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Trade Flows, Carbon Leakage, and the EU Emissions Trading System

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Abstract

The EU's Emission Trading Scheme (EU ETS) has been shown to have reduced emissions in the participating countries and industries since its adoption in 2005. However, there is less evidence on the shifting of production outside EU to avoid emission controls. We study this so-called carbon leakage with gravity analysis of international trade flows and carbon intensities of trade. We provide a simple theoretical framework and study its implications empirically. Our findings with the new OECD data indicate that carbon leakage has in fact occurred due to the EU ETS, resulting in higher CO_2 intensity of imports to the EU, and lower CO_2 intensity of exports from the EU. The evidence on the value of imports also shows some increases from nonparticipating countries due to the ETS. We find that our results are broadly consistent with the theory.

Tiivistelmä

Kauppavirrat, hiilivuoto ja EU:n päästökauppajärjestelmä

Euroopan unioni pyrkii hiilineutraaliksi vuoteen 2050 mennessä. Tärkeä väline tavoitteen saavuttamiseen on vuonna 2005 käynnistetty EU:n päästökauppajärjestelmä. Päästökauppajärjestelmä asettaa kattomäärät päästöille järjestelmän piiriin kuuluvilla toimialoilla. Päästöoikeuksia on tähän mennessä sekä huutokaupattu että jaettu ilmaiseksi. Ilmastopolitiikan tiukentuessa huutokaupattavien päästölupien osuus kasvaa ja määrä vähenee, mikä nostaa päästöoikeuksien hintaa ja siten päästöjen kustannuksia yrityksille.

Ilmastopolitiikan kiristyessä huolenaiheena on, että tuotanto siirtyy EU:n ulkopuolelle maihin, joissa sääntely ei ole yhtä tiukkaa, eli tapahtuu niin sanottua hiilivuotoa.

Tässä tutkimuksessa arvioidaan, onko päästökaupan seurauksena tapahtunut hiilivuotoa ja minkä verran. Analysoimme tilastollisesti vuosien 2000–2018 kansainvälisiä kauppavirtoja sekä niiden sisältämiä päästöjä 60 maan osalta. Merkkejä hiilivuodosta etsimme niin EU:n tuonnin ja viennin kokonaismäärästä kuin sen hiili-intensiteetistäkin.

Tulokset osoittavat, että hiilivuotoa on tapahtunut jonkin verran päästökaupan seurauksena. Esimerkiksi tuonnin hiili-intensiteetti on kasvanut 4 prosenttia verrattuna siihen, että päästökauppaa ei olisi ollut. Toisaalta viennin hiili-intensiteetti on laskenut, mikä viittaa siihen, että päästökauppajärjestelmä on vähentänyt EU:n sisäisen tuotannon päästöjä. Tuloksemme ovat kiinnostavia, sillä empiirisissä tutkimuksissa ei ole aiemmin löydetty selvää näyttöä EU:n päästökauppajärjestelmän aiheuttamasta hiilivuodosta. Uutta näyttöä tarvitaan erityisesti suunniteltaessa ja perusteltaessa erilaisia talouspolitiikan mekanismeja, kuten EU:n suunnittelemaa hiilitullijärjestelmää.

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Keywords: Carbon leakage, EU ETS, Gravity model

Asiasanat: Hiilivuoto, EU ETS, Gravitaatiomalli

JEL: J23, J24, O33

1 Introduction

In line with the UNFCCC and the Paris Climate Agreement, the European Union (EU) has committed itself to significantly reducing its human-induced carbon dioxide (CO_2) emissions and other greenhouse gas (GHG) emissions influenced in order to mitigate global climate change. This is expected to lead to an increase in the price of CO_2 through, inter alia, the EU Emissions Trading Scheme (ETS) and the tightening of carbon/energy taxation. A pivotal question, both for the climate and for the economy, is, do rising prices lead to carbon leakage, i.e., the transfer of polluting production to countries that are not committed to strong mitigation measures? Empirical research on carbon leakage is still lacking, and collection of new evidence is necessary from the perspective of design and justification of climate policy, including unilateral measures such as the carbon border adjustment mechanism (CBAM) that would impose higher customs duties or other trade restrictions on high-emission products from non-EU countries.

In this paper, we measure the implications of the EU ETS on carbon leakage. The scheme, launched in 2005 and upgraded in three phases, is a cap-and-trade system that allocates a limited number of allowances for emissions in specific industries. In the context of the EU ETS, carbon leakage would mainly occur through two channels: 1) changes in market shares, so that foreign firms that produce outside the EU with cheaper costs would gain higher shares, and 2) relocation of domestic firms to countries that do not implement strict environmental policies (Naegele & Zaklan, 2019). In both cases, imports to EU from non-ETS countries would increase, and the reductions in emissions in the EU would be partly offset by the increases elsewhere. In addition, the lower demand for fossil fuels in countries with strict environmental policies can lead to lower energy prices, which then increases the demand in the non-stringent countries (Antoci et al., 2021). Our study analyzes the impact of the EU ETS on bilateral trade flows, specifically imports and their carbon content. Trade flows show both channels of carbon leakage, as the firms that have relocated outside the EU would export more of their production into the EU, and the increased market shares of the non-ETS countries would also mean more imports to the EU.

We use a simple theoretical framework that incorporates CO_2 emissions into the gravity model of international trade, and investigate the effect of the ETS phases from differences in the structure of trade across countries and sectors that either participated or did not participate to the scheme. We use recently updated data on emissions embodied in trade with a long time period that covers Phases 1-3 of the ETS, which allows us to study the effects of each phase separately in addition to the general impact.

We contribute to existing research by showing impacts of the EU ETS with discussion on how the gradually stricter system might affect carbon leakage. Previous studies have mostly shown small or nonexistent carbon leakage due to the ETS, but our results indicate that there in fact has been an increase in the carbon intensity of imports to the EU ETS countries as compared to countries that are not affected by it. In addition, the value of imports is shown to also have increased.

In what follows, we first briefly summarize the characteristics of the EU ETS in the rest of this introductory section. Then, in section 2 we discuss relevant literature. Section 3 details our theoretical framework, section 4 outlines our empirical method while section 5 describes the data. Our results are presented in section 6, and section 7 concludes our work.

1.1 The EU ETS

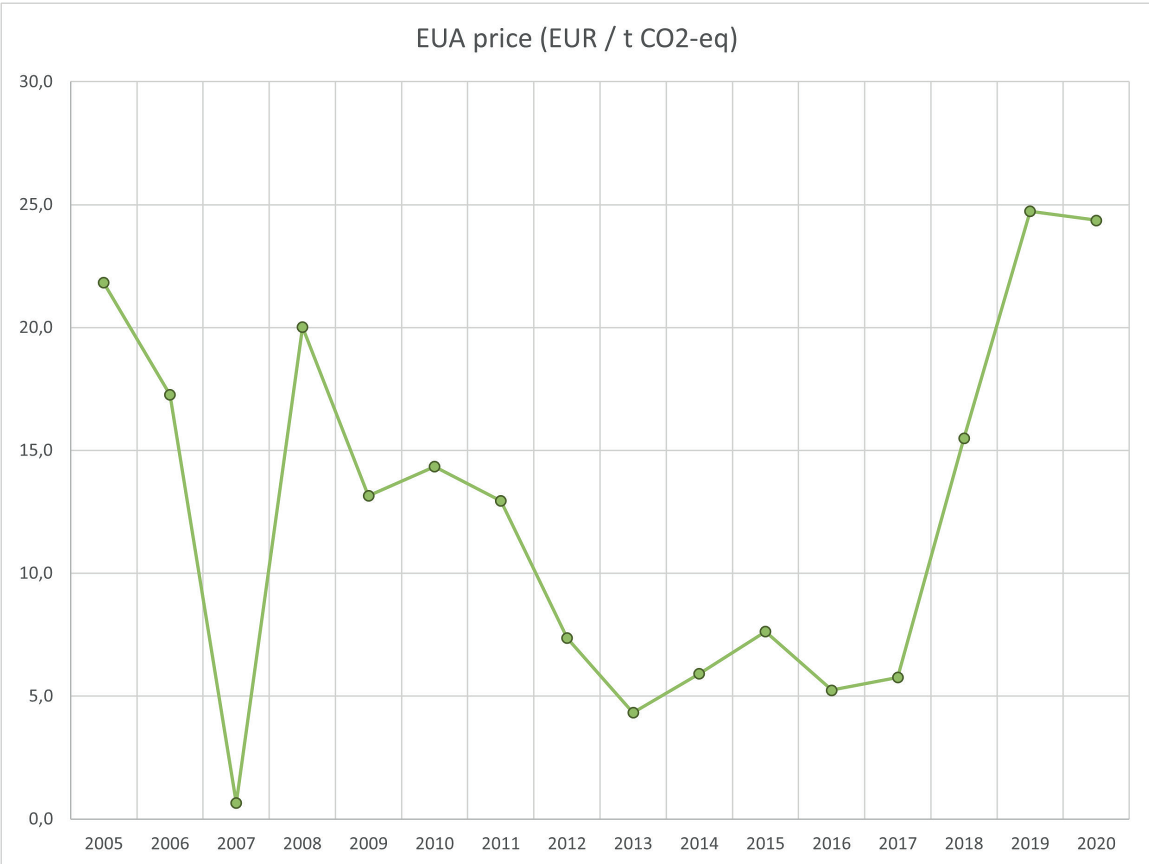
In this section, we provide a brief overview of the EU ETS. The first phase of the system was a pilot period during 2005–2007, used for testing price formation in the carbon market and establishing the necessary infrastructure for the functioning of the system. The participants in this phase were the EU27 countries, although Bulgaria and Romania only joined the system in 2007 along with their EU membership. The second phase, 2008–2012, included more actual commitments, although the system still gave most of the allowances for free. Norway, Iceland and Liechtenstein also joined the ETS starting from this phase. During the third phase in 2013–2020 the system has been harmonized across the EU (as previously the allowances had varied nationally). When Croatia joined the EU in 2013, it also became a participant of the EU ETS. Phase 4 started in the beginning of 2021. According to the European Commission the goal for this phase is that the sectors covered by the system should reduce their emissions by 43 % compared to 2005 levels. To achieve this goal, phase 4 includes lower emission caps and fewer allowances given out for free. The total amount of emission allowances is lower every year, and during Phase 4 the total amount of emission allowances is reduced by 2.2 % every year.

