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Searching for carbon leaks in multinational companies ☆

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Does a unilateral climate change policy cause companies to shift the location of production, thereby creating carbon leakage? In this paper, we analyze the effect of the European Union Emissions Trading System (EU ETS) on the geographic distribution of carbon emissions by multinational companies. The empirical evidence is based on unique data for the period 2007–2014 from the Carbon Disclosure Project, which tracks the emissions of multinational businesses by geographic region within each company. Because they already operate from multiple locations, multinational firms should be the most prone to carbon leakage. Our data includes the regional emissions of 1,122 companies, of which 261 are subject to EU ETS regulation. We find no evidence that the EU ETS has led to a displacement of carbon emissions from Europe toward the rest of the world, including to countries with lax climate policies and within energy-intensive companies. A large number of robustness checks confirm this finding. Overall, the paper suggests that modest differences in carbon prices between countries do not induce carbon leakage.

1. Introduction

With its implementation of the European Union Emissions Trading System (EU ETS) and a range of other ambitious policies that support the deployment of low-carbon technologies such as renewable energy, the European Union is widely perceived as being in the vanguard of climate change policy globally. However, this unilateral set of policies has raised concern that EU governments are threatening the international competitiveness of Europe-based companies, and in particular in carbon- and energy-intensive industries. This paper analyzes a unique dataset to explore whether multinationals have displaced their carbon emissions from Europe toward the rest of the world when they are subject to carbon pricing. In a frictionless free-trade world economic model,

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the adoption of unilateral climate policies that increase the price paid by firms for their direct carbon emissions (or for carbon-intensive inputs such as energy) relative to their foreign competitors would lead to a pollution-haven effect (Copeland and Taylor, 2004; Levinson and Taylor, 2008): Countries with relatively weaker regulations specialize in the production of carbon-intensive products, in which they have a newly acquired competitive advantage, and subsequently export these back to "virtuous" countries. The relocation of economic activity toward less-regulated regions means that the policy is not only ineffective from a climate change point of view, but also costly from an economic point of view, because it reduces jobs and economic activity in more strictly regulated countries. This has been referred to as "carbon leakage" and has attracted a lot of attention in both the policy arena and recent literature (see Branger and Quirion, 2014, and Fowlie and Reguant, 2018, for recent reviews). Some authors (e.g., Baylis et al., 2014) also suggest that there could be such a thing as negative leakage, whereby carbon regulation in one sector or jurisdiction can lead to carbon reductions, even in unregulated ones.

In this paper, we explore the possibility of carbon leakage as a result of the EU ETS using a unique panel dataset that tracks the geographic distribution of carbon emissions within 1,122 multinational companies. Such companies, with operations across a wide range of jurisdictions, might be particularly reactive to environmental regulations that impose higher production costs in a given location by shifting production to less-regulated regions in which they already operate. Our data come from the Carbon Disclosure Project (CDP), a nonprofit data collection initiative established by the investment community to collect climate change-relevant data at the level of individual businesses; the initiative's aim is to understand the exposure of companies to future climate change policies. The unique feature of the CDP data is that the emissions of multinational businesses are broken down by country or geographic region. Hence, we are able to study whether multinationals subject to the EU ETS reduce emissions in one location, only to increase them elsewhere. Specifically, we compare emissions in Europe with emissions outside Europe within the same company between 2007 and 2014.[1] We find no evidence that the EU ETS has led to a displacement of carbon emissions from Europe toward the rest of the world within multinational companies. Specifically, our empirical findings rule out that any meaningful leakage has taken place. That is, any leakage rate above 14% can be ruled out based on our results. Numerous robustness checks confirm this finding. Treated firms not only reduced emissions within the EU but also in non-EU countries as a result of the regulation. This would explain the absence of carbon leakage, a conclusion that not only emerges for the average firm in our sample but also for various subsamples—including, most importantly, firms that are deemed by the European Commission to be particularly at risk of carbon leakage because they are highly carbon-intensive and/or trade-exposed.

