While the preferred specifications are restricted to the manufacturing sector, some figures and tables in Appendix B and Appendix C consider all the affected sectors. I follow the empirical trade literature studying the 2018-2019 trade war or NAFTA tariff changes, and only consider the tariff increases from the trade war (Cherniwchan, 2017; Fajgelbaum et al., 2020; Flaaen and Pierce, 2024). This approach assumes that baseline tariff rates outside of the trade war tariffs across trading partners remain unchanged. This assumption is reasonable given the unprecedented nature of trade war tariff changes (Autor et al., 2024). I also follow Cherniwchan (2017) and Bombardini and Li (2020) by only considering changes in tariffs as opposed to additionally considering changes in non-tariff barriers.

4.2 Trade data

Trade data are used to trade-weight the construction of the industry-level tariffs. I collect 2010 to 2021 US Census trade data from Schott (2008).I use the 2010 to 2017 data to construct the industry-level tariffs to avoid the impact of the change in tariffs may have had on industry-level trade.

4.3 Greenhouse gas data

The outcome variable of interest is manufacturing plant-level greenhouse gas emissions. I use US plant data to estimate the emission effect of tariff changes. Yearly plant-level GHG data measured in CO_2 equivalent (CO_2e) are obtained from the US EPA mandatory greenhouse gas reporting program (GHGRP). Variables provided include yearly CO_2e emissions, the six-digit North American Industrial Classification System (NAICS-6) code, geographic information, facility name, and parent firm name from 2010 to 2021. The US EPA mandates all facilities that emit more than 25,000 tonnes of CO_2e per year to report their emissions. The sample considered in this analysis includes about 5,500 reporting facilities per year, about half of which are in the manufacturing sector.

4.4 Industry-level tariffs

I construct industry-level tariffs using the commodity tariff data, and the trade data. Export tariffs are my main variable of interest, and I control for import tariffs. Ad valorem tariffs and trade value between the US and its trading partners are first assigned to NAICS-6 codes using the concordance tables created by Pierce and Schott (2012). I then aggregate the tariff data to the NAICS-6 level by taking a trade-weighted average of the tariffs using the average 2010-2017 trade values as weights. This procedure yields an export or import tariff at the NAICS-6 level, τ_{it}, for NAICS-6 i and year t. I then assign these tariff measures to each US manufacturing plant, p, based on the plants' NAICS-6 code i. There are more than 225 unique manufacturing NAICS-6 industries in the GHGRP. More than half of them were directly targeted by the trade war.

4.5 Industry-level input tariffs

Since tariffs can affect plants not only through their output but their inputs, I follow several papers in the empirical trade literature and build input tariffs from the export and import tariffs (Cherniwchan, 2017; Goswami, 2019; Flaaen and Pierce, 2024). I construct industry-level input tariffs using the industry-level export and import tariffs calculated above in combination with the 2012 US input-output (IO) table from the US Bureau of Economic Analysis. The *use* table of IO tables provides a dollar value of output use from industry j as input in industry i at the NAICS-6 level. For each NAICS-6 code, I calculate the cost share of output use from other NAICS-6 industries. I then multiply the industry-level export and import tariffs of the use industry by the cost share and aggregate the input tariff at the NAICS-6 level.

4.6 Summary statistics and descriptive analysis

Figure 1 shows the distribution of the number of manufacturing facilities facing increases in new industry-level export tariffs between 2018 and 2019. Most GHG emitting plants facing tariff increases faced increases of less than 1 pp. A few hundred plants faced increases in output export tariffs of 2 pp or more, whereas a smaller number of facilities faced larger export tariff increases on their inputs. I exploit this intensity of tariff increases in my empirical strategy.[5] For manufacturing industries facing retaliatory tariffs, the average industry-level increase in export tariff on output was of about 1 pp and 0.4 pp on inputs.

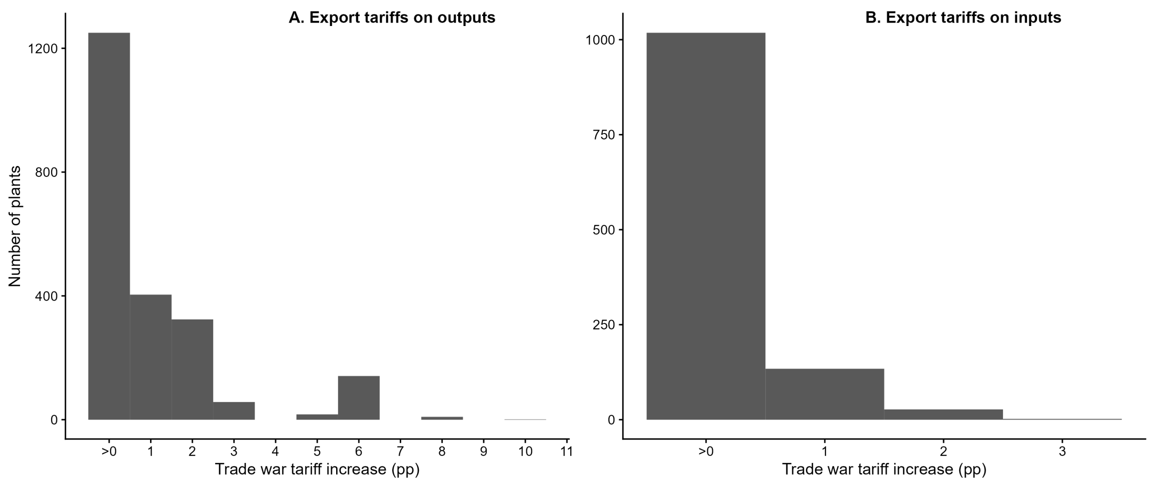

Figure 1: Distribution of NAICS-6 level export tariff increases facing U.S. GHG emitting facilities

Notes: Figure 1 shows the distribution of GHG emitting manufacturing facilities facing increases in export tariffs on their output or input during the 2018-2019 trade war.

Table 1 shows various summary statistics of NAICS-6 level export tariffs increase and manufacturing facility GHG emissions at the NAICS-3 level. The table highlights the downstream impacts of tariffs for industries not directly targeted by the trade war export tariffs. Tables A1 and A2 respectively show the export and import tariffs and further decomposed summary statistics of the NAICS-6 level industry tariffs at the NAICS-3 level for the manufacturing sector. They show that most facilities within the same industries often face both export and import tariff increases on their output or inputs, and hence the importance of accounting for all tariff changes.

[5] Figure A1 in Appendix B shows the distribution of GHG emitting US manufacturing plants for the increases in output and input import tariffs.

Table 1: NAICS-3 manufacturing variation in trade war export tariffs increases and greenhouse gas emissions

		Export tariff increases (pp)						
		Output		Input		CO2e (kt)		
Manufacturing industry	NAICS-3	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	# plants
Food	311	0.69	1.1	0.11	0.29	114	348	330
Beverage and tobacco products	312	1.75	3.07	0.25	0.66	48	30	27
Textile mills	313	0.24	0.27	0.02	0.05	70	47	7
Textile product mills	314	0.32	0.48	0.03	0.03	46	22	6
Wood products	321	0.34	0.92	0.02	0.05	119	124	25
Paper	322	0.45	0.61	0.1	0.11	671	747	226
Printing and related activities	323	0.29	0.42	0.04	0.05	31	7	2
Petroleum and coal products	324	0.4	0.9	0.08	0.09	1,205	1,583	173
Chemical	325	0.66	0.8	0.07	0.12	306	725	650
Plastics and rubber products	326	0.24	0.45	0.13	0.18	39	19	34
Nonmetallic mineral products	327	0.6	1.4	0.06	0.08	304	412	344
Primary metal	331	1.11	1.73	0.26	0.58	304	1,041	274
Fabricated metal products	332	0.44	0.65	0.52	0.8	40	31	26
Machinery	333	0.44	0.47	0.29	0.31	38	21	18
Computer and electronic products	334	0.59	0.88	0.09	0.09	126	146	51
Electrical equipment and appliances	335	0.78	0.76	0.32	0.32	26	18	14
Transportation equipment	336	0.51	1.34	0.37	0.56	46	26	81
Furniture and related products	337	0.61	1.14	0.22	0.36	20	NA	1
Miscellaneous	339	0.39	0.39	0.13	0.13	62	25	3

Notes: pp = percentage point. kt = kiloton. Std. dev. = Standard deviation.

As a complement to the NAICS-3 level summary statistics in Table 1 for the policy and outcome variables, Figure 2 presents a scatter plot of percentiles of the policy variables used in the analysis, namely the increase in upstream and downstream export tariffs for GHG emitting NAICS-6 digit industries. Industries at the top-right of the figure, such as certain some food, and iron and steel product manufacturers, faced the largest increased on both their inputs and outputs. Industries at the bottom of the figure only faced direct export tariffs on their output, such as upstream food manufacturers and raw steel and aluminum manufacturers. The dark bottom-left dot represents the overlapping set of industries that did not face any export tariff exposure, used as controls in the empirical analysis. This leaves the top-left quadrant industries, such as transportation part manufacturers and other food manufacturers, only facing downstream export tariffs. The discontinuity below the 50th percentile for the downstream export tariff increase reflects the fact that for about one half of the industries, they did not face any downstream exposure.