TABLE 1: Industries in the EU ETS (source: EU ETS Handbook)

Phase 1	**Phase 2**	**Phase 3**
Power stations and other combustion plants larger than 20MW Oil refineries Coke ovens Iron and steel plants Cement clinker Glass Lime Bricks Ceramics Pulp Paper and board	Same as Phase 1, plus aviation from 2012	Same as Phase 2, plus aluminium, petrochemicals, ammonia, nitric, adipic and glyoxylic acid production, CO_2 capture, transport in pipelines and geological storage of CO_2

When considering the effect of the EU ETS on carbon leakage, a few factors come into play. As a a part of the implementation, the free allocation of emission allowances was designed to avoid carbon leakage. According to European Commission (2015), in Phases 1 and 2 most of the allowances were given out for free with a grandfathering rule, i.e. based on historical emissions. In Phases 3 and 4, a hybrid model where both historical production levels and an efficiency benchmark for each sector play a role, i.e. a fixed installation cap, has been used to determine the amount of free allowances. The amount is also affected by the carbon leakage rate of the sector along with a linear reduction factor or cross-sectoral correction factor to ensure that free allowances are not over-allocated and the cap is reduced. In principle, no free allowances are allocated for electricity production, and district heating is allocated some allowances. For industry sectors not deemed to be exposed to carbon leakage, the amount of free allocation has been cut substantially during 2013–2020. On the other hand, sectors and subsectors deemed to be exposed to carbon leakage are allocated free allowances 100 % of the benchmark. (European Commission, 2015)

FIGURE 1: Emission allowance auction prices (source: European Energy Exchange AG)



Furthermore, the prices of the allowances have also varied significantly over the years. According to the European Energy Exchange data, in January 2022 the spot price has been hovering at around 80 euros per tonne of CO_2, while in 2013 the price was only approximately 3 euros (see Figure 1). In comparison, according to the OECD, a low-end estimate of carbon costs in 2018 was 30 euros, and a midpoint estimate in 2020 it was 60 euros (OECD, 2018).

As such, the system has been criticized for the over-allocation of free permits and the volatility of carbon prices. However, the prices do appear to have been increasing in the recent years. In addition, according to the European Commission, the amount of total emissions in the EU has decreased according to the target for 2020 (emissions that are 21 % lower than in 2005). Recent research has also shown that emissions have indeed decreased for firms under the ETS, as discussed below.

2 Previous literature

Previous studies on the effects of the EU ETS have mainly focused on firm competitiveness, although the effect on pollution has naturally been a topic of interest, too. It has been argued that emission levels have decreased in the EU due to the EU ETS, but at the same time, firm competitiveness has not suffered negative impacts (see, e.g., Arlinghaus (2015), for a survey). For example, Abrell et al. (2011) use firm-level panel data to show that the shift from the first to the second phase of the EU ETS reduced emissions by firms while the impact on company performance was modest. Dechezleprêtre et al. (2018) study the impact of the EU ETS in 2005–2012 on emissions and company performance by using data on installation-level carbon emissions from France, Netherlands, Norway and the United Kingdom. Their results indicate that the ETS reduced emissions (by 10 percent) while having a positive impact on company revenues. Dechezleprêtre & Sato (2017) discuss whether the so-called Porter hypothesis could apply. That is, more regulation and consequent innovation in green technologies could in fact increase firms' competitiveness and thus more than fully offset the costs of compliance. However, according to Dechezleprêtre & Sato (2017), although the EU ETS has indeed been shown to have fostered innovation, it has not affected firm competitiveness.

Although the effect of environmental regulation on firm performance has been the topic of many studies, research on carbon leakage is not yet conclusive. One example of an ex post study on this topic with trade flow data is Aichele & Felbermayr (2015), which study the impact of the ratification of the Kyoto Protocol in 2001-2003 on carbon leakage with data from 1995 to 2007. Their findings suggest that there has been some amount of carbon leakage from countries party to the protocol to countries that are not party to it. To be specific, they estimate that the amount of imports from the non-participants to participating countries were 8 % higher than if the Kyoto Protocol did not exist and that the carbon intensity of these imports was also 3 % higher than without the protocol. They also found variation between different industries. A similar study but specifically on the EU ETS by Naegele & Zaklan (2019), who use a similar but somewhat adjusted methodology to that of Aichele & Felbermayr (2015) in order to study the impacts of the EU ETS with data from the computable general equilibrium model GTAP (Global Trade Analysis) database for the years 2004, 2007, and 2011. Their results do not show any significant carbon leakage, but it should be kept in mind that their data has only a few years available for analysis.

Another approach to studying carbon leakage is to find whether or not EU companies have shifted their production via relocation and foreign direct investment (FDI) outside of the ETS regulation. For example, Dechezleprêtre et al. (2019) study within-firm carbon emissions data to find the distribution of the carbon emissions of multinational firms across countries between 2007 and 2014. Their findings show no significant evidence of carbon leakage with regards to company decisions on relocating to different countries. Koch & Basse Mama (2019) use data on German multinational firms in 1999–2013 and conclude that the EU ETS had led to very small and statistically insignificant effects on FDI. The study does indicate that a comparatively small number of firms have shifted part of their production to non-EU ETS countries. However, these relocating firms neither operate in the targeted energy-intensive sectors and are not they emission-intensive, so conclusions with regards to EU ETS cannot be directly drawn. A similar study with Italian manufacturing firms by Borghesi et al. (2020) finds that the EU ETS had a weak effect on the number of new locations abroad, whereas the impact on production taking place in foreign subsidiaries was larger, especially in trade-intensive sectors.

Studies that try to estimate the possibility of carbon leakage because of environmental regulation most often use a CGE type of model for the ex ante evaluation of future changes in policy. The estimates for possible carbon leakage rates (as a percentage of the domestic emission reductions that are offset by foreign increases) are generally moderate, in the range between 2 and 20 % (Larch & Wanner, 2017). In a review of the CGE literature and environmental policy, Carbone & Rivers (2017) found that previous studies have mostly been in agreement that there will be some amount of carbon leakage in response to unilateral climate policies. Studies also show variation in carbon leakage between different industries. For example, Santamaría et al. (2014) found that the cement sector would be the most vulnerable to carbon leakage, whereas the risk of leakage is smaller for steel and oil refining. However, their study only uses Spanish data. On the other hand, Fischer & Fox (2012) simulated a US-based carbon tax on a multi-region CGE model and found an overall leakage rate of 7 %, while iron and steel experience respective leakage rates of 58 and 57 %. The CGE estimates in general can have large variations because of different model assumptions.

The effects of free allocation should also be mentioned, as quite a large part of the allowances have so far been given out for free to prevent carbon leakage. However, there is not yet much research on this specific topic. Only study we have found is a recent working paper by Ulmer (2021), who studies free allocation and carbon leakage in the Phase 3 of the EU ETS by comparing sectors at the margin of receiving free allowances to sectors that had to purchase the allowances by auction. The results show evidence that the free allocation has not had a great impact on trading patterns of firms.

It can be concluded that most of the studies on EU ETS and carbon leakage have found small or statistically non-significant effects. However, it should be noted that the data available in many previous studies is only until around the end of Phase 2. As the system becomes gradually stricter and free allocation decreases, the possibility of carbon leakage can increase.

3 Theoretical framework

3.1 Carbon content in trade and value chains

It is useful to consider emissions in the context of world input-output structure.[1] For a given year, the first element of the calculation is the input coefficient matrix, A, that contains the input coefficients a_{ij}, which give the global value units of intermediate goods from industry i that are required to produce one value unit of gross output in industry j. In A, the numbers of rows and columns are the same and equal the numbers of total national industries (the number of countries, C, times the number of industries, I). For the final demand block, we similarly define a vector of final demand flows, Q, the elements being the different final demand classes indicating flows from i to j, with the length $C * I$. The emission intensities, i.e. ratios of emissions to gross output in industries in country s are contained in a row vector $\tilde{n}$. The length of this vector equals the numbers of industries, with value-added ratios for industries as the first elements, n and zeros elsewhere. Then, we collect the actual emission distribution in the global emission matrix (E) to technique component η and scale component Q, that is

$$E = \tilde{n}(I - A)^{-1}Q \equiv \eta Q. \tag{1}$$

The E matrix has the same dimensions as A, including the contributions of each industry to the emissions of other industries. The element $(I - A)^{-1}$ is the well-known Leontief inverse, in which I is the identity matrix of appropriate dimensions. When multiplied with the emission intensities, the Leontief inverse calculates the total carbon intensities in the industries producing the final products, as collected in η. In particular, η can be interpreted as the limiting value of the infinitely long sum of emission contributions, with the number of production stages varying from 1 to ∞. When multiplied by the amount of final production, it yields the total emissions.

3.2 Taking stock from a simple theoretical model of carbon leakage

We contextualize our findings with a theoretical model of international trade. It incorporates CO_2 emissions into the gravity model of international trade. The gravity model has been the workhorse of international trade analysis since early 2000s when its theoretical foundation

[1]In what follows, we apply structure from the calculations of value-added contents that are analogous to the measurement of carbon contents, and the notation from Los et al. (2016)

was developed by e.g. Eaton & Kortum (2002) and Anderson & van Wincoop (2003). The basic idea of the gravity model (in analogy with physics) is that international trade between two countries depends on the distance and size between them. We use a model with a sectoral structure and technological differences across sectors and countries in order to investigate the effect of environmental policy that only affects certain countries and sectors. The framework is similar to the one used by Aichele & Felbermayr (2015).