The EU ETS was launched in 2005, currently covers 31 countries across Europe (all 28 European Union Member States plus Iceland, Liechtenstein, and Norway), and is linked to the Swiss ETS. In total, close to 14,000 power stations and industrial facilities are covered, representing roughly 40% of the EU's total greenhouse gas emissions. These are regulated according to their main carbon-emitting activity, such as combustion of fossil fuel, cement production, or paper and pulp production. Firms that operate regulated installations make abatement and investment decisions according to the carbon price revealed in the market. An important feature of the EU ETS is that not all carbon-emitting installations operating in these sectors are regulated, in order to minimize administrative costs. Activity-specific capacity criteria determine which installations are included in the EU ETS and which are exempt. This allows us to compare multinationals that own regulated installations with those that do not. Since the start of the policy, there has been concern that the EU ETS would cause emissions and industrial activity to relocate outside of Europe, and the specter of carbon leakage continues to influence key legislation, such as the most recent EU ETS-related directive, EU Directive 2018/410.[2]

This paper contributes to the literature that seeks to understand the impact of unilateral climate change policies on carbon leakage (see Sato and Dechezleprêtre, 2015, and Dechezleprêtre and Sato, 2017, for recent reviews).[3] A large number of studies, based on computable general equilibrium (CGE) models (see Carbone and Rivers, 2017, for a review), find mixed evidence, which is highly sensitive to model assumptions and suggests large levels of uncertainty. These studies have estimated a wide range of leakage rates associated with different emissions-reduction targets under the Kyoto Protocol, going from negative leakage due to spillover effects (e.g., Barker et al., 2007) to positive leakage rates as high as 100%.

Compared with the extensive CGE literature, few empirical studies have sought to estimate the magnitude of the effect of climate change regulation on carbon leakage. Aichele and Felbermayr (2012) and Aichele and Felbermayr (2015) analyze the impact of carbon emissions reduction commitments under the Kyoto Protocol on the extent of bilateral trade flows and their carbon content by sector. They find that signing the protocol caused a 14% reduction in exports and an 8% increase in embodied carbon imports by committed countries from noncommitted countries. This suggests that some carbon leakage is happening, especially in the most affected sectors, such as basic metals, nonmetallic mineral products, and paper and pulp. In a recent study, Ben-David et al. (2021) use variation in a composite index of environmental regulatory stringency across countries to examine whether environmental regulation induces firms to shift polluting activities abroad. They find that firms headquartered in countries with stricter environmental laws emit less greenhouse gas at home and more abroad.

In the absence of carbon pricing policies in most countries, changes in relative energy prices have provided an interesting source of variation for analyzing the impact of unilateral climate change policy on production location and trade flows (Aldy and Pizer,

[1] The CDP dataset started in 2000, but the sample of firms included was extremely limited until 2006.

[2] Provision 10, for instance, states, "Experience gathered during the operation of the EU ETS has confirmed that sectors and subsectors are at risk of carbon leakage to varying degrees". Free allowance allocation is a direct consequence of this concern. Direct link: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0410&from=EN.

[3] See also Sato (2013) for a comprehensive review of the literature that seeks to measure the carbon content of trade.

2015; Sato and Dechezleprêtre, 2015). These studies tend to find a small effect of energy price on net imports, with an elasticity between 0.1% and 0.8%, and only significant for energy-intensive industries.

Our paper is closely related to the limited number of studies that have sought to empirically assess the impact of the EU ETS on carbon leakage by focusing on different outcome variables, such as trade flows, business downsizing, and foreign direct investments (see Martin et al., 2016, for a review). For instance, Naegele and Zaklan (2019) analyze the impact of the EU ETS on the carbon emissions embodied in traded goods and on trade value, using data from the Global Trade Analysis Project (GTAP). They find no evidence that the EU ETS caused any increase in net imports (either in value or in terms of embodied carbon emissions). These findings confirm earlier results in specific sectors (see Branger et al., 2016 for the cement and steel sectors and Sartor, 2013 for the aluminum sector). Focusing on the downsizing of businesses in Europe, Martin et al. (2014b) and Martin et al. (2014a) survey roughly 800 manufacturing firms in six EU countries. They find that firms regulated under the EU ETS are more likely than non-EU ETS firms to report that in response to future carbon pricing, they would consider downsizing their operations in the EU by up to 10%. Using administrative data for French manufacturing firms, Colmer et al. (2020) find that firms regulated in the EU ETS reduce carbon emissions by 8%–12% in Phase 2, compared to unregulated firms, without a reduction in employment or value-added.[4] Furthermore, they find no impact of the EU ETS on total imports of intermediate goods by regulated companies, whether measured by their value or carbon content.