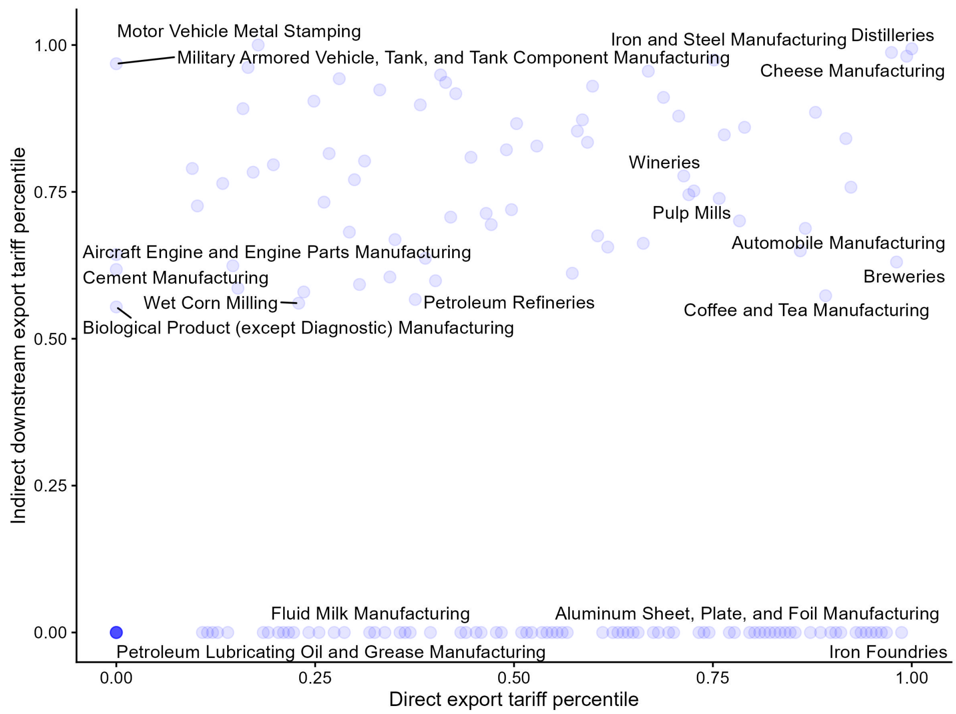

Figure 2: Percentiles of NAICS-6 level export tariff increases facing U.S. GHG emitting industries

Notes: Figure 2 plots the percentile of the average retaliatory tariff increase on outputs and inputs for GHG emitting U.S. NAICS-6 industries during the 2018-2019 trade war.

While the stylized model in Section 3 established the equivalence of upstream and downstream emission effects from industry-average carbon tariffs versus trade tariffs, such an argument assumes that these are imposed on the same set industries. However, the directly and indirectly targeted industries from the trade war export tariffs are not the same set of industries targeted in carbon tariff proposals. I discuss the potential empirical overlap of the industries targeted by trade war export tariffs and proposed carbon tariffs using the current list of products considered by the EU CBAM legislation. I select CBAM exposed NAICS codes based on the product list on Annex I of the EU Regulation 2023/956 (European Union, 2023).[6]

[6]The relevant NAICS codes are 32531, 32731, 331, 3321, 33231, 3324, 3325, 3326, 33272, and 3328 based on list of cement, fertilizer, iron and steel, and aluminum traded products included in Annex I of the of the EU 2023/956 CBAM regulation.

Of the 27 NAICS-6 digit that would be directly targeted by EU CBAM tariffs, about 3/4 of them were targeted by the 2018-2019 trade war export tariffs. Using this list of 27 NAICS-6 industries, I construct the cost share for downstream customers of that use those outputs as inputs using the 2012 US input-output table. Out of the 74 NAICS-6 downstream industries that would be affected by the upstream CBAM, 71 of them are also downstream industries affected by the export tariffs during the trade war. More formally, Figure 3 shows the relationship between the percentile of downstream trade war export increases and the percentile of cost-share from the upstream CBAM industries. While only a highly suggestive figure, there is a positive relationship in the more affected downstream industries by export tariffs, and industries more dependent on inputs from upstream CBAM industries. A limitation of this analysis is that it ignore how carbon intensity of upstream industries affects the downstream cost ranking.

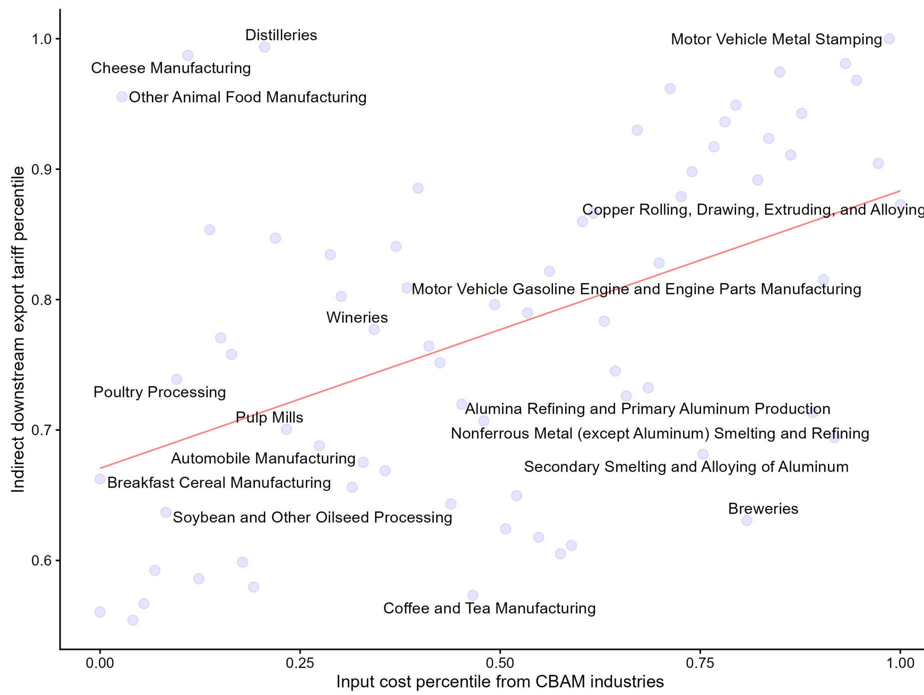

Figure 3: Percentiles of NAICS-6 level export tariff increases facing U.S. GHG emitting industries

Notes: Figure 2 plots the percentile of the average retaliatory tariff increase on outputs and inputs for GHG emitting U.S. NAICS-6 industries during the 2018-2019 trade war.

The illustrative analysis of the empirical overlap between the trade war export tariff exposure and hypothetical EU CBAM tariff exposure shows an important overlap for both the upstream and downstream industries. The next section more formally describes how variation in upstream and downstream export tariff exposure across industries and time is empirically exploited.

5 Empirical framework

The conceptual model predicts that upstream carbon tariffs would have two effects on foreign GHG emissions: decrease directly targeted upstream emissions, and increase downstream emissions. Through supply chain linkages, the downward pressure on domestic foreign price of suppliers benefits downstream consumers untargeted by the carbon tariff. I now turn to empirically testing the upstream and downstream effects of export tariffs on plant-level changes in GHG emissions.

The ideal experiment to understand the importance of supply chain leakage from upstream carbon tariffs would involve exploiting exogenous changes in export tariffs on the same upstream products being targeted by the EU CBAM, namely on cement, fertilizers, aluminum, and iron and steel products. In this setting, we could estimate the causal direct and indirect emission effect of the carbon tariff by comparing changes in emissions between plants facing high and low levels of direct or indirect tariffs. Without such an experiment, I exploit quasi-experimental increases in tariffs caused by the 2018-2019 trade war. Empirically, there are two important differences between the ideal experiment and exploiting the trade war. First, the trade war tariffs did not target the same set of products as the proposed carbon tariffs. On this first difference, Section 4 provides suggestive evidence of positive correlation and representativeness of the same downstream industries affected by the trade war and the CBAM tariffs, and also overlap in the upstream industries. Second, the trade war tariffs were both import and export tariffs, not just export tariffs as for carbon tariffs. I will address this difference through econometrically controlling for contemporaneous changes in import tariffs.

To estimate the effect of export tariff increases on changes in US manufacturing plant emissions, I use difference-in-differences (DiD) models and event-study (ES) models. The unit of observation is at the facility-industry-year level, the outcome variable yearly greenhouse gas emissions, and the treatment variable NAICS-6 industry-level tariff increases from the 2018-2019 trade war. The main sample is restricted to facilities in the manufacturing sector.

To identify the causal impact of trade tariffs on facility-level greenhouse gas emissions, the DiD and ES research designs exploit both the temporal and industry variation in tariff increases brought by the 2018-2019 trade war. Since the tariff increases affected different industries, I compare changes in emissions for facilities facing high tariff exposures, to ones who face lower or no tariff changes, before and after the trade war. These two differences allow me to account for national trends and shocks in emission changes affecting the whole manufacturing sector, and time-invariant differences between facilities that affect their emissions. Also, the varying levels of export and import tariffs mean that I can simultaneously estimate the effects of the multiple different types of tariff increases.

Before studying the effect of export tariffs on facility-level GHG emissions, I first look into the effect of the constructed NAICS-6 industry-level tariffs on industry-level net export value. For example, industry-level export tariff increases should be correlated to decreases in the corresponding net export values through restricted foreign market access. In contrast, downstream exposure to export tariff increases should be related to increased net exports through lowered input costs. While numerous studies have previously estimated the effects of the trade war tariffs on trade (Amiti, Redding and Weinstein, 2019; Fajgelbaum et al., 2020, 2021; Flaaen and Pierce, 2024), I nevertheless want to establish the correlation between the build industry-level tariff variables in Section 4 with their effects on industry-level trade before moving to facility-level GHG emissions. I therefore run the following DiD model:

$$y_{it} = \beta_1 \Delta\tau_i^O \times Post_t + \beta_2 \Delta\tau_i^I \times Post_t + X_{it}\theta + \mu_i + \eta_t + \epsilon_{it} \tag{8}$$

where y_{it} is net exports in millions of US dollars at the NAICS-6 industry i and year t level. $\Delta\tau_i^O$ is the averaged 2018-2019 export tariff increase faced by NAICS-6 industry i on its output, and $\Delta\tau_i^I$ is the exposure to the export tariff increase through its input use. $Post_t$ is equal to one after 2017 once the trade war began. β_1 and β_2 are respectively identify the change in net export value from a 1 pp increase in either the output or input export tariff. X_{it} are control variables for the industry exposure to output and input import tariff increases during the trade war. Not controlling for the output and input import tariff increases could introduce omitted variable bias, as they are correlated with the export tariff increases as evident from Table A1. NAICS-6 fixed effects are accounted for by μ_i, and η_t are year-fixed effects. Standard errors are clustered at the NAICS-6 digit level. There are over 500 different NAICS-6 treated industries in the industry-level trade value sample. I also consider a specification with two-digit NAICS-by-year fixed effects to account for broad industrial sector-specific shocks.