We are particularly interested on the impacts of tightening regulation on the technique component η and scale component Q, which we later study empirically. In what follows, we postulate predictions for the impacts of the regulation on them.

To derive theoretical results, we first employ a linearization of the impact of changes in the price of carbon, t, both on the emissions in imports and exports. We consider two regions that include the EU and the non-EU countries. We denote the relative changes in the carbon price in the EU (both for the imports to the EU and exports from the EU) by $\hat{t}^{EU} > 0$. While this is the direct impact, we also expect that the tightening EU policy may lower the non-EU carbon price in regions that do not have tightening climate policy due to decrease in demand for emission-intensive energy; an effect that we denote by $\hat{t}^{nonEU} < 0$.

After denoting the elasticity of emission scale component, Q, as a response to change in the price of carbon, κ_Q, and the corresponding elasticity for the technique component, η, as $\kappa_{\eta,i}$, we build a decomposition of the changes in emission a response to the policy change both for the exports from the EU and imports to the EU (ceteris paribus). We divide the effects by the regional carbon price changes as:

$$\begin{aligned}\hat{E} = \kappa_{Q,EUexports} * \hat{t}^{EU} + \kappa_{\eta,EUexports} * \hat{t}^{EU} \\ +\kappa_{Q,EUimports} * \hat{t}^{EU} + \kappa_{\eta,EUimports} * \hat{t}^{EU} \\ +\kappa_{Q,nonEUexports} * \hat{t}^{nonEU} + \kappa_{\eta,nonEUexports} * \hat{t}^{nonEU} \\ +\kappa_{Q,nonEUimports} * \hat{t}^{nonEU} + \kappa_{\eta,nonEUimports} * \hat{t}^{nonEU},\end{aligned} \tag{2}$$

where $\kappa_{Q,i}$ and $\kappa_{\eta,i}$ correspond to changes in the components of the emission flow, which involves either exports from EU ($EUexports$), or imports to the EU ($EUimports$), in case of $\hat{t}^{EU}$. Similarly, we measure exports from the non-EU region ($EUexports$), or imports to the EU ($EUimports$), in case of $\hat{t}^{nonEU}$

We then follow Aichele & Felbermayr (2015) in elaborating the underlying dynamics of the EU ETS. In order to provide tractable findings, we use the simplified model described more closely in the Appendix B of their paper. In particular, we assume that

- there are two regions, k, (in our case, $k = non - EU, EU$) with population (employment), L_k.
- In both regions, there is a homogeneous good that operates as a numeraire, and a manufacturing good that is a Cobb-Douglas composite of final goods from different sectors. The population consumes the homogenous and manufacturing final good composite according to a Cobb-Douglas aggregator.

- Each sector combines their final, sectoral goods from varieties from intermediate output produced by the corresponding intermediate, manufacturing sectors from all countries. They are combined according to a CES aggregator to a domestic final, manufacturing good with the elasticity of substitution, σ. There are trade costs, τ.
- Each sector produces manufacturing intermediate goods according to a Cobb-Douglas production function, that combines labor and energy. The cost share of energy is denoted ξ. The price of energy, t, is assumed to be changing according to changes in the regulation.

This simple model is sufficient to show that the tightening of the EU ETS is likely to affect all components of trade. Moreover, it allows us to discuss underlying patterns in the emission trade, as well as their effects on the impact of the EU ETS. For the sake of simplicity, we do not consider higher-tier intermediate-product trade or technological changes. [2]

Next, we first elaborate the elasticities, κ, for carbon price changes in the EU, $\hat{t}^{EU}$. The following analysis straight-forwardly applies to the elasticities that involve $\hat{t}^{nonEU}$, while the roles of the regions are reversed.

The effect of increased EU carbon price on EU's exported emissions

Given our assumptions, the technique effect of increasing carbon price in the EU is a decrease in carbon intensity of the EU exports. That is, $\kappa_{\eta,EUexports}$ is negative. Formally, the elasticity of the technique component is

$$\kappa_{\eta,EUexports} = -(1-\rho) < 0 \tag{3}$$

and it straight forwardly depends on the emission intensity, i.e. the cost share of energy, $1 > \rho > 0$, in production.[3]

EU exports' scale effect, as a result of $\hat{t}^{EU}$, is given by

$$\kappa_{Q,EUexports} = -\sigma\rho - \frac{\kappa_{\lambda,EU} F_{non-EU}}{F_{EU} + \phi F_{non-EU}} < 0 \tag{4}$$

The first term is the direct price effect of the policy on the export demand of EU products in the non-EU area. In the term, σ is the consumption substitution elasticity across products. The term $\sigma\rho$ is expected to be positive.

The second term in Eq. 4 collects the indirect effect of the pricing thought the foreign market. Here, λ is the ratio of the number of product varieties produced in the non-EU area to the number of corresponding number in the EU. $\kappa_{\lambda,EU}$ captures the elasticity of ratio

[2]In case of higher-tier trade, we expect that its addition to the model would strengthen the predicted leakage, whereas technological changes may neutralize some of its effects

[3]It is likely that this effect would emerge stronger in a more extensive model if reallocation of polluting, higher-tier intermediate production to the non-EU market would occur.

on changes in the carbon pricing in the EU. Aichele & Felbermayr (2015)[4] show that this elasticity is positive, that is, the share of non-EU products increases when the EU increases its carbon pricing. The latter part of the second term in Eq. 4 reflects changes in the relative potential of the non-EU market. F_j denotes a trade cost weighted measure of the area j market potential. It is given by $F_j = \sum_{k=EU,non-EU} \frac{\varphi_{jk} L_k}{\varphi_k}$, where φ_{jk} is an entry of the inverse trade cost matrix and $\varphi_k = \sum_{i=EU,non-EU} \varphi_{ki} t_i^{\rho(\sigma-1)}$ is a cost-weighted measure of country k's inverse centrality (proximity to trade partners). [5]

The effect of increased EU carbon price on EU's imported emissions

In this simple framework, there is no feedback effect on the carbon intensity of the non-EU imports to the EU as a result of a carbon price change in the EU, i.e. $\kappa_{\eta,EUimports} = 0$. However, it is likely that a positive effect would emerge in an extended model with higher-tier intermediate production linkages or when there are technological spillovers.

The scale effect on EU imports due to $\hat{t}^{EU}$ is

$$\kappa_{Q,EUimports} = \frac{\rho(\sigma-1)F_{EU} - \kappa_{\lambda,EU}F_{EU}}{F_{EU} + \phi F_{non-EU}} > 0 \tag{5}$$

Again, there is a primary effect (the first term in the numerator) through a lowering cost competitiveness on the EU production, weighted by the market potential of the EU production. This effect is again stronger when the energy cost share is higher, but in this the substitution works towards decreasing the role of EU's own production. Beyond this effect, the EU ETS affects trade volumes through changes in the number of product varieties. This effect is dependent on the elasticity of the variety shares in the EU and non-EU area as well as the the market potential of the EU production. [6]

Overall inflow and outflow of emissions

In total, the effect of the policy comprises on the direct effect of the EU ETS on the EU carbon price and the indirect effect of the system on the non-EU carbon price. They, on the other hand, result in changes in the emission inflows to the EU and outflows from the EU. Assuming that $\hat{t}^{EU} > 0$ and $\hat{t}^{nonEU} < 0$, the scale effect of the ETS on EU's emission outflows through carbon price changes is

$$\kappa_{\eta,EUexports} * \hat{t}^{EU} + \kappa_{\eta,nonEUimports} * \hat{t}^{nonEU} < 0, \tag{6}$$

as both the EU and the non-EU price effect terms are negative. The corresponding scale effect on EU's emission inflows through carbon price changes, on the other hand, is

[4]Appendix, page 18

[5]Again, while our model does not include the effect, it is likely that highter-tier outsourcing of intermediate production towards the non-EU area would strengthen this negative effect.

[6]Outsourcing of higher-tier intermediate production is likely to strengthen this positive effect.

$$\kappa_{Q,EUimports} * \hat{t}^{EU} + \kappa_{Q,nonEUexports} * \hat{t}^{nonEU} > 0, \tag{7}$$

where both the EU and the non-EU price effect components are positive.

The technique component of the EU emission outflows is

$$\kappa_{\eta,EUexports} * \hat{t}^{EU} + \kappa_{\eta,nonEUimports} * \hat{t}^{nonEU} < 0 \tag{8}$$

as the first term is negative while the second term is 0. Finally, the technique component of the EU emission inflows is

$$\kappa_{\eta,EUimports} * \hat{t}^{EU} + \kappa_{\eta,nonEUexports} * \hat{t}^{nonEU} > 0, \tag{9}$$

as the second term is positive.

It is worth noticing that the secondary carbon price effect on the non-EU market may be expected to be weaker than the primary carbon price effect on the EU, and thus the technique effect on EU imports may be small. On the other hand, as we discussed above, the sign of the effects are likely to be the same also in case that there would be higher-tier intermediate production in the model.

4 Empirical strategy

4.1 The regression model

Let us next describe our empirical model. In our baseline regressions, we estimate the following equations:

$$Y_{mxst} = \exp\left[\beta * ETS_{mxst} + \gamma * \mathbf{POL}_{mxt} + \xi * \mathbf{INTL}_{mxt} + \nu_{mt} + \nu_{xt} + \nu_{st} + \nu_{mxs}\right] * \epsilon_{mxst}, \tag{10}$$

and

$$Y_{mxst} = \exp\left[\beta_1 * ETS1_{mxst} + \beta_2 * ETS2_{mxst} + \beta_3 * ETS3_{mxst} + \gamma * \mathbf{POL}_{mxt} + \xi * \mathbf{INTL}_{mxt} + \nu_{mt} + \nu_{xt} + \nu_{st} + \nu_{mxs}\right] * \epsilon_{mxst}, \tag{11}$$

where Y_{mxst} are the imports from country x to country m in sector s and time t. We also replace this variable with carbon intensity of imports, η_{mxst}, and carbon content of imports, E_{mxst}, to study the effect of ETS on these factors.