Other studies have used firm-level data to investigate the impact of the EU ETS on foreign direct investment, which could be viewed as indicative of carbon leakage. Koch and Basse Mama (2019) use data from Germany, and Borghesi et al. (2020) focus on Italy. In contrast to this paper, they do not have geographically disaggregated data on carbon emissions, and focus instead on whether the EU ETS led to increases in investment in unregulated (or less-regulated) countries. Borghesi et al. (2020) find that the EU ETS had a small positive effect on the number of new subsidiaries abroad and a larger impact on production in foreign subsidiaries, especially in trade-intensive sectors. Koch and Basse Mama (2019) also find evidence that the EU ETS encourages outward FDI by German multinationals. However, the effect is concentrated in a small subset of firms that are less capital intensive and therefore likely to be more geographically mobile.

Our paper contributes to this literature by providing new evidence on the link between EU ETS regulation and carbon leakage. Thanks to the unprecedented data collection effort by the CDP, we are able to track firm-level CO_2 emissions by geographic region for 8 years since 2007. Exploiting information on the country of origin of carbon emissions, we can directly assess the carbon leakage hypothesis by comparing the trends of multinational firms' CO_2 emissions in Europe relative to non-European countries, depending on whether they are regulated by the EU ETS. The novelty of the research lies in our ability to track greenhouse gas emissions within multinational companies in all jurisdictions in which they operate. To the best of our knowledge, we are the first to be able to do this. However, with the benefits of such data come some limitations. First, fine-grained, within-firm emissions data have only become available in recent years and are therefore unavailable for pre-treatment periods before the EU ETS was established. Furthermore, carbon accounting is an imprecise science that can lead to noise in the data. In our analysis, we work around both issues as best we can.

The rest of the paper is structured as follows. Section 2 presents our empirical methodology, and Section 3 describes the datasets used—in particular, the one obtained from the CDP. Section 4 discusses the main results. Extensions and robustness tests are presented in Section 5, and Section 6 concludes.

2. Theory and methods

2.1. Definition of leakage and a simple model

To study leakage *within* firms, we define leakage from the EU by firm i as an increase in rest of the world (RoW) emissions by firm i in response to changes in EU carbon pricing τ; i.e.,

$$\frac{\Delta CO2_i^{RoW}}{\Delta \tau} > 0 \tag{1}$$

Because multinational firms have already sunk the fixed cost of operating in multiple countries, at the margin they would face lower costs of moving parts of their production from a jurisdiction with a high carbon price to one with a lower carbon price if they already operate in both. We would therefore expect multinational firms to react more strongly to carbon pricing compared with firms without an established presence outside the EU. Of course, there are other forms of leakage. In particular, leakage might occur externally to a given firm, with EU firms losing global market share (along with emissions) while RoW firms are gaining.[5]

We introduce a simple model to study within-firm leakage in more detail. We consider multinational firms that produce a final good Q. To produce Q, firms can invest capital K_R in two regions $R \in \{EU, RoW\}$. Capital inputs translate into final output according to a CES production function: $Q = \left[\left(A_{EU}K_{EU}\right)^{\frac{\gamma-1}{\gamma}} + \left(A_{RoW}K_{RoW}\right)^{\frac{\gamma-1}{\gamma}}\right]^{\frac{\gamma}{\gamma-1}}$, where γ is the elasticity of substitution between

[4] Similar findings come from Dechezleprêtre et al. (2020), who use administrative data from France, the Netherlands, Norway, and the United Kingdom to find emissions decreases of 10% in European emissions of EU ETS-regulated firms.