After estimating the effect of the industry-level tariff increases on industry-level trade, the main estimating strategy explores the effects of the export tariff increases on facility-level GHG emission changes. Specifically, I estimate the following DiD model:

$$\ln\left(\text{CO}_2\text{e}_{pit}\right) = \delta_1 \Delta\tau_i^O \times Post_t + \delta_2 \Delta\tau_i^I \times Post_t + X_{it}\Theta + \psi_p + \omega_t + \varepsilon_{pit} \tag{9}$$

where $\text{CO}_2\text{e}_{pit}$ are greenhouse gas emissions measured in CO_2e for a US industrial plant p, in NAICS-6 industry i and year t. $\Delta\tau_i^O$ is the averaged 2018-2019 export tariff increase faced by NAICS-6 industry i on its output, and $\Delta\tau_i^I$ is the exposure to the export tariff increase through its input use. $Post_t$ is equal to one after 2017 once the trade war began. δ_1 and δ_2 are semi-elasticities interpreted as the percentage change in GHG emissions from a 1 pp increase in output or input export tariff exposure.[7] X_{it} are control variables for the industry exposure to output and input import tariff increases during the trade war. ψ_p, and ω_t are respectively plant and year fixed effects; and ε_{pit} an error term. Standard errors are clustered at the level of treatment variation, namely at the NAICS-6 level. There nearly 225 different GHG emitting NAICS-6 treated manufacturing industries in the facility-level sample.

The plant-fixed effects account for time-invariant differences between industrial facilities, such as emission intensity, and size. The year-fixed effects account for changes in national policies and shocks that affect manufacturing emissions, such as economic growth and exchange rate fluctuations. I also consider specifications with state-by-year and two-digit NAICS-by-year fixed effects. The state-by-year fixed effects control for important changes in state-level environmental policy changes, such as California's cap-and-trade system, and differences in COVID-19 stay-at-home policies. The varying composition of NAICS-6 industry plants within each state allows me to use state-by-year fixed effects. The two-digit NAICS-by-year fixed effects capture differential yearly emission changes in the broad categories of industrial sectors, namely in the food and textile manufacturing sector (NAICS-2 31), the wood, chemical, and non-metallic manufacturing sector (NAICS-2 32), and the automotive, machinery, and metals manufacturing sector (NAICS-2 33).

More formally, to build confidence on the estimation procedure and to interpret δ_1 and δ_2 as causal, I test for differences in pre-trends by running an event-study version of equation (9). I interact the tariff increases with year dummies. I omit the year 2017, to interpret the interacted coefficients as differences in emission changes between facilities facing high tariff increases to those facing low or no tariff increases relative to that change in the year before the trade war began. Specifically, I estimate the following event-study regression:

$$\ln\left(\text{CO}_2\text{e}_{pit}\right) = \sum_{\substack{2010 \le \tau \le 2021 \\ \tau \ne 2017}} \delta_1^\tau \Delta\tau_i^O \times \mathbf{1}(\tau = t) + \sum_{\substack{2010 \le \tau \le 2021 \\ \tau \ne 2017}} \delta_2^\tau \Delta\tau_i^I \times \mathbf{1}(\tau = t) + X_{it}\Theta + \psi_p + \omega_t + \varepsilon_{pit} \tag{10}$$

[7] Since changes in trade war tariffs, or $\Delta\tau_i^O$ and $\Delta\tau_i^I$, are often zero for control industries, I focus on estimating semi-elasticities instead of elasticities. I also report results in Appendix C with the dependent variable in levels, consistent with equation (8) in which net exports can't be logged.

In equation (10) the main reduced-form coefficients of interest are now the δ_1^τ and δ_2^τ. When $\tau < 2017$, δ_1^τ and δ_2^τ tests for differences in pre-trends in the change of emissions between manufacturing facilities facing high versus low or not tariff increases, relative to the year before the trade war.

5.1 Upstream and downstream effects of export tariffs

While the coefficients β_1, β_2, δ_1, and δ_2 give the increases in industry-level net exports or facility-level emissions from a 1 pp increase in output or input tariffs, these are not the exact coefficients I want to compare the upstream and downstream effects of incomplete carbon tariffs. Instead, I scale the input tariff semi-elasticities β_2 and δ_2 by the implied input tariff increase from a 1 pp increase in upstream tariffs. Indeed, through input-output linkages in the manufacturing sample considered, a 1 pp increase in export tariffs in output corresponds to a 0.4 pp increase in input tariff on average for downstream industries.[8] Therefore, in the result figures and tables below, I compare the net export effect of a 1 pp point increase in export tariff on the direct upstream effect using β_1 and δ_1 to the respectively indirect downstream effect using scaled β_2 and δ_2 by the implied downstream input tariff exposure from a 1 pp upstream output export tariff. Standard errors are adjusted using the delta method.

6 Results

This section presents estimates of the upstream and downstream effects of export tariff increases on industry-level trade and US manufacturing plant GHG emissions using equations (8), (9), and (10). For the main estimates for facility-level GHG emissions, I first test for common pre-trends. I then discuss the overall difference-and-differences estimates, conduct robustness checks, and finally interact the export tariff variable with measures of emission and trade intensity to explore potential heterogeneity of responses.

6.1 Export tariff effects on industry-level net exports

Table 2 presents the estimates of the effect of the output and input export tariffs exposure on industry-level net exports using equation (8). The first column only includes industry and year-fixed effects, and the second column further includes NAICS-2 by year fixed effects to account for sector-specific shocks. The estimates show that net exports decrease for industries for which their output was targeted by export tariff increases. This reduction in net exports is consistent with these industries facing restrictions in foreign market access. Specifically, a 1 pp increase in export tariff on output is related to a nearly 300 million USD reduction in net exports for the average manufacturing industry. These upstream estimates are statistically precise in both columns.

Net exports increase for industries exposed to export tariff increases on their inputs. This effect is consistent with the notion that domestic reductions in prices of affected output by export tariffs can be beneficial for US buyers of these products. Estimates suggest that a 1 pp increase in export tariffs on domestic products used for inputs increases net export value for industrial sectors by about 800 million to 1 billion USD, and the estimates are statistically different than zero. These larger net export effects in downstream industries are partly explained by the fact that the average downstream manufacturing industry is larger and accounts for more trade value than the average upstream industry. Indeed, the mean upstream industry

[8] I calculate the implied indirect downstream tariff from a 1 pp increase in direct tariff by dividing the average indirect tariff faced by downstream facilities during the trade war by the average direct tariff increase faced by directly targeted facilities.

has export values of $ 3,9 billion, $ 6.2 million of imports, and a mean total value of sales (TVS) of $ 16 billion. The average downstream industry is about 1.5X larger on all variables with an average export value of $ 5.8 billion, $ 9.3 billion for imports, and $ 23 billion for TVS. Scaling the estimates of column 2 by average TVS, the downstream trade response is about 2X larger than the upstream effect, and the size of the scaled effects are not statistically distinguishable from each other.

Table 2: Industry-level US net export effect from a 1pp increase in trade war export tariffs

	Net exports (mil $)	
	(1)	(2)
Direct effect from export tariffs	-274.231^{*}	-291.702^{**}
	(143.325)	(142.274)
Indirect downstream effect from export tariffs	$1{,}039.853^{**}$	841.812^{**}
	(418.756)	(387.221)
Adj. R2	0.94	0.94
NAICS-2 X Year	×	✓
Observations	4,168	4,168

Notes: Estimates of effect from a 1 pp increase in export tariffs on NAICS-6 level net exports in millions of USD. All models include year fixed effects and NAICS-6 fixed effects. Facilities are restricted to the manufacturing sector. Column 1 is the baseline model, whereas column 2 further includes NAICS-2 by year fixed effects. Robust standard errors clustered at NAICS-6 level in parentheses (* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$).

Although imprecise, the finding of larger downstream effects on input users than upstream effect on directly targeted output has been found across settings in different empirical trade papers. Cherniwchan (2017) finds greater downstream changes from NAFTA import tariff reductions on US facility-level $PM_{2.5}$ emissions compared to upstream import tariff emission responses by a factor of three. Studying the 2018-2019 trade war, Flaaen and Pierce (2024) find cumulative effects of 2.4 to 10 times larger from rising input costs versus import tariffs on output across employment, production, and producer price for US manufacturing. Lastly, Cox (2023) finds that the employment changes from downstream effects of the 2002-2003 US steel tariffs to be greater than the total upstream steel industry employment.

Table 2 provides evidence of the relevance of the NAICS-6 industry-level export tariff variables. These estimates also suggest that downstream industries are more responsive to upstream export tariff increases than the targeted upstream industries. Table A3 presents a consistent story for net export effects for industries exposed to the output or input import tariff increases.

6.2 Export tariff effects on facility-level GHG emissions

I now turn to my main estimating strategy, namely the effect of the export tariff increase on manufacturing facility-level GHG emission changes. I first estimate the event-study version of equation (9) to compare changes in GHG emissions for facilities in NAICS-6 industries that faced export tariff increases to other manufacturing facilities in NAICS-6 industries that were not targeted by the trade war tariff changes. This allows me to visually test for pre-trends and the effect of the export tariff increases.

We would expect manufacturing facilities facing increases in export tariffs on their output to reduce their emissions, and facilities that use these outputs for their production to increase their emissions. These effects are consistent with the economic intuition of reduction in output from reduced access to foreign markets, and reduced domestic prices for the use of those outputs as inputs.