In our baseline approach, following Aichele & Felbermayr (2015), our main variable of interest is $ETS_{mxst} = \{1, 0, -1\}$, which is defined as the difference in ETS status between the importer and exporter in sector s. It receives value 1 if the importer is in the system, while the exporter is not. The value 0 indicates that the status is the same, whereas value -1 means that only the exporter is in the system.

There are good reasons for the use of this formulation. Theoretically, the term combines the two positive scale effects: (1) the positive impact on inflow in Eq. 7; and (2) the (opposite of) negative effect on outflow in Eq. 6. The corresponding positive technique (intensity) effects combines: (1) the positive impact on in Eq. 9 for inflow; and (2) the (opposite of) negative effect on outflow in Eq. 8. Thus, the approach provides a single indicator for both the technique and the scale components of the EU ETS effects, and thus a useful overall test for the existence of the carbon leakage. That is, our hypothesis is that $\beta > 0$.[7] However, the effects on imports and exports are not expected to be symmetric, and therefore later in this paper we also distinguish between the effects on imports and exports.

The ETS status is further separated into the three phases in equation 11. As opposed to earlier studies, our longer dataset gives us the opportunity to inspect the different phases. It would be plausible to assume that when the EU ETS has become more restrictive with later phases, its effects would also be more visible. As already discussed, the first phase in 2005–2007 was considered as a trial period, and only in phases 2 and 3 did the system include more actual commitments.

The variables in POL are controls for whether the country pair has entered a new regional trade agreement (RTA) or if one of them joined the EU during 2000–2018. In addition, the gravity theory uses fixed effects to account for the multilateral resistance[8] of different countries. The fixed effects we use are for importer-year, exporter-year and country-pair-sector to account for country-level time-variant changes as well as time-invariant factors at the country and sector level. We also include a fixed effect for sector-year to account for global shocks at the sector level.

In our estimation, we include both international and intra-national trade flows. Including intra-national data is recommended for several reasons, mostly to better comply with gravity theory and having both home and international production and consumption (Yotov et al., 2016). In addition, having intra-national trade data enables the identification and estimation of the effects of non-discriminatory trade policies (e.g. tariffs) (Heid et al., 2021). It also allows us to capture the effects of globalization on international trade, as now both global and intra-country trade can be compared (Bergstrand et al., 2015). In our estimations, globalization is taken into account by including the $INTL$ dummies that equal 1 if the country pair has a different importer and exporter in a specific year t in our data. As we have 18 years, we also have 18 dummies, but one is dropped out to avoid collinearity with the fixed effects. In robustness checks, we also test whether the inclusion of intra-trade data affects our results significantly.

We use the Poisson Pseudo Maximum Likelihood (PPML) method in our estimations instead of converting the dependent variable into logarithms. This approach has been

[7]It is worth noticing that Aichele & Felbermayr (2015) uses the average effect also to control for potential endogeneity problem that arises from the selection of countries to the Kyoto protocol. As an EU-wide system, the EU ETS do not suffer from similar problems

[8]Multilateral resistance describes the ease of market access for imports and exports. It absorbs e.g. country size, various national policies, institutions, and exchange rates (Yotov et al., 2016).

recommended in the gravity theory because using PPML can avoid issues arising from possibly heteroscedastic trade data, as it gives the same weight to each observation in the estimation and reduces the possible bias (Silva & Tenreyro, 2006). In addition, with PPML it is also possible to keep zeros in the data.

Defining the EU ETS variable as the differential status between the importer and exporter means that the effect of the EU ETS is considered to be symmetric when only the importer is in the ETS (ETS status 1) and when only the exporter is (ETS status -1). However, we also check how separating the effects for the EU ETS importer and exporter affects the results. When separating the effects, we estimate:

$$Y_{mxst} = \exp\left[\beta_m * ETS_{mst} + \beta_x * ETS_{xst} + \gamma * \mathbf{POL}_{mxt} + \xi * \mathbf{INTL}_{mxt} + \nu_{mt} + \nu_{xt} + \nu_{st} + \nu_{mxs}\right] * \epsilon_{mxst}, \tag{12}$$

and

$$Y_{mxst} = \exp\Big[\sum_{n=1}^{3} \beta_{mn} * ETSn_{mst} + \sum_{n=1}^{3} \beta_{xn} * ETSn_{xst} + \gamma * \mathbf{POL}_{mxt} + \xi * \mathbf{INTL}_{mxt} + \nu_{mt} + \nu_{xt} + \nu_{st} + \nu_{mxs}\Big] * \epsilon_{mxst}. \tag{13}$$

Now, the EU ETS variable is separated as ETS_{mst} that equals 1 when the importer and industry are in the EU ETS and ETS_{xst} that also equals 1 when the exporter and industry are in the system. Using the previously defined ETS variable, we now have $ETS_{mxst} = ETS_{mst} - ETS_{mxt}$.

As can be seen, the difference between equations 10 and 12 is that in the first one we assumed that $\beta_m = -\beta_x$. The estimation strategy with symmetric effects for importer and exporter is simpler and gives greater statistical power than the second, but requiring the symmetry is also more restrictive, and as our theoretical model shows, is typically only an approximation. Therefore, we evaluate both approaches.

4.2 Estimation challenges and possible sources of bias

Using the gravity model to estimate the effects of different trade policies is well-established in empirical literature, but there are still challenges with different biases and the identification of the model. These challenges include heteroscedasticity of the data, the large number of zero trade, and endogeneity of trade agreements (Yotov et al., 2016). However, in the case of the EU ETS, the selection into the system does not include great concerns of endogeneity. That is, the selection was decided on the basis of being in the EU (except in the case of Norway, Iceland and Liechtenstein) as opposed to being an individual choice of each country like in the case of e.g. Kyoto agreement. Most of our data also does not include zeros, although in the case of carbon intensity of imports, it is possible to include those. Heteroscedasticity can still remain an issue, and using PPML as the main method solves this. In robustness checks we do check if the results would change with log-transformation of the dependent variable, as it has also been used in previous studies.

PPML has been generally recommended when using the gravity model, but Weidner & Zylkin (2021) show in a recent paper that the basic PPML estimator can also have bias in the estimated coefficients and standard errors because of incidental parameter problems (IPPs). IPPs can arise when the estimation includes fixed effects that cause noise, which contaminates the scores of the main parameters of interest (Weidner & Zylkin, 2021). Weidner & Zylkin (2021) show how to solve this issue in three-way gravity models that include the importer-year, exporter-year and country pair fixed effects by using different kinds of bias correction methods. However, their solutions do not include industry-level fixed effects and as such cannot be directly applied to our analysis. Weidner & Zylkin (2021) note that the asymptotic bias problem may be more severe when including industries, but their "four-way" model is slightly different than ours and includes country-year-industry and country-partner-time fixed effects but no industry-time effects. In addition, according to Weidner & Zylkin (2021) the problem is more benign if the number of countries, industries and years all get larger at the same time. We have a relatively long time period of 18 years in addition to 60 countries and 14 industries. As such, the bias would be expected to remain moderate.

5 Data and descriptives

5.1 Data

In our empirical analysis, we first use data on international manufacturing trade flows for 2000–2018 from the UN Comtrade database. We construct import data by mirroring exports to the opposite direction, as exports are reported in free on board (FOB) format that excludes transport costs. The Comtrade data is reported in 6-digit HS1996 format that we convert into ISIC Rev. 3 by using an industry concordance table by the World Bank's WITS page. We also combine the trade value data with data on emission intensities of imports from OECD's "Carbon dioxide emissions embodied in international trade" database. The intensities are measured as tons of CO_2 per one million USD. This gives us data on how much emissions are imported in tons of CO_2. The OECD data includes zeros when there has been no trade between the countries, whereas in the Comtrade data the observations are treated as missing in these cases. For consistency and in order to have a similar number of observations, we mark the zeros as missing also in the OECD data. In robustness checks, we then see if the inclusion of zeros affects the results. The OECD data uses a similar classification system as ISIC Rev. 3, but some categories are combined. Table 2 presents the final industrial categories that we use. We only include categories in the manufacturing sector and leave out e.g. mining and quarrying, as we want the industries to be similar.

The ISIC Rev. 3 categories that match the ETS application are 21–22, 23, 26, and 27 in the first and second phases and category 24 in addition to the previous ones in Phase 3. It

TABLE 2: Included sectors

ISIC Rev. 3	Industry
15–16	Food products, beverages, and tobacco
17–19	Textiles, wearing apparel, leather, and related products
20	Wood and products of wood and cork
21–22	Paper products and printing
23	Coke and refined petroleum products (and nuclear fuel)
24	Chemicals and chemical/pharmaceutical products
25	Rubber and plastic products
26	Other non-metallic mineral products
27	Basic metals
28	Fabricated metal products, except machinery and equipment
29	Machines and equipment n.e.c.
30–33	Computers, and electronic and electrical equipment
34	Motor vehicles, trailers, and semi-trailers
35	Other transport equipment

should be noted that categories 21–22 include both paper products and printing, although the ETS only applies to paper and pulp, not to printing (due to the OECD classification).

Importantly, in addition to international trade flow data, we also utilize intra-national data as discussed in the empirical strategy. We construct the intra-national trade data by first using UNIDO's Indstat 2 data on production and then taking exports out. This gives us an estimate of how much of a country's production is consumed within the country. The carbon intensity of intra-national trade is taken from the OECD data by using the exporter's carbon intensities as the carbon intensities of home production. Combining the Comtrade, OECD and UNIDO data leaves 60 countries that have mostly non-missing data, so we use those in our analysis.

The carbon content of imports is calculated by multiplying the imports (USD million) with the carbon intensity of imports (tonnes per USD million). This gives the amount of carbon in tonnes that is imported into different countries.