[5] The IPCC (2007) defines this as "the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries". Graichen et al. (2008) distinguish between two forms of leakage: investment leakage and operational leakage. The former follows in the medium-to-long run from the decision of firms to not expand their production facilities or failure to reinvest in the regulated region (the EU in this case). The latter describes the short-term reaction of production being stopped or decreased in the EU and relocated to other countries with no carbon pricing.

EU and RoW emissions and A_{EU} and A_{RoW} are region-specific productivity shocks. Suppose that emissions are a linear function of capital: $CO2_R = \rho_R K_R$ for $R \in \{EU, RoW\}$. For simplicity, suppose that capital costs r are uniform across regions. However, there is a charge τ_{EU} for emitting carbon in the EU and an even higher charge τ_{ETS} for ETS-regulated firms.[6]

Final output demand is described by a simple log linear form: $Q = \Lambda^{\eta-1} P^{-\eta}$, where Λ is a firms specific demand shock. Profit maximization implies markup pricing $P = \mu c(r, \tau)$, where $\mu = \frac{1}{1-\frac{1}{\eta}}$. Equilibrium output is consequently determined by $Q = \Lambda^{\eta-1} (\mu c(r, \tau))^{-\eta}$. Hence

$$CO2_{EU} = \rho \Lambda^{\eta-1} \mu^{-\eta} c(r, \tau)^{\gamma-\eta} A_{EU}^{\gamma-1} (r + \rho\tau)^{-\gamma} \tag{2}$$

$$CO2_{RoW} = \rho \Lambda^{\eta-1} \mu^{-\eta} c(r, \tau)^{\gamma-\eta} A_{RoW}^{\gamma-1} r^{-\gamma} \ . \tag{3}$$

We can also derive a firm's global profit as $\Pi = QP - Qc(r, \tau) = Q(\mu - 1)c(r, \tau) = \Lambda^{\eta-1} \frac{\mu-1}{\mu^\eta} c(r, \tau)^{1-\eta}$. It follows that carbon leakage from the EU can be precisely defined and measured as the change of RoW emissions by a multinational company due to an increase in CO_2 pricing in the EU:

$$\Delta CO2_{RoW}^{Leak} = \frac{\partial CO2_{RoW}}{\partial \tau} \Delta\tau \ . \tag{4}$$

Looking at Eq. (3), we see that leakage can be positive (which represents carbon leakage) or negative; i.e., RoW emissions decrease because of EU policy. The sign will depend on the relative size of the elasticity of substitution γ and the price elasticity of demand η. An increase in tax τ will always lead to an increase in unit costs $c(r, \tau)$. As a result, RoW CO_2 emissions will increase if $\gamma > \eta$. Put differently, leakage will be negative if EU and RoW capital are highly complementary ($\gamma \to 0$), or if the demand for a firm's output is highly inelastic ($\eta \to \infty$). There is at least one further mechanism that is relevant for leakage effects, particularly in the context of multinational firms: investments in abatement efforts that can lead to technology spillovers. Such investments could include both investments in tangible capital that reduce pollution or in intangible capital, such as research on how to reduce a company's carbon footprint. We can capture this phenomenon by defining the pollution intensity of capital in the EU as follows: $\rho_{EU} = \phi_0 \frac{1}{1+e_EU}$, where e is the abatement effort. We also assume that $\rho_{RoW} = \phi_0 \frac{1}{1+\phi e_E U}$, which allows for effort undertaken in the EU to spill over to a multinational firm's operations in other jurisdictions, with ϕ representing the degree of spillover. Suppose that one unit of abatement effort comes at a cost δ. Firms will determine the amount of effort by maximizing $\Pi(\rho_{EU}(e)) - e\delta$. This leads to the first-order condition $\frac{\partial \Pi}{\partial e} \leq \delta$, which will hold with equality for $e > 0$.