Figure 4 shows the percentage change in emissions for facilities facing increases in export tariffs on their outputs or their inputs during the trade war. Relative to 2017, the coefficients for years before the trade war for both panels are not statistically distinguishable from zero. For facilities facing export tariffs increase on their output, there is a decrease in emissions after the export tariff increases. For facilities exposed to export tariffs on their inputs, their emission increased after the beginning of the trade war, however these treatment effects are imprecisely estimated at the 5% significance level. The increase in downstream and upstream effects over time is consistent with shorter time studies on the 2018-2019 trade war on manufacturing output. Indeed, Flaaen and Pierce (2024) fail to finds precisely estimated effects on the 2018-2019 trade war on US manufacturing production level using monthly data from January 2017 to September 2019. They explain the lack of precision on production responses due to order backlogs which supported short term production and the adjustment time required for firms to reevaluate customer and supplier relationships. The growing effect sizes on emissions over the longer term period from 2018 to 2021 in Figure 4 is consistent with this medium to longer term effect of the tariffs. This story is also consistent with anecdotal data from US manufacturers in the automobile and food sectors who altered their production decisions later in the trade war (Tariffs and the Industry, 6 January 2020; Bown, 2021). The event-study graphs for facilities facing output and input import tariffs are shown in Figure A2.

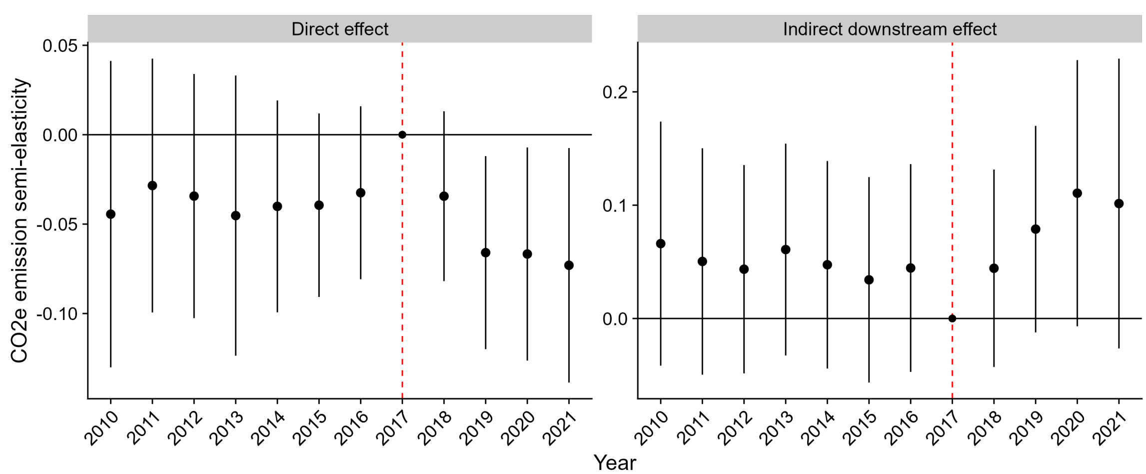

Figure 4: Event-study model of the effect of trade war export tariffs on CO2e emissions

Notes: Point estimates and 95% confidence intervals of the semi-elasticity effect of a 1 pp increase in export tariff on direct and indirect downstream log CO_2e emissions relative to 2017 using an event study version of equation (9). Estimates for the sample restricted to the manufacturing sector are shown. Standard errors are clustered at the NAICS-6 level.

Figure 4 provides evidence of a decrease in GHG emissions for facilities facing an increase in export tariffs, but offers a cautionary tale of a potential rebound of emissions from input users downstream. Table 3 presents the semi-elasticities of the export tariffs across different sets of fixed effects using equation (9).

The first column only includes plant and year fixed effects, columns 2 and 3 respectively add state-by-year, and two-digit NAICS-by-year fixed effects to account for more unobserved shocks correlated with the trade war. Estimates from equation (9) in column 3 suggest that a 1 pp increase in export tariff on output reduces industrial facility emissions by 2%. In turn, a 1 pp increase in export tariffs leads to a 4% increase in downstream emissions. Coefficients for both the upstream and downstream emission effects are nearly all statistically different than zero.

As discussed above, while the upstream and downstream effects are not statistically different from each other, the larger point estimate of downstream producers is consistent with previous studies across empirical trade settings that have found larger responses for tariff exposures on inputs versus ouputs (Cherniwchan, 2017; Flaaen and Pierce, 2024; Cox, 2023). While Cherniwchan (2017) only studies the supply chain implications of NAFTA import tariffs as opposed to through export tariffs changes also, the absolute value of the upstream and downstream effects on facility-level $PM_{2.5}$ for a 1 pp increase in tariff are quantitatively similar to the reported estimates in Table 3. Table A4 presents all the coefficients for both the upstream and downstream emission effects for both the export and import tariffs. The signs of the import coefficients are of the expected sign, and the estimates also show a large point estimate for downstream input exposure for import tariff increases relative to output import tariff exposure.

Table 3: Semi-elasticity of the trade war export tariffs on facility-level CO2e emissions

	ln(CO2e)		
	(1)	(2)	(3)
Direct effect from export tariffs	-0.019	-0.027^{**}	-0.027^{**}
	(0.017)	(0.013)	(0.013)
Indirect downstream effect from export tariffs	0.040^{*}	0.045^{*}	0.041^{*}
	(0.024)	(0.023)	(0.025)
Adj. R2	0.87	0.87	0.87
State X Year	×	✓	✓
NAICS-2 X Year	×	×	✓
Observations	27,514	27,514	27,514

Notes: Estimates of the emission semi-elasticity from a 1 pp increase in export tariffs. All models include year fixed effects and plant fixed effects. The control and treatment groups are restricted to facilities in the manufacturing sector. Column 1 is the baseline model. Column 2 further includes state by year fixed effects. Column 3 additional controls for NAICS-2 by year fixed effects. Robust standard errors clustered at NAICS-6 level in parentheses (* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$).

6.2.1 Net emission effect of export tariffs

The estimates from equation (9) in Table 3 suggest that the emission rebound of downstream facilities to upstream carbon tariffs could offset emission reductions from upstream facilities in directly targeted industries. . However, the estimates do not say by how much. To determine the net emission effect from a 1 pp export tariff increase, two additional ingredients are needed besides the semi-elasticity estimates from

Table 3, namely the size of GHG emissions in the upstream and the downstream industries. In the context of the 2018-2019 trade war, the respective GHG emission size of upstream industries and downstream industries affected by the export tariffs on outputs is 808 and 584 Mt. Combining these numbers with the semi-elasticities from the column (2) in Table 3, a 1 pp increase in export tariff-reduced upstream emissions by about 22 Mt, however, increased downstream emissions by 24 Mt. The net effect in this case is that overall foreign emission increase of 2 Mt as a response of the incomplete carbon tariff. It is important to note that the 95% confidence interval of the overall net emission effect is [-24 Mt, 29 Mt], suggesting that while the downstream effect offsets the upstream emission reductions, we can not reject that overall foreign emissions would still decrease.

6.2.2 Robustness checks

I conduct several robustness checks of the effects of the export and import tariffs on upstream and downstream GHG emissions. I find that the estimates are qualitatively robust to transformations of the outcome variable, variations of the estimating sample, and of different augmented specifications. Table A5 presents qualitatively similar results if the dependent variable is in levels of facility GHG emissions instead of log emissions. The magnitude and precision of the semi-elasticities shown in Table 3 are also robust to considering all the broad affected industrial sectors as opposed to only manufacturing as shown in Table A6. Similarly, Figure A3 shows robust event-study estimates to the sample of all NAICS-3 treated industries as opposed to only the manufacturing sector.

Finally, Table A7 presents estimates of variations of specification (3) of Table 3 for different samples, and augmented specifications. Columns (1) to (7) estimate specification (3) of Table 3 for a balanced panel, single plant firms, multi-plant firms, below and above median size emitters, trimmed sample of outliers in emissions, and weighted regression by pre-treatment facility level GHG emissions. While the coefficient estimates are statistically noisier for some of these samples, the sign and magnitude of the estimated semi-elasticities are generally robust to these sample restrictions. The last two columns add more granular controls for differential industry shocks or trends. Column (8) includes more granular NAICS3-by-year fixed effects, and Column (9) NAICS4-specific time trends. The magnitude and precision of the results are lessened relative to the estimates in Table 3 because these finer industry-specific controls are correlated with the treatment variable which varies at the NAICS6-by-year level.

6.2.3 Heterogeneity

I now turn to heterogeneity analyses of the export tariff effects on two dimensions: industry-level trade intensity and GHG emission intensity. We expect trade and carbon tariffs to affect more tradable industries. While we also expect more carbon-intensive industries to respond more to carbon tariffs, it is unclear whether they should respond more or less to trade tariffs.

To measure trade intensity, I calculate for each NAICS-6 industry the ratio of total trade value (import + export) to total value of sales from the NBER-CES manufacturing database (Becker, Gray and Marvakov, 2021). I average the share of trade over the pre-trade war period of 2010-2017. Low values of the ratio imply low trade intensity, whereas trade-intensive industries have a higher value of the ratio. To explore the effect of trade intensity, I interact the export tariff variables in equation (9) with a dummy variable equal to 1 if the NAICS-6 treated industries have a higher share of trade than the median NAICS-6 treated industry. A value of 1 for the trade intensity dummy indicates a relatively trade-intensive industry.

Table 4 presents estimates of equation (9) by trade intensity. While noisy, the results show that emissions for facilities in more trade-intensive industries reduce more as a response to export tariffs affecting their output. The opposite is true for trade-intensive industries exposed to export tariffs on their inputs, they increase their emissions less. This suggests that the more trade-intensive downstream sectors benefited less from the reduction in the domestic price of inputs than the less trade-intensive downstream industries. One potential explanation could be that less trade-intensive downstream industries are also more reliant on domestic inputs, therefore benefiting more from the domestic input cost reductions than more trade exposed downstream plants also using more foreign inputs.