The RTA and EU controls have been created by using Mario Larch's Regional Trade Agreements Database. This database includes all multilateral and bilateral regional trade agreements that have been notified to the WTO between 1950–2019. We keep the agreements that have been made after 2000 in our data. There were 371 new RTAs between different country pairs during this time (of course many of these are agreements that involved multiple countries, such as NAFTA, and not only separate agreements between each country pair).

5.2 Descriptive statistics

TABLE 3: Means of the dependent variables

	Country ETS status: 1			Country ETS status: 0			Country ETS status: -1		
Industry	Imports	CO2 intensity	CO2 content	Imports	CO2 intensity	CO2 content	Imports	CO2 intensity	CO2 content
15-16	56	526	23742	318	479	117162	74	421	20587
17-19	125	547	79162	304	473	171559	63	353	15971
20	11	619	9665	51	524	28448	11	413	3713
21-22	21	756	14604	126	642	68971	32	490	12807
23	117	1061	129519	270	1097	224926	60	1114	47821
24	156	1008	107443	583	795	344886	218	703	74926
25	32	1872	39439	158	1399	119896	34	497	11494
26	14	1724	28603	67	1446	92541	20	1143	16213
27	111	1950	231982	375	1680	581527	81	1446	92096
28	31	963	37695	131	800	103110	36	549	13584
29	114	755	81565	464	623	238088	200	467	55980
30-33	361	706	230128	1385	578	776909	240	406	63233
34	92	653	50780	608	546	236786	183	386	53118
35	64	647	39681	141	522	65692	93	399	25446

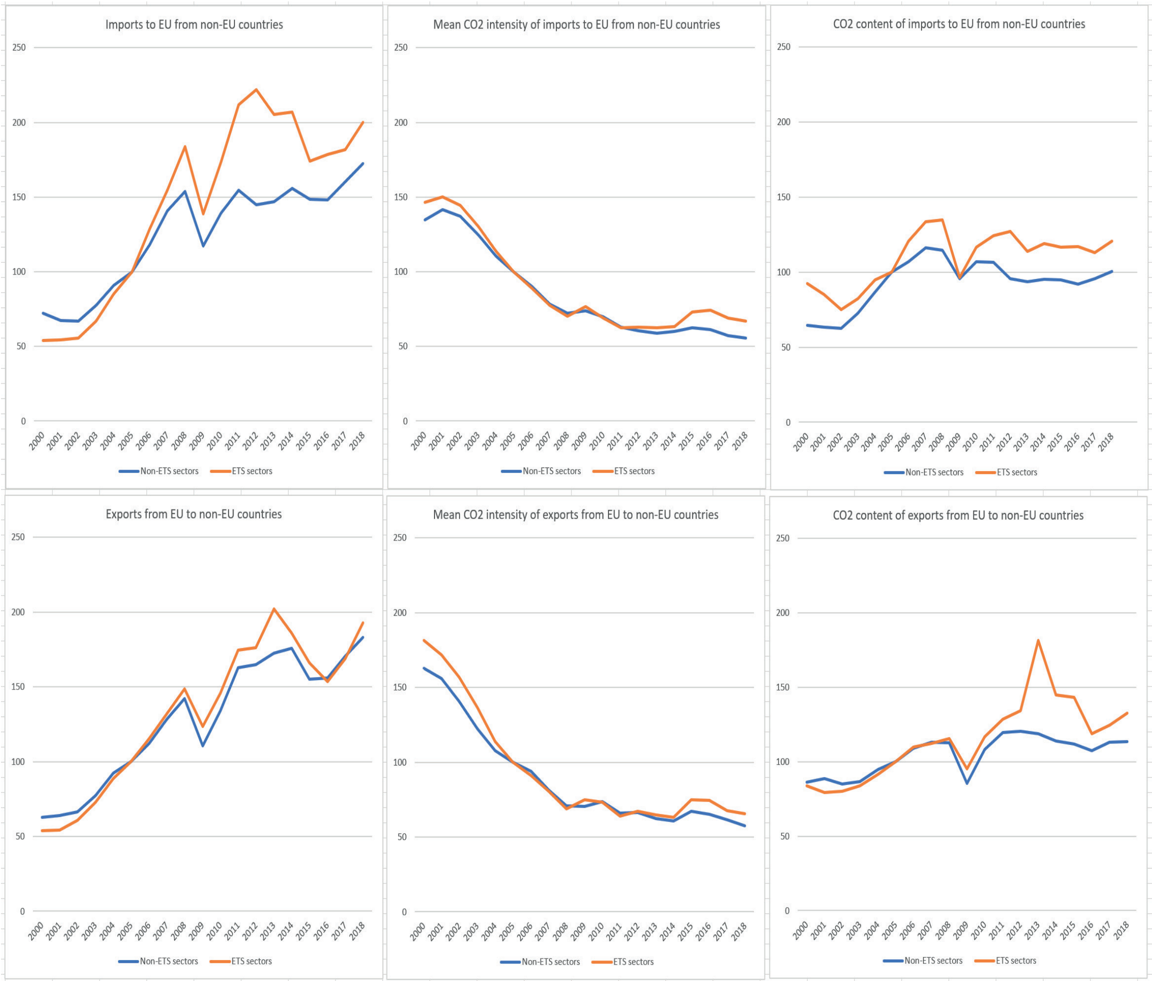
In order to form a basis for our analysis, we first check whether the country groups with different EU ETS status have significant differences in their imports, CO_2 intensity of imports and CO_2 content of imports. Table 3 shows the mean values of each of these dependent variables we use for each EU ETS group and industry. The standard deviations of these variables are quite large and have not been listed here. Imports are shown as million USD, CO_2 intensities as tons/USD million and CO_2 content of imports as tons of CO_2. The industries included in the ETS are bolded. It appears that the group 0 with neither or both countries in the EU ETS has the highest amount of imports, which is not surprising considering that it includes e.g. USA-China and intra-EU trade. The CO_2 intensity of imports appears to be the highest when only the importer is in the ETS. In addition, the industries that are included in the ETS have high CO_2 intensities as compared to the non-ETS ones. This can mean both that the due to the EU ETS, imports have become more CO_2 intensive and that these industries have high CO_2 intensities in the first place and have thus been selected to the ETS.

Next, we introduce trends in CO_2 intensity and CO_2 content of imports in our data. Figure 2 shows the development of these variables as an index with the start of the EU ETS in 2005 as the base year. We only keep the trade between EU and non-EU countries [9] to focus on the possible effects of the EU ETS. It is notable that the there has been a substantial increase in the overall amount of imports to the EU during the last decades, while the trend has slowed after the onset of the great recession in 2008. Meanwhile there has been a decline in the overall carbon intensity of the EU imports, but again, the trend has slowed down considerably after the great recession.

An inspection of the non-ETS and ETS sectors shows that the sectors share similar patterns. However, after the system was introduced in 2005, there has been divergence,

[9] Norway, Iceland and Liechtenstein are dropped from the data, as they only joined the EU ETS in the second phase.

FIGURE 2: Trends in imports, CO2 intensity and CO2 content of imports



namely, the carbon content of the ETS sector imports have moderately increased, while in the non-ETS sector the decline has continued, albeit at a slower pace. As compared to the previous trends in the overall imports of carbon emissions, the turnover towards declining emissions has been weaker in the ETS sector.

As for exports from EU to non-EU countries, the trends in our variables of interest appear similar to the imports. However, Figure 2 shows that in 2013, there was a spike specifically in the ETS sector export values and carbon content of exports. This is the year that the Phase 3 of the EU ETS started, which is interesting in terms of our analysis.

These patterns are interesting in the light of our theoretical model. First, they suggest that intensified globalization, and the resulting closer proximity of markets, contributes to an increase in the impact of the EU ETS on the carbon leakage through the scale effect of imported pollution. On the other hand, the trend decline in the intensity of carbon imports suggest fever carbon leakage both though lesser impact on the scale and intensity of carbon imports to the EU. That is the case, if the trends imply lower overall cost share of energy in production, i.e., a decline in β of our simplified model. In addition, the trends are parallel for the ETS and non-ETS sectors before the beginning of the EU ETS in 2005, so the assumption of parallel trends appears to hold.

Figure 3 shows estimated coefficients for leads and lags of our dependent variables. We define leads for years 2002, 2003 and 2004, and lags for the years 2006-2018. In other words, we estimate

$$Y_{mxst} = \exp\Big[\sum_{l=0}^{L} \beta_{-l} * ETS_{mxst-l} + \sum_{k=1}^{K} \beta_{t+k} * ETS_{mxst+k} + \gamma * \mathbf{POL}_{mxt} + \xi * \mathbf{INTL}_{mxt} + \nu_{mt} + \nu_{xt} + \nu_{st} + \nu_{mxs} \Big] * \epsilon_{mxst}, \quad (14)$$

with L as the number of leads and K the number of lags.

The figures show an increase from around 0 to positive estimates around the time of the adoption of the EU ETS, although the timing varies slightly for each variable. For imports and the carbon content of imports, the pre-treatment coefficients are nearly on the zero line, which shows that before the adoption of the ETS the trends were similar to both ETS and non-ETS imports. Around the time of the treatment in 2005, the paths started to diverge. This also suggests that the parallel trend assumption should hold. The carbon intensity of imports is slightly different, as it shows that the signs of the coefficients shifted in 2005.

Year 2012 stands out as especially noticeable for all variables, and as this was the year before the start of Phase 3 of the ETS, it is possible that there were some anticipatory effects. We could also see this in Figure 2, as in 2012 the imports in the ETS sectors increased, while at the same time the non-ETS sector imports decreased. Overall, the figures show support to our hypothesis that the ETS has had an impact on the variables of our interest, and that without it the ETS and non-ETS groups would have had similar trends.