Table 4: Semi-elasticity of the trade war export tariffs on facility-level CO2e emissions by trade intensity

	ln(CO2e)		
	(1)	(2)	(3)
Direct effect from export tariffs	0.012	−0.008	−0.007
	(0.022)	(0.020)	(0.021)
Indirect downstream effect from export tariffs	0.033	0.053*	0.059*
	(0.032)	(0.031)	(0.032)
Direct effect from export tariffs X Trade intensity	−0.044*	−0.021	−0.020
	(0.026)	(0.023)	(0.024)
Indirect downstream effect from export tariffs X Trade intensity	−0.009	−0.036	−0.052
	(0.036)	(0.034)	(0.036)
Adj. R2	0.87	0.87	0.87
State X Year	×	✓	✓
NAICS-2 X Year	×	×	✓
Observations	27,514	27,514	27,514

Notes: Estimates of the emission semi-elasticity of the trade war export tariffs by trade intensity. trade intensity is a dummy variable equal to 1 if the NAICS-6 industries total trade value per total value of sales is greater than the median value. All models include year fixed effects and plant fixed effects. Facilities are restricted to the manufacturing sector. Column 1 is the baseline model. Column 2 further includes state by year fixed effects. Column 3 additional controls for NAICS-2 by year fixed effects. Robust standard errors clustered at NAICS-6 level in parentheses (* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$).

The GHG emission intensity measure is the average 2010-2017 NAICS-6 industry total US emission from the GHGRP over the total value of sales for the same industry from the NBER-CES manufacturing database (Becker, Gray and Marvakov, 2021). Similar to the trade intensity estimates, I interact the export tariff variables in equation (9) with a GHG intensity dummy variable equal to 1 if the NAICS-6 treated industries' GHG emission per sales is greater than the median value for treated industries.

Table 5 shows the estimates by GHG emission intensity. The interacted results suggest that the emissions from plants in more emission-intensive industries generally respond more strongly to export tariff increases on their inputs or outputs. While mostly imprecise, the interacted coefficients on the preferred specification in column 3 show a greater increase for facilities in industries targeted by export tariffs on their output, and greater increases in emissions from downstream facilities in GHG-intensive industries. If tariffs are leading to similar output changes for similarly affected industries, then these results are consistent with the fact that more emission intensive industries see greater emission changes.

Table 5: Semi-elasticity of the trade war export tariffs on facility-level CO2e emissions by GHG intensity

	ln(CO2e)		
	(1)	(2)	(3)
Direct effect from export tariffs	−0.016	−0.016	−0.007
	(0.021)	(0.017)	(0.018)
Indirect downstream effect from export tariffs	0.038	0.037	0.025
	(0.025)	(0.024)	(0.026)
Direct effect from export tariffs X GHG intensity	0.014	−0.013	−0.030
	(0.038)	(0.024)	(0.024)
Indirect downstream effect from export tariffs X GHG intensity	0.193	0.177	0.196*
	(0.135)	(0.120)	(0.104)
Adj. R2	0.87	0.87	0.87
State X Year	×	✓	✓
NAICS-2 X Year	×	×	✓
Observations	27,514	27,514	27,514

Notes: Estimates of the emission semi-elasticity of the trade war export tariffs by greenhouse gas (GHG) intensity. GHG intensity is a dummy variable equal to 1 if the NAICS-6 industries GHG emissions per total value of sales is greater than the median value. All models include year fixed effects and plant fixed effects. Facilities are restricted to the manufacturing sector. Column 1 is the baseline model. Column 2 further includes state by year fixed effects. Column 3 additional controls for NAICS-2 by year fixed effects. Robust standard errors clustered at NAICS-6 level in parentheses (* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$).

Interacting the main DiD model with measures of trade and GHG intensity suggests that the emission response from the trade war export tariff increases have different effects. For trade intensity, the relative effect of emission changes for facilities in upstream and downstream industries goes in the opposite effect, whereas they move in the same direction for facilities in GHG-intensive industries. The first effect is consistent with downstream industries using relatively more domestic inputs benefiting more from lower input prices, whereas the second effect could simply reflect larger emission responses for the same average output response in more emission intensive industries.

7 Conclusion

In this paper, I attempt to predict the effect of proposed upstream carbon tariffs on upstream and downstream foreign emission changes for manufacturing GHG emitting facilities. Using a stylized two-country general equilibrium model, I first show that as a response to the introduction of an upstream carbon tariff, foreign emissions are reduced from the upstream industries. However, through downward pressure on the price of the upstream good, downstream customers of the tariffed good benefit from input cost reductions and increase their emissions. The incomplete nature of the carbon tariffs leads to a movement of the emission leakage down the supply chain.

Empirically, I exploit changes in trade tariffs during the 2018-2019 trade war to estimate the emission effects from export tariff increases for US manufacturing facilities. While controlling for other tariff changes, I find evidence that US emitting facilities respond to export tariff increases targeting their output by reducing their emissions. Importantly, results also highlight that downstream facilities that use the targeted outputs as inputs respond by increasing their emissions. Back-of-the-envelope calculations suggest this rebound effect from downstream emissions could offset the upstream emission reductions in the case of US GHG-emitting manufacturing facilities affected by the 2018-2019 trade war.

The offsetting emission effect from downstream facilities highlights a potential issue with incomplete carbon tariffs applied to upstream products, such as the proposed EU CBAM policy. The EU CBAM will only cover five product categories: cement, iron and steel, aluminum, fertilizers, and electricity. This paper highlights the importance of considering input-output linkages for the net emission effect of incomplete carbon tariffs. Specifically, if uncovered downstream producers represent a major source of domestic emissions and are responsive to input cost changes, then their emission increases could offset the upstream emission reductions from incomplete carbon tariffs. As discussed in Titievskaia, Simões and Dobreva (2022), the EU Commission is aware of the potential emission reshuffling risks of downstream producers not currently considered under their CBAM, and is planning to re-evaluate in the coming years the inclusion of downstream products. Results in this paper suggest focusing on covering products of downstream producers that are responsive to changes in input costs, emission intensive, and large emitters.

A limitation of this paper is that the export tariffs facing US industrial facilities during the 2018-2019 trade war are not fully representative of the covered sectors under CBAM. The trade war export tariff increases mostly affected the food, steel, iron, and aluminum sectors. Further research should study the net emission response to export tariffs of other covered sectors by the EU CBAM, namely the cement, fertilizers, and electricity sectors.

References

Aichele, Rahel, and Gabriel Felbermayr. 2015. "Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade." *Review of Economics and Statistics*, 97(1): 104–115.

Amiti, Mary, Stephen J Redding, and David E Weinstein. 2019. "The Impact of the 2018 Tariffs on Prices and Welfare." *Journal of Economic Perspectives*, 33(4): 187–210.

Autor, David, Anne Beck, David Dorn, and Gordon H Hanson. 2024. "Help for the Heartland? The Employment and Electoral Effects of the Trump Tariffs in the United States." National Bureau of Economic Research.

Becker, Randy, Wayne Gray, and Jordan Marvakov. 2021. "NBER-CES Manufacturing Industry Database (1958-2018, version 2021a)." National Bureau of Economic Research.

Blanchard, Emily J, Chad P Bown, and Davin Chor. 2019. "Did Trump's Trade War Impact the 2018 Election?" National Bureau of Economic Research.

Böhringer, Christoph, Jared C Carbone, and Thomas F Rutherford. 2018. "Embodied carbon tariffs." *The Scandinavian Journal of Economics*, 120(1): 183–210.

Bombardini, Matilde, and Bingjing Li. 2020. "Trade, pollution and mortality in china." *Journal of International Economics*, 103321.

Bown, Chad P. 2021. "Anatomy of a flop: Why Trump's US-China phase one trade deal fell short." *Peterson Institute for International Economics Trade and Investment Policy Watch, February*, 8.

Brunel, Claire, and Arik Levinson. 2024. "Carbon tariffs 101." National Bureau of Economic Research.

Campolmi, Alessia, Harald Fadinger, Chiara Forlati, Sabine Stillger, and Ulrich J Wagner. 2023. "Designing Effective Carbon Border Adjustment with Minimal Information Requirements. Theory and Empirics."

Cherniwchan, Jevan. 2017. "Trade liberalization and the environment: Evidence from NAFTA and US manufacturing." *Journal of International Economics*, 105: 130–149.

Cicala, Steve, David Hémous, and Morten Olsen. 2022. "Adverse Selection as a Policy Instrument: Unraveling Climate Change." National Bureau of Economic Research.

Clausing, Kimberly A, and Catherine Wolfram. 2023. "Carbon border adjustments, climate clubs, and subsidy races when climate policies vary."

Cox, Lydia. 2023. "The Long-Term Impact of Steel Tariffs on US Manufacturing."

Drake, David F. 2018. "Carbon tariffs: Effects in settings with technology choice and foreign production cost advantage." *Manufacturing & Service Operations Management*, 20(4): 667–686.

European Union. 2023. "Regulation (EU) 2023/956 of the European Parliament and of the council of 10 May 2023 establishing a carbon border adjustment mechanism." *Official Journal of the European Union*, 66: 130–152.

Fajgelbaum, Pablo D, Pinelopi K Goldberg, Patrick J Kennedy, and Amit K Khandelwal. 2020. "The return to protectionism." *The Quarterly Journal of Economics*, 135(1): 1–55.

Fajgelbaum, Pablo, Pinelopi K Goldberg, Patrick J Kennedy, Amit Khandelwal, and Daria Taglioni. 2021. "The US-China trade war and global reallocations." National Bureau of Economic Research.

Farrokhi, Farid, and Ahmad Lashkaripour. 2021. "Can trade policy mitigate climate change."

Flaaen, Aaron, and Justin Pierce. 2024. "Disentangling the Effects of the 2018-2019 Tariffs on a Globally Connected U.S. Manufacturing Sector." *The Review of Economics and Statistics*, 1–45.

Fontagné, Lionel, and Katheline Schubert. 2023. "The economics of border carbon adjustment: rationale and impacts of compensating for carbon at the border." *Annual Review of Economics*, 15(1): 389–424.

Fowlie, Meredith, and Mar Reguant. 2018. "Challenges in the measurement of leakage risk." Vol. 108, 124–29.

Fowlie, Meredith, Claire Petersen, and Mar Reguant. 2021. "Border carbon adjustments when carbon intensity varies across producers: evidence from California." Vol. 111, 401–405, American Economic Association 2014 Broadway, Suite 305, Nashville, TN 37203.

Fowlie, Meredith L, and Mar Reguant. 2022. "Mitigating emissions leakage in incomplete carbon markets." *Journal of the Association of Environmental and Resource Economists*, 9(2): 307–343.

Fowlie, Meredith, Mar Reguant, and Stephen P Ryan. 2016. "Market-based emissions regulation and industry dynamics." *Journal of Political Economy*, 124(1): 249–302.

Goswami, Sanjana. 2019. "Employment Consequences of US Trade Wars."

Hsiao, Allan. 2020. "Coordination and Commitment in International Climate Action: Evidence from Palm Oil."

Kortum, Samuel S, and David A Weisbach. 2021. "Optimal unilateral carbon policy." COWLES foundation discussion paper.

Markusen, James R. 1975. "International externalities and optimal tax structures." *Journal of international economics*, 5(1): 15–29.

NOAA. 2022. "Trends in Atmospheric Carbon Dioxide."

Nordhaus, William. 2015. "Climate clubs: Overcoming free-riding in international climate policy." *American Economic Review*, 105(4): 1339–70.

Phaneuf, Daniel J., and Till Requate. 2016. *A Course in Environmental Economics: Theory, Policy, and Practice.* Cambridge University Press.

Pierce, Justin R, and Peter K Schott. 2012. "A concordance between ten-digit US Harmonized System Codes and SIC/NAICS product classes and industries." *Journal of Economic and Social Measurement*, 37(1-2): 61–96.

Schott, Peter K. 2008. "The relative sophistication of Chinese exports." *Economic policy*, 23(53): 6–49.

Shapiro, Joseph S. 2021. "The environmental bias of trade policy." *The Quarterly Journal of Economics*, 136(2): 831–886.

Simmons, Rebecca J., David J. Gilberg, Aaron M. Levine, and Elianne Neuman Schiff. 2021. "Agreement Reached on International Carbon Credit Trading Rules at COP26." The Columbia Law School's Blog on Corporations and the Capital Markets. https://clsbluesky.law.columbia.edu/2021/12/20/agreement-reached-on-international-carbon-credit-trading-rules-at-cop26/.Accessed: 2022-02-15.

Tariffs and the Industry. 6 January 2020. *The Grapevine Magazine*.

Titievskaia, J, HM Simões, and A Dobreva. 2022. "EU Carbon Border Adjustment Mechanism, Implications for Climate and Competitiveness." European Parliamentary Research Service.

Waugh, Michael E. 2019. "The consumption response to trade shocks: Evidence from the US-China trade war." National Bureau of Economic Research.

Weisbach, David A, Samuel Kortum, Michael Wang, and Yujia Yao. 2023. "Trade, leakage, and the design of a carbon tax." *Environmental and Energy Policy and the Economy*, 4(1): 43–90.

A Theory appendix

After differentiating the system of six equations with respect to the domestic carbon tax τ, then system can be rewritten in the following matrix form $M \cdot a = b$, where

$$M = \begin{bmatrix} P'_h(c_h) & 0 & 0 & 0 & -1 & 0 \\ 0 & P'_f(c_f) & 0 & 0 & 0 & -1 \\ 0 & 0 & \frac{\partial^2 C_h}{\partial q_h^2} & 0 & -1 & 0 \\ 0 & 0 & 0 & \frac{\partial^2 C_f}{\partial q_f^2} & 0 & -1 \\ 1 & 1 & -1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1 & 1 \end{bmatrix} \tag{A.1}$$

$$a' = \left(\frac{dc_h}{d\tau}, \frac{dc_f}{d\tau}, \frac{dq_h}{d\tau}, \frac{dq_f}{d\tau}, \frac{dp_h}{d\tau}, \frac{dp_f}{d\tau} \right) \tag{A.2}$$

$$b' = (0, 0, e_h^u, 0, 0, 0) \tag{A.3}$$

The determinant of the matrix M is given by

$$\text{Det}(M) = \left(\frac{\partial^2 C_f}{\partial q_f^2} \frac{\partial^2 C_h}{\partial q_h^2} \left(P'_h(c_h) + P'_f(c_f) \right) \right) - \left(P'_h(c_h) P'_f(c_f) \left(\frac{\partial^2 C_f}{\partial q_f^2} + \frac{\partial^2 C_h}{\partial q_h^2} \right) \right) \tag{A.4}$$

which, since $P'_i(c_i) < 0$ and $\frac{\partial^2 C_i}{\partial q_i^2} > 0$, is by inspection is negative. Then, solving for a, we can sign the effect of the domestic carbon price on foreign and domestic production, which are proportional to the emission responses:

$$\frac{dq_h}{d\tau} = \frac{-e_h^u \left(\frac{\partial^2 C_f}{\partial q_f^2} P'_f(c_f) + \frac{\partial^2 C_f}{\partial q_f^2} P'_h(c_h) - P'_f(c_f) P'_h(c_h) \right)}{\text{Det}(M)} < 0 \tag{A.5}$$

$$\frac{dq_f}{d\tau} = \frac{-e_h^u P'_h(c_h) P'_f(c_f)}{\text{Det}(M)} > 0 \tag{A.6}$$

where the signs can be verified by inspection.

Now the matrix M, a, and b are modified to accomodate the introduction of the foreign exports, the upstream carbon tariff, and the modified global price constraints, where:

$$
M = \begin{bmatrix}
P_h'(c_h) & 0 & 0 & 0 & & 0-1 & 0 \\
0 & P_f'(c_f) & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & \frac{\partial^2 C_h}{\partial q_h^2} & 0 & 0 & -1 & 0 \\
0 & 0 & 0 & \frac{\partial^2 C_f}{\partial q_f^2} & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & \frac{\partial^2 C_e}{\partial q_e^2} & 0 & -1 \\
1 & 1 & -1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -1 & 1
\end{bmatrix} \tag{A.7}
$$

$$
a' = \left(\frac{dc_h}{d\tau_C}, \frac{dc_f}{d\tau_C}, \frac{dq_h}{d\tau_C}, \frac{dq_f}{d\tau_C}, \frac{dq_e}{d\tau_C}, \frac{dp_h}{d\tau_C}, \frac{dp_f}{d\tau_C} \right) \tag{A.8}
$$

$$
b' = (0, 0, 0, 0, -e_f^u, 0, -e_f^u) \tag{A.9}
$$

Similarly to the domestic carbon price case above, the $\mathrm{Det}(M) < 0$, and through solving the system of equations, it can be easily shown that:

$$
\frac{dc_f}{d\tau_C} > 0 \tag{A.10}
$$

$$
\frac{dq_f}{d\tau_C} < 0 \tag{A.11}
$$

$$
\frac{dq_e}{d\tau_C} < 0 \tag{A.12}
$$

$$
\frac{dp_f}{d\tau} < 0 \tag{A.13}
$$

B Figure appendix

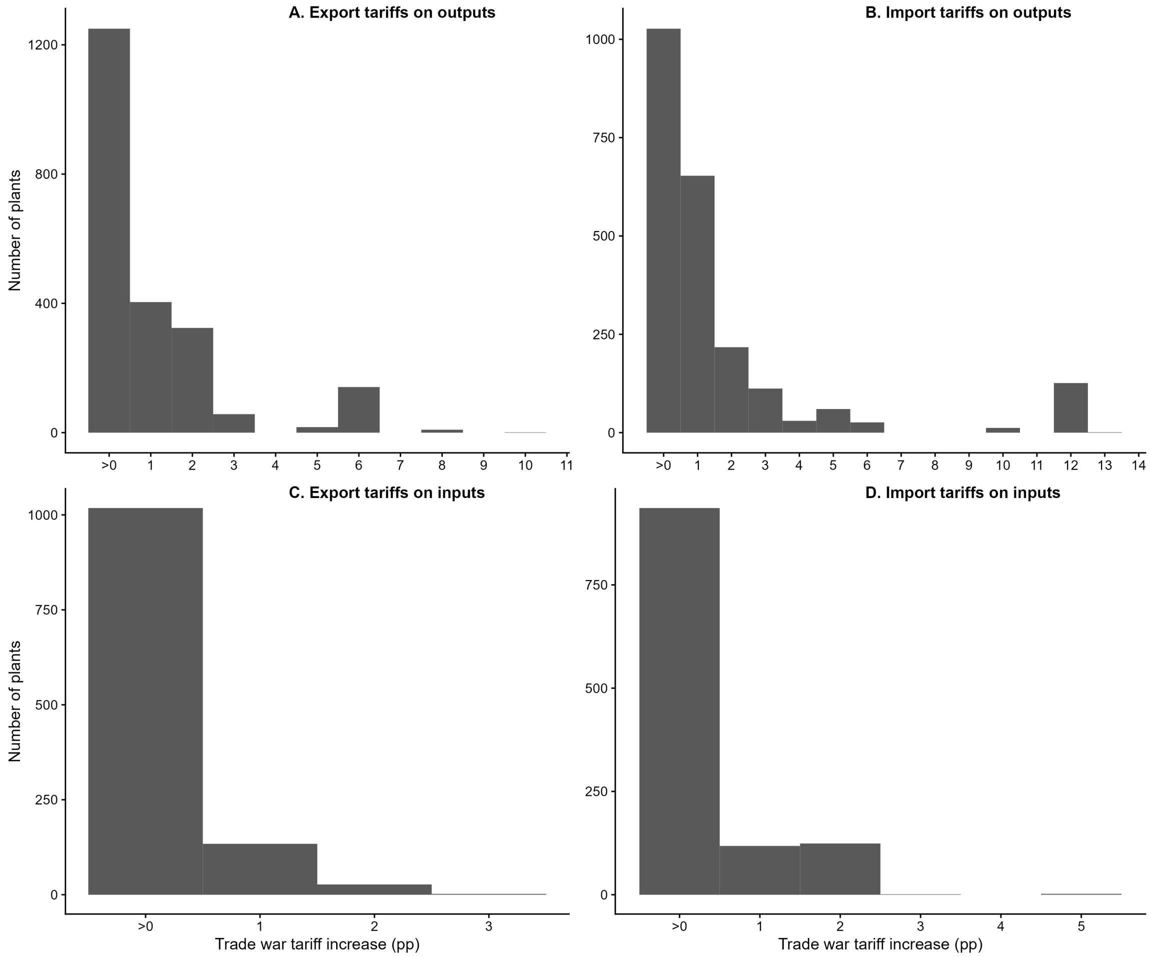

Figure A1: Distribution of NAICS-6 level trade-war tariff increases facing U.S. GHG emitting facilities

Notes: Figure A1 shows the distribution of GHG emitting manufacturing facilities facing increases in export or import tariffs on their output or input during the 2018-2019 trade war.