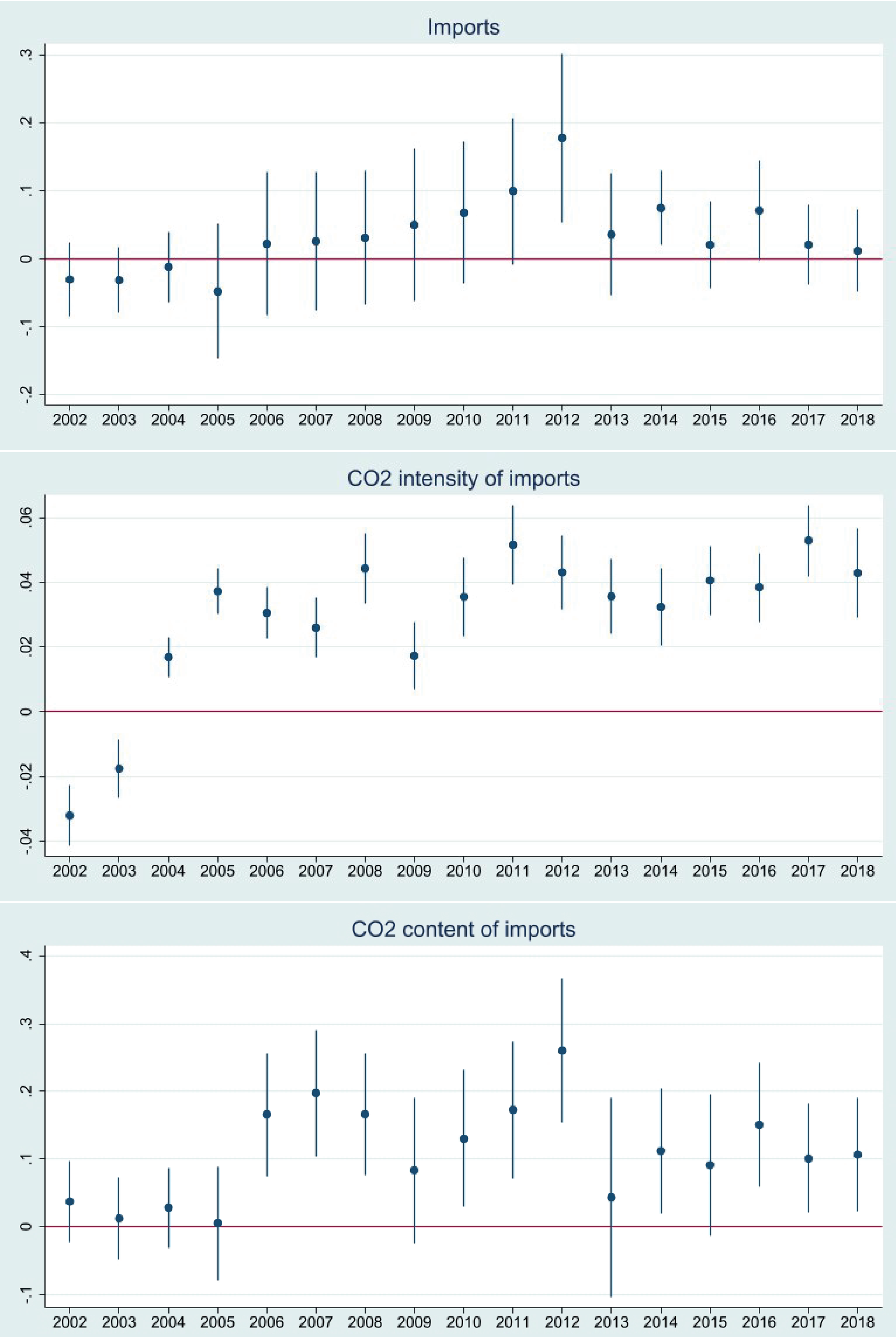
6 Results

6.1 Baseline regression results

Table 4 shows the results of our baseline regressions with pooled sectoral data. Imports, CO_2 intensity and CO_2 content of imports all show positive signs due to the EU ETS in general and also when divided into the separate phases. The effect appears the most statistically significant on the CO_2 intensity of imports in column (2), where the results imply that countries and sectors that are in the EU ETS have an approximately 4 % higher CO_2 intensity of imports than the non-participant country and sector pairs [10]. When separating the effect on carbon intensity into the different phases in column (5), all phases show an

[10] We use the Poisson Pseudo Maximum Likelihood estimation (PPML) method, so the results should be translated into percentages by using the formula $(\exp^{\beta} - 1) * 100$, where β is the coefficient.

FIGURE 3: Estimated coefficients and standard errors for leads and lags



approximately 2 % increase with the highest level of statistical significance. In other words, the effect of the EU ETS on the carbon intensity of imports has been steady over each phase.

TABLE 4: Baseline regressions

	(1)	(2)	(3)	(4)	(5)	(6)
	Imports	CO2 intensity	CO2 content	Imports	CO2 intensity	CO2 content
EU membership	0.323***	0.00341	0.319***	0.323***	0.00425	0.321***
	(6.72)	(0.49)	(6.43)	(6.72)	(0.60)	(6.44)
RTA	0.0444	-0.000877	0.0467	0.0444	-0.000913	0.0474
	(1.55)	(-0.18)	(1.38)	(1.55)	(-0.19)	(1.40)
EU ETS	0.0490*	0.0357***	0.115***			
	(2.15)	(8.88)	(3.62)			
EU ETS Phase 1				-0.0121	0.0249***	0.0750
				(-0.23)	(8.43)	(1.64)
EU ETS Phase 2				0.0677	0.0157***	0.120**
				(1.35)	(4.58)	(2.61)
EU ETS Phase 3				0.00488	0.0203***	-0.0205
				(0.32)	(5.31)	(-1.20)
Observations	831153	873641	801619	831153	873641	801619

Values for the globalization dummies and constant omitted. All regressions include a full set of country-time, sector-time and country-pair-sector dummies. Standard errors in parentheses clustered at country-pair-sector level.

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

For the value of imports, the results are not as clear as with the carbon intensity. The total EU ETS coefficient in column (1) implies a 5 % higher value in imports when the country and sector are in the EU ETS at the 5 % level of statistical significance. When we separate this impact into the phases in column (4), the results are not statistically significant. However, our estimation still does imply a higher value of imports in general when the trade is regulated by the EU ETS.

The CO_2 content is generated by multiplying the imports by the CO_2 intensity, so the estimated coefficients logically appear a combination of the two. Our results in column (3) indicate an approximately 12 % higher value for the carbon content of imports due to the differential EU ETS status. When studying the phases separately in column (6), Phase 2 shows a statistically significant and rather large impact of 13 %. Interestingly, the estimated coefficient turns negative in Phase 3, but this effect is not statistically significant.

The control variable for RTAs is not statistically significant in our estimations for any of the dependent variables, while the effect of new EU memberships after 2000 has had a positive impact on imports but no significant effect on the CO_2 of imports. This suggests that trade agreements have not significantly affected international trade when globalization is also taken into account (without the globalization dummies the RTA variable would have positive and statistically significant sign, but we omit these results here for brevity). On the other hand, a closer integration to the EU shows positive impacts on trade flows.

Our findings are broadly consistent with the theoretical findings in Section 3.2, where we show that both the average scale component and the technique (CO_2 intensity) components of trade are likely to increase as a result of more stringent policy in the EU.

6.2 Separate EU ETS variables for the importer and exporter

In order to see if our specification of the EU ETS variable affects the results, we also separate the effect for when the importer is in the EU ETS and when the exporter is. In the previous subsection we only had one coefficient, β, for the differential EU ETS status and thus assumed that the effect of the EU ETS is symmetric for importer and exporter, i.e. $\beta_m = -\beta_x$. However, this is not the case in our theoretical model, and therefore in this subsection the effects are separated. Table 5 shows the results.

The estimations now show how the effects of the EU ETS are divided for imports vs. exports. When the importer is in the EU ETS, the results show no statistical effects, whereas the impact is -8 % when the exporter is in the ETS. The negative impact on the exports is expected based on our theoretical results (see, Eq. 6). On the other hand, we would also have expected a positive impact for the importer based on the theory (Eq. 7). One reason for the weak impact may be the use of policies that support the cost competitiveness of the EU ETS sectors, such as the use of free allowances. While this explanation is reasonable, we leave it's further assessment for future work.

In the case of the CO_2 intensity of imports (technique component) in column (2), the effect appears slightly more symmetric and is more similar to our previous results with the assumption of $\beta_m = -\beta_x$. These results imply a substantial decrease of 6 % in the CO_2 intensity of exports, which is expected based on our theoretical considerations (see, Eq. 8). On the other hand, there is a moderate increase of 1 % in the CO_2 intensity when only the importer is in the EU ETS. Based on our theoretical considerations, this weaker result is likely to reflect carbon leakage through the secondary, lowering carbon price effect on the non-EU market (see, Eq. 9)[11], while its smaller size compared to the import effect is expected due to the direct role of the EU ETS on the EU production technique on the EU exports.

The combined effect, the estimated coefficient for the CO_2 content of imports in column (3) is positive for the importer in the EU ETS, and almost symmetrically negative for the case with the exporter. These results imply that the EU ETS has had an impact in decreasing the emissions in the production in the EU, as the estimated coefficient for the carbon content of exports is strongly negative with a 14 % decrease. However, as the carbon content of imports has increased, some of the gains from the emissions decreases are lost.

When we separate the effects into the phases, the imports in column (4) again do not appear to be significantly affected when the importer is in the EU ETS. On the other hand, the second and third phases have statistically significant and rather large negative coefficients

[11]The result may also reflect dynamics in the higher-tier intermediate production structure.