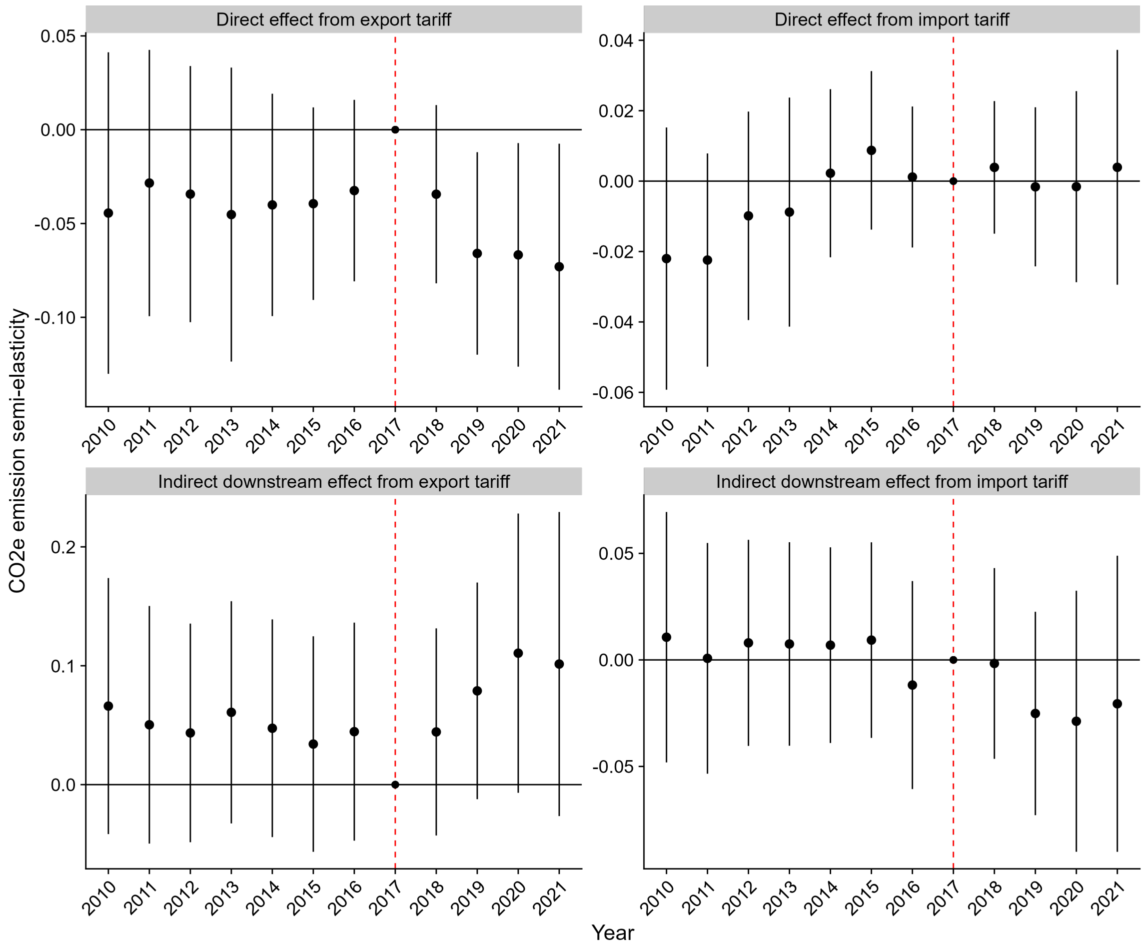

Figure A2: Event-study model of the effect of trade war tariffs on CO2e emissions

Notes: Point estimates and 95% confidence intervals of the semi-elasticity effect of output and input trade war tariffs on log CO_2e emissions relative to 2017 using an event study version of equation (9). Estimates for the sample restricted to the manufacturing sector are shown. Standard errors are clustered at the NAICS-6 level.

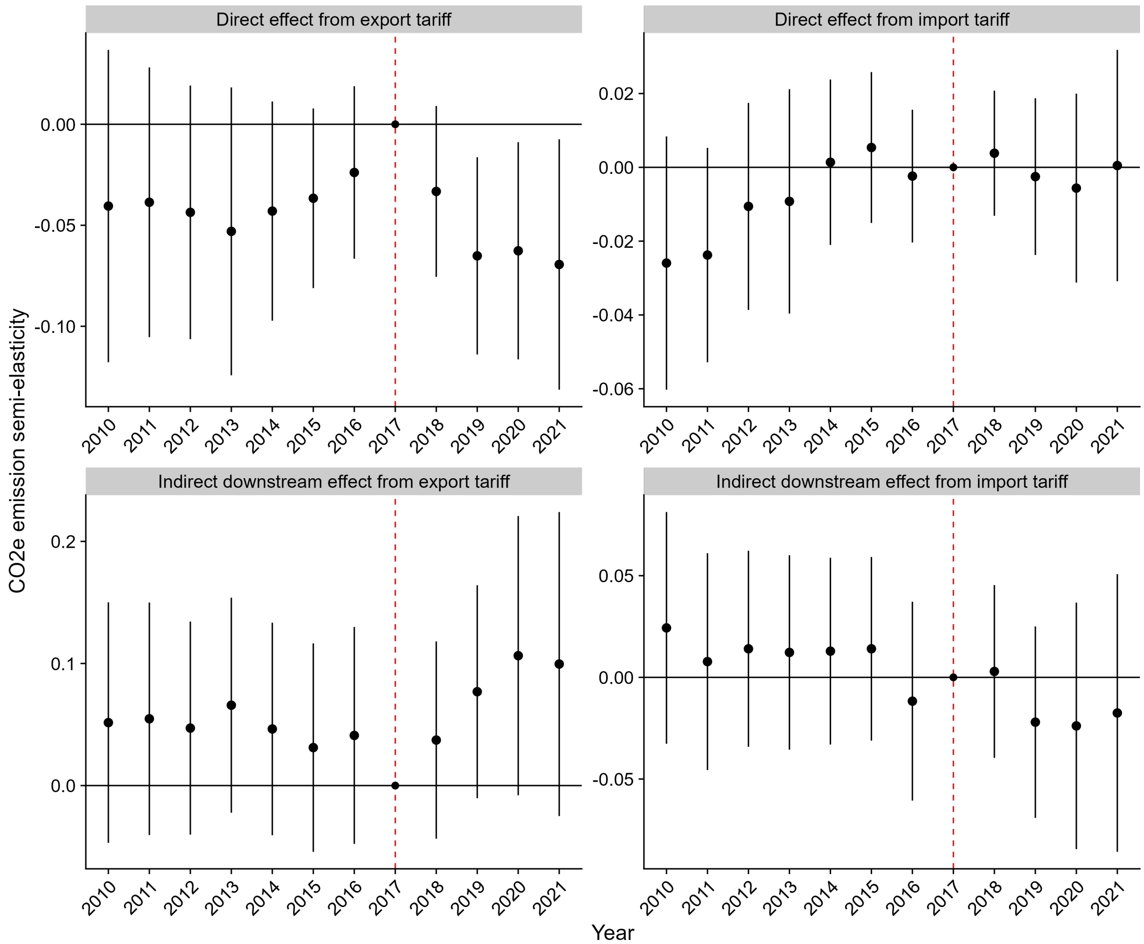

Figure A3: Event-study model of the effect of trade war tariffs on CO2e emissions

Notes: Point estimates and 95% confidence intervals of the semi-elasticity effect of output and input trade war tariffs on log CO_2e emissions relative to 2017 using an event study version of equation (9). Estimates for the sample restricted to NAICS-3 treated industries are shown. Standard errors are clustered at the NAICS-6 level.

C Table appendix

Table A1: NAICS-2 industry variation in trade war tariffs increases and greenhouse gas emissions

		Tariff increases (pp)										
		Export		Import		Export input		Import input		CO2e (kt)		
Sector	NAICS-2	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	# plants
Agriculture	11	1.4	3.08	0.2	0.57	0.03	0.08	0.05	0.16	48	17	7
Mining	21	0.7	1.56	0.45	1.59	0.03	0.05	0.05	0.1	175	331	1275
Water and sewage	22	0	0	0	0	0.01	0.01	0.02	0.02	114	337	260
Food and textile	31	0.7	1.36	0.96	1.78	0.09	0.31	0.07	0.17	107	330	370
Petroleum, chemical and wood	32	0.48	0.9	1.21	1.91	0.08	0.12	0.13	0.22	459	868	1454
Primary and secondary metal	33	0.58	0.96	2.22	3.07	0.3	0.5	0.67	0.98	205	806	468
Wholesale	42	0	0	0	0	0.01	0.01	0.04	0.03	22	24	4
Warehousing	49	0	0	0	0	0.02	0.02	0.04	0.04	52	65	8
Buidlings	53	0	0	0	0	0.02	0.02	0.05	0.07	66	31	5
Research and development	54	0	0	0	0	0.01	0.01	0.07	0.11	38	23	19

Notes: pp = percentage point. kt = kiloton. Std. dev. = Standard deviation.