Table 5: Separate EU ETS variables for importer and exporter

	(1) Imports	(2) CO2 intensity	(3) CO2 content	(4) Imports	(5) CO2 intensity	(6) CO2 content
EU membership	0.316***	0.00472	0.313***	0.316***	0.00471	0.313***
	(6.61)	(0.68)	(6.43)	(6.60)	(0.68)	(6.42)
RTA	0.0437	-0.000817	0.0467	0.0441	-0.000804	0.0467
	(1.52)	(-0.17)	(1.38)	(1.54)	(-0.17)	(1.38)
Importer in the EU ETS	0.00879	0.0118*	0.0894*			
	(0.27)	(1.97)	(2.29)			
Exporter in the EU ETS	-0.0868**	-0.0622***	-0.154***			
	(-2.81)	(-10.76)	(-3.87)			
Importer in the EU ETS, Phase 1				0.00000804	0.00419	0.0941*
				(0.00)	(0.92)	(2.26)
Importer in the EU ETS, Phase 2				0.0461	0.0120	0.114*
				(0.89)	(1.70)	(2.26)
Importer in the EU ETS, Phase 3				-0.00157	0.0169*	0.0771
				(-0.04)	(2.06)	(1.42)
Exporter in the EU ETS, Phase 1				-0.0147	-0.0660***	-0.155***
				(-0.28)	(-14.14)	(-3.58)
Exporter in the EU ETS, Phase 2				-0.142**	-0.0583***	-0.227***
				(-2.60)	(-8.64)	(-4.28)
Exporter in the EU ETS, Phase 3				-0.0855*	-0.0631***	-0.106
				(-2.23)	(-8.20)	(-1.80)
Observations	831153	873641	801619	831153	873641	801619

Values for the globalization dummies and constant omitted. All regressions include a full set of country-time, sector-time and country-pair-sector dummies. Standard errors in parentheses clustered at country-pair-sector level.

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

when the exporter is in the ETS. However, it should be noted that this degree of separating the effects can cause some issues with the estimation. This is apparent from the column (4) for the Phase 1 with importer in the EU ETS, as the coefficient and standard errors are not well defined. As such, these results should be interpreted with caution, as especially the standard errors could be biased. Our baseline model with one coefficient for differing EU ETS status is thus the preferred approach.

7 Conclusions

The EU has committed itself to significantly reducing its human-induced (CO_2) and other GHG emissions influenced in order to mitigate global climate change. In this paper, we studied whether rising emission prices lead to carbon leakage, i.e., the transfer of polluting production to countries that are not committed to strong mitigation measures. Empirical research on carbon leakage is still inconclusive, and collection of new evidence is necessary from the perspective of design and justification of climate policy.

We studied the impact of a key instrument of the EU climate policy, the EU ETS. Our approach was to utilize a simple theoretical framework that incorporates CO_2 emissions into the gravity model of international trade, and investigate the effect of the ETS phases from differences in the structure of trade across countries and sectors that either participated or did not participate to the scheme. With recently updated data on trade flows and their emissions, we have been able to clarify the underpinnings of the analysis with tractable, theoretical results.

Consistently with the theory, our findings indicate that carbon leakage has indeed occurred due to the EU ETS, and as expected it has become stronger in the later phases of the system. This result is the most apparent in the carbon intensity of imports to the EU ETS participants, where a general increase of approximately 4 % due to the system was found. In addition, the value of imports appears to have increased, but the evidence is not statistically as strong. The carbon content, i.e. the amount of carbon in tonnes, of imports has also increased by approximately 12 %. Moreover, we found evidence of lowering CO_2 intensity of the EU exports. This finding is consistent with our theoretical conjunctions and provides further support on the validity of our results.

Our findings are important, as previously no clear evidence of carbon leakage in the EU ETS has been found in empirical studies. Our analysis with longer data period and three different phases of the ETS has therefore been able to show some novel findings, which can be useful in determining the effectiveness of the system. In particular, the new evidence is necessary from the perspective of design and justification of unilateral measures such as the carbon border adjustment mechanisms or other trade restrictions on high-emission products from non-EU countries.

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A Country list

The countries included in our data are: Argentine, Australia, Austria, Belgium, Bulgaria, Brazil, Canada, Chile, China, Colombia, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hong Kong, Hungary, Iceland, Indonesia, India, Ireland, Israel, Italy, Japan, Kazakhstan, Latvia, Lithuania, Luxembourg, Morocco, Mexico, Malta, Malaysia, Netherlands, New Zealand, Norway, Peru, Philippines, Poland, Portugal, Romania, Russia, Saudi Arabia, Singapore, Slovakia, Slovenia, South Africa, South Korea, Spain, Sweden, Switzerland, Thailand, Tunisia, Turkey, USA, United Kingdom, and Vietnam.

B Separate sectors

TABLE A1: Separate variables for sectors

	(1) Imports	(2) CO2 intensity	(3) CO2 content
EU membership	0.324***	0.00513	0.319***
	(6.74)	(0.75)	(6.42)
RTA	0.0441	-0.000805	0.0460
	(1.54)	(-0.17)	(1.36)
21-22: Paper products and printing	0.0464	-0.0134**	0.00778
	(1.46)	(-3.04)	(0.20)
23: Coke and refined petroleum products	0.211**	-0.0641***	0.276**
	(2.76)	(-6.75)	(2.82)
24: Chemicals and chemical (/pharmaceutical) products	0.0140	0.0216***	0.0160
	(0.45)	(4.46)	(0.41)
26: Other non-metallic mineral products	0.189***	0.0396***	0.0831*
	(4.49)	(5.22)	(2.25)
27: Basic metals	0.0925	0.122***	0.183*
	(1.07)	(20.96)	(2.42)
Observations	831153	873641	801619

Values for the globalization dummies and constant omitted. All regressions include a full set of country-time, sector-time and country-pair-sector dummies. Standard errors in parentheses clustered at country-pair-sector level.

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

When separating the variables of interest into smaller and smaller categories, the statistical power of our analysis decreases and interpreting the results becomes more difficult. Nevertheless, it can still be a useful exercise to check which industries are the most affected by the EU ETS. Table A1 shows the estimated coefficients separately for each industry that is included in the ETS. These results suggest that it is the ISIC Rev. 3 categories 23 (coke and refined petroleum products) and 26 (other non-metallic mineral products) that have seen increased imports due to the ETS. On the other hand, basic metals appear to have had a large increase in the carbon intensity of imports, while the value of imports has not been statistically affected. Somewhat unexpectedly, the CO_2 intensity of imports has negative coefficients for categories 21-22 and 23. As we compare changes in both country and industry level, it can be possible that some non-ETS sectors have seen more increases in their CO_2 intensities of imports compared to these categories. However, as already noted, interpretation of the results at a more detailed level can be challenging.

C Robustness checks

C.1 No intra-trade data

Previous research on the effects of the EU ETS has not included the intra-trade data, and in order to better compare our results we also check how the inclusion of this data affects the outcomes. In this case, globalization dummies cannot be included either. Table A2 shows the results with our symmetric EU ETS variable.

The results are quite similar to our baseline results. The carbon intensity of imports is not affected by not including the intra-trade and globalization dummies, which is logical considering that the carbon intensities are calculated as mean values for each country instead of sums, and as such are not very different for intra vs. international trade. At the same time, imports do show slightly larger estimated coefficient for the symmetric EU ETS variable than in our baseline estimations (6 % vs. 5 % value, respectively). In addition, without intra-trade some estimated coefficients have higher statistical significance levels than with it. That is, the general ETS variable in column (1) of Table A2 is now significant on 1 percent instead of 5 percent level, and in column (4) the Phase 3 is now statistically significant on the 5 percent level, whereas it was not significant before. The results with separate variables for importer and exporter in the EU ETS are similar to the ones in Table A2, so we omit those here for brevity. The conclusions are still the same.

Interestingly, the EU control variable becomes statistically non-significant for imports when the intra-trade and globalization are not included, whereas in our baseline estimations it was large and highly significant. This result further suggests that the inclusion of intra-trade data and the effects of globalization would be the preferred method, as joining the EU should increase the trade between the new and previous EU members.

TABLE A2: No intra-trade

	(1) Imports	(2) CO2 intensity	(3) CO2 content	(4) Imports	(5) CO2 intensity	(6) CO2 content
EU membership	-0.00828	0.00299	0.157**	-0.00833	0.00382	0.160**
	(-0.19)	(0.42)	(3.01)	(-0.19)	(0.54)	(3.04)
RTA	0.0643*	-0.00146	0.0681*	0.0645*	-0.00151	0.0709*
	(2.10)	(-0.30)	(2.12)	(2.11)	(-0.31)	(2.21)
EU ETS	0.0627**	0.0358***	0.126***			
	(2.79)	(8.91)	(4.16)			
EU ETS Phase 1				-0.0257	0.0250***	0.0758
				(-0.53)	(8.45)	(1.90)
EU ETS Phase 2				0.0525	0.0151***	0.121**
				(1.11)	(4.45)	(2.79)
EU ETS Phase 3				0.0380*	0.0216***	0.00446
				(2.53)	(5.78)	(0.23)
Observations	818423	857778	788918	818423	857778	788918

Values for the constant omitted. All regressions include a full set of country-time, sector-time and country-pair-sector dummies. Standard errors in parentheses clustered at country-pair-sector level.

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

C.2 Zeros included

The trade data from Comtrade does not include zeros but instead only missing observations when there is no trade. As such, deciding which observations are truly missing and which are zero would be difficult. Some estimates say that about half of the country pairs in the available trade data do not have any trade with each other (Helpman et al., 2008), and marking zero trade flows as missing can potentially have an impact on trade analysis. However, our sample includes 60 countries, most of which are relatively large and have trade with each other. Consequently, only approximately 11 % of observations for imports in our data are missing and the rest have positive values. On the other hand, the OECD data that we use to derive the carbon intensity of imports does include zero values. This allows us to check whether the inclusion of these values impacts our results. We also replace the value for imports with zeros when the CO2 intensity of imports is zero in the OECD data, and thus can compare all the variables with and without zeros.

Table A3 shows the results. The estimated coefficient are similar as to the ones in Table 4. The same applies to the estimations with separate ETS variables for importer and

TABLE A3: Regressions with zeros

	(1) Imports	(2) CO2 intensity	(3) CO2 content	(4) Imports	(5) CO2 intensity	(6) CO2 content
EU membership	0.321***	-0.0738***	0.315***	0.321***	-0.0727***	0.317***
	(6.68)	(-8.06)	(6.35)	(6.67)	(-7.90)	(6.37)
RTA	0.0440	-0.00777	0.0461	0.0440	-0.00777	0.0468
	(1.54)	(-1.22)	(1.37)	(1.54)	(-1.22)	(1.39)
EU ETS	0.0491*	0.0481***	0.115***			
	(2.16)	(8.13)	(3.62)			
EU ETS Phase 1				-0.0123	0.0240***	0.0746
				(-0.23)	(4.77)	(1.63)
EU ETS Phase 2				0.0678	0.0165**	0.120**
				(1.35)	(3.26)	(2.60)
EU ETS Phase 3				0.00491	0.0367***	-0.0203
				(0.32)	(6.97)	(-1.19)
Observations	850548	939092	850522	850548	939092	850522

Values for the globalization dummies and constant omitted. All regressions include a full set of country-time, sector-time and country-pair-sector dummies. Standard errors in parentheses clustered at country-pair-sector level.

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

exporter, so we omit those here. As such, not including the zeros in our main estimation does not appear to induce a great bias in the estimation of the carbon intensity variable.

C.3 China removed from the data

China joined the WTO in 2001, and its international trade has grown at a fast speed in the 21st century. In our data, China's exports to the 59 other countries increased 10 times during 2000–2018, from 200 billion to 2000 billion USD. For comparison, USA's exports "only" doubled during this time. As such, we also check whether or not the inclusion of China changes our results. Table A4 shows the results with China excluded.

As can be seen, the estimated coefficients for the EU ETS and its phases do not change much. Only notable change is that without China, the value of imports shows a 6 % increase instead of 5 %. Overall, China does not appear to drive our results.

Table A4: No China

	(1) Imports	(2) CO2 intensity	(3) CO2 content	(4) Imports	(5) CO2 intensity	(6) CO2 content
EU membership	0.351***	0.00362	0.377***	0.350***	0.00456	0.377***
	(7.13)	(0.50)	(7.52)	(7.12)	(0.63)	(7.48)
RTA	0.0592	-0.000811	0.0724*	0.0591	-0.000858	0.0722*
	(1.88)	(-0.15)	(2.27)	(1.88)	(-0.16)	(2.26)
EU ETS	0.0590*	0.0399***	0.120***			
	(2.48)	(9.49)	(3.84)			
EU ETS Phase 1				-0.00874	0.0261***	0.0604
				(-0.16)	(8.60)	(1.28)
EU ETS Phase 2				0.0852	0.0168***	0.151**
				(1.60)	(4.70)	(2.95)
EU ETS Phase 3				0.0102	0.0241***	0.000457
				(0.67)	(6.06)	(0.03)
Observations	800296	842547	771088	800296	842547	771088

Values for the globalization dummies and constant omitted. All regressions include a full set of country-time, sector-time and country-pair-sector dummies. Standard errors in parentheses clustered at country-pair-sector level.

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

C.4 Dependent variable in logarithms

As explained in the main text, PPML has been the recommended method for gravity analysis with the effects of trade agreements and restrictions. However, previous studies (e.g. Aichele & Felbermayr (2015) and Naegele & Zaklan (2019)) have also utilized log-transformation of the dependent variable. This method is computationally faster, but can cause issues with heteroscedasticity of the data, as a large number of imports are quite small and become negative after the log-transformation, causing larger variance with the smaller countries.

With log-transformation, the equations we estimate are of the form

$$y_{mxst} = \beta * ETS_{mxst} + \gamma * \mathbf{POL}_{mxt} + \xi * \mathbf{INTL}_{mxt} + \nu_{mt} + \nu_{xt} + \nu_{st} + \nu_{mxs} + \epsilon_{mxst}, \quad (15)$$

where y_{mxst} is the value of imports in logs (this can also be replaced with either the carbon intensity of imports or carbon content of imports in logs).

The results in Tables A5 and A6 are not very different from our baseline estimations, but there are some changes in the magnitude. The estimated coefficient for the symmetric EU ETS variable in A5 column (1) is positive similarly to our baseline estimations, but larger with approximately 14 % increase in imports due to the ETS, as compared to the 5 %

TABLE A5: Symmetric ETS variable, logs

	(1) Ln imports	(2) Ln CO2 intensity	(3) Ln CO2 content	(4) Ln imports	(5) Ln CO2 intensity	(6) Ln CO2 content
EU membership	-0.0186	-0.00491	-0.0146	-0.0183	-0.00492	-0.0142
	(-0.81)	(-1.55)	(-0.63)	(-0.79)	(-1.56)	(-0.61)
RTA	0.0549***	-0.000303	0.0617***	0.0551***	-0.000285	0.0620***
	(3.38)	(-0.12)	(3.80)	(3.39)	(-0.12)	(3.81)
EU ETS	0.141***	0.0142***	0.150***			
	(9.00)	(6.52)	(9.65)			
EU ETS Phase 1				0.0293	0.0104***	0.0417*
				(1.67)	(5.40)	(2.40)
EU ETS Phase 2				0.0147	-0.000632	0.0128
				(0.93)	(-0.34)	(0.82)
EU ETS Phase 3				0.0754***	0.0126***	0.0879***
				(5.48)	(6.27)	(6.47)
Observations	831127	873641	801619	831127	873641	801619

Values for the globalization dummies and constant omitted. All regressions include a full set of country-time, sector-time and country-pair-sector dummies. Standard errors in parentheses clustered at country-pair-sector level.

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

value with PPML. On the other hand, the coefficient for the carbon intensity of imports in column (2) is now smaller with a 1 % increase in the intensity when the country and sector are in the EU ETS. The carbon content of imports gets similar estimations as with PPML. The results are now more statistically significant, both with the general ETS variables and when we separate the impacts into the different phases in columns (4)-(7).

When estimating the effects with separate variables for ETS importer and exporter, the results in Table A6 are otherwise similar as before with PPML, but now the estimated coefficients for imports are positive and statistically significant when the importer is in the EU ETS. This effect is especially strong in Phase 3 in column (4). The effects of the EU ETS thus appear more moderate with PPML, and this result is backed by the gravity theory.

Table A6: Separate ETS variables for importer and exporter, logs

	(1) Ln imports	(2) Ln CO2 intensity	(3) Ln CO2 content	(4) Ln imports	(5) Ln CO2 intensity	(6) Ln CO2 content
EU membership	-0.0186	-0.00494	-0.0145	-0.0186	-0.00494	-0.0146
	(-0.81)	(-1.57)	(-0.63)	(-0.81)	(-1.57)	(-0.63)
RTA	0.0549***	-0.000291	0.0617***	0.0548***	-0.000294	0.0616***
	(3.38)	(-0.12)	(3.79)	(3.38)	(-0.12)	(3.79)
Importer in the EU ETS	0.135***	0.00247	0.133***			
	(6.55)	(0.81)	(6.56)			
Exporter in the EU ETS	-0.148***	-0.0259***	-0.167***			
	(-7.03)	(-8.23)	(-8.03)			
Importer in the EU ETS, Phase 1				0.0583*	0.000841	0.0721**
				(2.44)	(0.30)	(3.07)
Importer in the EU ETS, Phase 2				0.106***	0.00290	0.106***
				(4.24)	(0.84)	(4.31)
Importer in the EU ETS, Phase 3				0.183***	0.00283	0.175***
				(7.06)	(0.73)	(6.79)
Exporter in the EU ETS, Phase 1				-0.121***	-0.0290***	-0.135***
				(-5.07)	(-9.95)	(-5.76)
Exporter in the EU ETS, Phase 2				-0.124***	-0.0168***	-0.134***
				(-4.88)	(-4.70)	(-5.36)
Exporter in the EU ETS, Phase 3				-0.174***	-0.0303***	-0.201***
				(-6.60)	(-7.65)	(-7.65)
Observations	831127	873641	801619	831127	873641	801619

Values for the globalization dummies and constant omitted. All regressions include a full set of country-time, sector-time and country-pair-sector dummies. Standard errors in parentheses clustered at country-pair-sector level.

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

C.5 Adjusted dataset

Our data on trade flows comes from the Comtrade database, and we mirror exports into imports to get the prices without transport costs. However, it is possible that this data has some errors, as countries might not always be accurate in their reporting. Our observation period spans the years 2000–2018, and we want to make sure that the value of trade does not increase during this time simply because it has been recorded better over time. CEPII has a dataset called BACI on trade flows, which are based on the Comtrade data but the differences reported by the exporter and the importer are reconciled, and transport costs also removed. This data has approximately 60 000 more observations than just the Comtrade data we use in the main estimations, which is likely the result of combining both export and import data. The results in Table A7 are again very similar to our baseline results, and as such problems with data quality are unlikely to have caused issues.

Table A7: Data from the BACI database

	(1) Imports	(2) CO2 intensity	(3) CO2 content	(4) Imports	(5) CO2 intensity	(6) CO2 content
EU membership	0.337***	0.00341	0.312***	0.337***	0.00425	0.315***
	(8.01)	(0.49)	(7.21)	(8.01)	(0.60)	(7.22)
RTA	0.0273	-0.000877	0.0354	0.0273	-0.000913	0.0365
	(1.02)	(-0.18)	(1.11)	(1.02)	(-0.19)	(1.14)
EU ETS	0.0534**	0.0357***	0.122***			
	(2.58)	(8.88)	(4.14)			
EU ETS Phase 1				-0.0465	0.0249***	0.0352
				(-1.29)	(8.43)	(0.78)
EU ETS Phase 2				0.0178	0.0157***	0.0653
				(0.62)	(4.58)	(1.86)
EU ETS Phase 3				0.00547	0.0203***	-0.0179
				(0.36)	(5.31)	(-1.12)
Observations	890655	873641	844563	890655	873641	844563

Values for the globalization dummies and constant omitted. All regressions include a full set of country-time, sector-time and country-pair-sector dummies. Standard errors in parentheses clustered at country-pair-sector level.

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

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