Table A2: NAICS-3 manufacturing variation in trade war tariffs increases and greenhouse gas emissions

		Tariff increases (pp)										
		Export		Import		Export input		Import input		CO2e (kt)		
Sector	NAICS-3	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.	# plants
Food	311	0.69	1.1	0.55	1.11	0.11	0.29	0.07	0.16	114	348	330
Beverage and tobacco products	312	1.75	3.07	0.3	0.79	0.25	0.66	0.18	0.32	48	30	27
Textile mills	313	0.24	0.27	1.73	2.07	0.02	0.05	0.04	0.08	70	47	7
Textile product mills	314	0.32	0.48	1.93	2.31	0.03	0.03	0.07	0.08	46	22	6
Wood products	321	0.34	0.92	1.31	1.65	0.02	0.05	0.05	0.16	119	124	25
Paper	322	0.45	0.61	2.18	3.12	0.1	0.11	0.14	0.18	671	747	226
Printing and related activities	323	0.29	0.42	0.64	1.22	0.04	0.05	0.14	0.18	31	7	2
Petroleum and coal products	324	0.4	0.9	0.09	0.13	0.08	0.09	0.09	0.12	1,205	1,583	173
Chemical	325	0.66	0.8	0.71	1	0.07	0.12	0.15	0.25	306	725	650
Plastics and rubber products	326	0.24	0.45	1.44	1.89	0.13	0.18	0.16	0.24	39	19	34
Nonmetallic mineral products	327	0.6	1.4	1.51	2.27	0.06	0.08	0.16	0.22	304	412	344
Primary metal	331	1.11	1.73	3.75	4.61	0.26	0.58	0.63	1.13	304	1,041	274
Fabricated metal products	332	0.44	0.65	1.65	2.5	0.52	0.8	1.01	1.5	40	31	26
Machinery	333	0.44	0.47	2	1.75	0.29	0.31	0.7	0.72	38	21	18
Computer and electronic products	334	0.59	0.88	2.29	2.45	0.09	0.09	0.27	0.28	126	146	51
Electrical equipment and appliances	335	0.78	0.76	3.41	4.2	0.32	0.32	0.74	0.79	26	18	14
Transportation equipment	336	0.51	1.34	1.11	2.06	0.37	0.56	0.85	1.02	46	26	81
Furniture and related products	337	0.61	1.14	3.93	4.61	0.22	0.36	0.51	0.74	20	NA	1
Miscellaneous	339	0.39	0.39	1.17	2.07	0.13	0.13	0.22	0.26	62	25	3

Notes: pp = percentage point. kt = kiloton. Std. dev. = Standard deviation.

Table A3: Industry-level US net export effect from a 1pp increase in trade war tariffs

	Net exports (mil $)	
	(1)	(2)
Direct effect from export tariffs	-274.231^{*}	-291.702^{**}
	(143.325)	(142.274)
Direct effect from import tariffs	159.131^{**}	204.924^{***}
	(69.195)	(72.922)
Indirect downstream effect from export tariffs	$1{,}039.853^{**}$	841.812^{**}
	(418.756)	(387.221)
Indirect downstream effect from import tariffs	-703.348^{***}	-523.849^{**}
	(243.127)	(215.693)
Adj. R2	0.94	0.94
NAICS-2 X Year	×	✓
Observations	4,168	4,168

Notes: Estimates of the effect of a 1pp increase of trade war export tariffs on NAICS-6 level net exports in millions of USD. All models include year fixed effects and NAICS-6 fixed effects. Facilities are restricted to the manufacturing sector. Column 1 is the baseline model, whereas column 2 further includes NAICS-2 by year fixed effects. Robust standard errors clustered at NAICS-6 level in parentheses (* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$).

Table A4: Semi-elasticity of the trade war tariffs on facility-level CO2e emissions

	ln(CO2e)		
	(1)	(2)	(3)
Direct effect from export tariffs	-0.019	-0.027^{**}	-0.027^{**}
	(0.017)	(0.013)	(0.013)
Direct effect from import tariffs	-0.002	0.004	0.007
	(0.009)	(0.008)	(0.008)
Indirect downstream effect from export tariffs	0.040^{*}	0.045^{*}	0.041^{*}
	(0.024)	(0.023)	(0.025)
Indirect downstream effect from import tariffs	-0.026^{**}	-0.029^{**}	-0.023
	(0.013)	(0.014)	(0.016)
Adj. R2	0.87	0.87	0.87
State X Year	×	✓	✓
NAICS-2 X Year	×	×	✓
Observations	27,514	27,514	27,514

Notes: Estimates of the emission semi-elasticity of the trade war tariffs. All models include year fixed effects and plant fixed effects. The control and treatment groups are restricted to facilities in the manufacturing sector. Column 1 is the baseline model. Column 2 further includes state by year fixed effects. Column 3 additional controls for NAICS-2 by year fixed effects. Robust standard errors clustered at NAICS-6 level in parentheses (* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$).

Table A5: Facility-level CO2e emission effect of the trade war tariffs

	CO2e (kt)		
	(1)	(2)	(3)
Direct effect from export tariffs	-5.853	-6.753^{*}	-2.786
	(4.174)	(3.892)	(2.751)
Direct effect from import tariffs	-0.664	-0.636	-4.657^{*}
	(2.042)	(2.471)	(2.414)
Indirect downstream effect from export tariffs	9.127^{**}	12.002^{***}	7.714^{*}
	(4.270)	(4.338)	(4.252)
Indirect downstream effect from import tariffs	-8.001^{***}	-8.983^{***}	-6.007^{**}
	(2.291)	(2.636)	(2.379)
Adj. R2	0.96	0.97	0.97
State X Year	×	✓	✓
NAICS-2 X Year	×	×	✓
Observations	27,514	27,514	27,514

Notes: Estimates of the emission effect of the trade war tariffs. All models include year fixed effects and plant fixed effects. The control and treatment groups are restricted to facilities in the manufacturing sector. Column 1 is the baseline model. Column 2 further includes state by year fixed effects. Column 3 additional controls for NAICS-2 by year fixed effects. Robust standard errors clustered at NAICS-6 level in parentheses (* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$).

Table A6: Semi-elasticity of the trade war tariffs on facility-level CO2e emissions

	ln(CO2e)		
	(1)	(2)	(3)
Direct effect from export tariffs	-0.008	-0.019	-0.023^{*}
	(0.018)	(0.012)	(0.012)
Direct effect from import tariffs	0.001	0.008	0.007
	(0.009)	(0.008)	(0.008)
Indirect downstream effect from export tariffs	0.036	0.045^{*}	0.038
	(0.026)	(0.024)	(0.024)
Indirect downstream effect from import tariffs	-0.028^{**}	-0.032^{**}	-0.024
	(0.014)	(0.014)	(0.016)
Adj. R2	0.85	0.85	0.85
State X Year	×	✓	✓
NAICS-2 X Year	×	×	✓
Observations	46,875	46,875	46,875

Notes: Estimates of the emission semi-elasticity of the trade war tariffs. All models include year fixed effects and plant fixed effects. The control group is restricted to facilities in the same NAICS-3 industries as the treated facilities. Column 1 is the baseline model. Column 2 further includes state by year fixed effects. Column 3 additional controls for NAICS-2 by year fixed effects. Robust standard errors clustered at NAICS-6 level in parentheses (* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$).

Table A7: Robustness checks of semi-elasticities of the trade war tariffs on facility-level CO2e emissions

	ln(CO2e)								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Direct effect from export tariff	-0.016	0.011	-0.037^{***}	-0.032^{**}	-0.012	-0.023^{*}	-0.054^{**}	-0.007	-0.009
	(0.015)	(0.028)	(0.014)	(0.015)	(0.027)	(0.013)	(0.025)	(0.013)	(0.012)
Direct effect from import tariff	-0.002	0.013	0.005	0.016^{*}	0.0005	0.006	0.012	-0.004	0.004
	(0.009)	(0.013)	(0.009)	(0.010)	(0.014)	(0.008)	(0.017)	(0.011)	(0.008)
Indirect downstream effect from export tariff	0.009	0.025	0.045	0.039	0.036	0.035	0.114^{***}	0.035^{*}	0.022
	(0.018)	(0.051)	(0.033)	(0.030)	(0.034)	(0.025)	(0.043)	(0.019)	(0.016)
Indirect downstream effect from import tariff	-0.003	-0.003	-0.023	-0.016	-0.033	-0.021	-0.060^{**}	-0.017	-0.001
	(0.014)	(0.024)	(0.021)	(0.017)	(0.026)	(0.016)	(0.031)	(0.016)	(0.013)
Adj. R2	0.91	0.81	0.88	0.56	0.85	0.88	0.92	0.87	0.87
Sample	Balanced	Single	Multi	Small	Large	Trimmed	Weighted	Manuf.	Manuf.
Observations	21,619	6,566	20,946	12,570	14,582	27,441	27,168	27,514	27,514

Notes: Estimates of the emission semi-elasticity of the trade war tariffs for different samples or specifications. The first column restricts the sample to a balanced panel of plants. The second and third columns respectively restrict the plants to single and multi plant firms. The fourth and fifth columns restrict the samples to above and below median CO2e emitters for the years before the trade war. The sixth column trims the sample of all years of a plants that have reported pre-treatment GHG emissions that are 100 times the 99 percentile of the distribution of emissions. Column seven weights the regression by the 2010-2017 average plant-level GHG emission level. All models include year fixed effects, plant fixed effects, state-by-year and NAICS2-by-year fixed effects. Columns (8) and (9) are restricted to facilities in the manufacturing sector, and respectively replace NAICS2-by-year fixed effects with NAICS3-by-year fixed effects, and include NAICS4 time trends. Robust standard errors clustered at NAICS6 level in parentheses (* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$).