Further, note that $\frac{\partial c(r,\tau,\rho)}{\partial \rho} = c(r, \tau, \rho)^\gamma \left(\frac{\rho\tau+r}{A_{EU}}\right)^{-\gamma} \frac{\tau}{A_{EU}}$. As a result,[7] the first-order condition becomes

$$\frac{\partial \Pi}{\partial e} = \frac{\Lambda^{\eta-1}}{\mu^\eta} c(r, \tau, \rho)^{\gamma-\eta} \left(\frac{\rho\tau + r}{A_{EU}}\right)^{-\gamma} \frac{\tau}{A_{EU}} \frac{1}{(1+e)^2} \leq \delta \ . \tag{5}$$

Given that marginal profits are downward sloping in e, a solution always exists. Fig. 1 illustrates a number of cases. In the baseline we consider a case with $\gamma = 2.25$ and $\eta = 2$. If the elasticity of substitution increases (e.g., to 4.25), the marginal profit line moves left; this implies a lower level of abatement, all else equal: Firms will find it easier to substitute emissions abroad rather than engage in more abatement efforts. If we increase the carbon price, the marginal profit line moves rightward, leading to more abatement efforts initially. However, an increase in the carbon price also tilts the curve, which at some point leads to a reduction in abatement efforts and eventually to no abatement effort at all: If carbon prices are so high that firms shift most of their production abroad, there is little incentive to invest in abatement.

This dynamic leads to an inverted U-shaped curve for the relationship between carbon prices and abatement efforts, as illustrated in Fig. 2, Panel (a). The model also implies a minimum price threshold for companies to engage in any abatement efforts. As a result, there is an optimal range for carbon prices as far as abatement efforts are concerned. Looking at RoW emissions in Panel (b), we see that, as a consequence of the interaction between spillovers and outsourcing production, emissions will initially go up, then down, and then up again as the EU carbon price increases. We analyze this question empirically in an extension of our empirical framework in Section 5.4.3.

Overall, our model shows that the key factor that determines the occurrence of leakage is a sufficient degree of technological substitutability between EU and RoW emissions. In particular, this elasticity of substitution between EU and RoW emissions (γ) must (in absolute terms) be higher than the elasticity of demand (η) the firm faces. If, on the other hand, $\eta > \gamma$, we might have what could be described as negative leakage in which RoW emissions decline because of EU climate policy.[8] In such a case, a lack of emissions

[6] For a given quantity of output Q, cost minimization implies the following cost function: $C(Q, r, \tau) = Qc(r, \tau) = Q\left[\left(\frac{\rho\tau+r}{A_{EU}}\right)^{1-\gamma} + \left(\frac{r}{A_{RoW}}\right)^{1-\gamma}\right]^{\frac{1}{1-\gamma}}$, where we assume, for simplicity, that firms always invest in both locations. Emissions in each location are then given by: $CO2_{EU} = \rho_{EU} Q A_{EU}^{\gamma-1} \left(\frac{\rho_{EU}\tau+r}{c(r,\tau)}\right)^{-\gamma}$ and $CO2_{RoW} = \rho_{RoW} Q A_{RoW}^{\gamma-1} \left(\frac{r}{c(r,\tau)}\right)^{-\gamma}$.

[7] Note that $\frac{\partial \Pi}{\partial e} = \Lambda^{\eta-1} \frac{\mu-1}{\mu^\eta} (1-\eta) c(r, \tau, \rho)^{-\eta} \frac{\partial c(r,\tau,\rho)}{\partial \rho} \frac{\partial \rho}{\partial e} = \Lambda^{\eta-1} \frac{\mu-1}{\mu^\eta} (\eta - 1) c(r, \tau, \rho)^{-\eta} \frac{\partial c(r,\tau,\rho)}{\partial \rho} \frac{1}{(1+e)^2} = \frac{\Lambda^{\eta-1}}{\mu^\eta} c(r, \tau, \rho)^{-\eta} \frac{\partial c(r,\tau,\rho)}{\partial \rho} \frac{1}{(1+e)^2}$ where the last equality follows from $\frac{\mu-1}{\mu^\eta}(\eta - 1) = \mu^{-\eta}$.

[8] Negative leakage has also been discussed by Baylis et al. (2014). They describe a somewhat different mechanism, whereby carbon pricing-induced shifts between factors of production lead to increases in carbon-mitigation and mobile capital. As a result, costs increase in both regulated and unregulated regions.

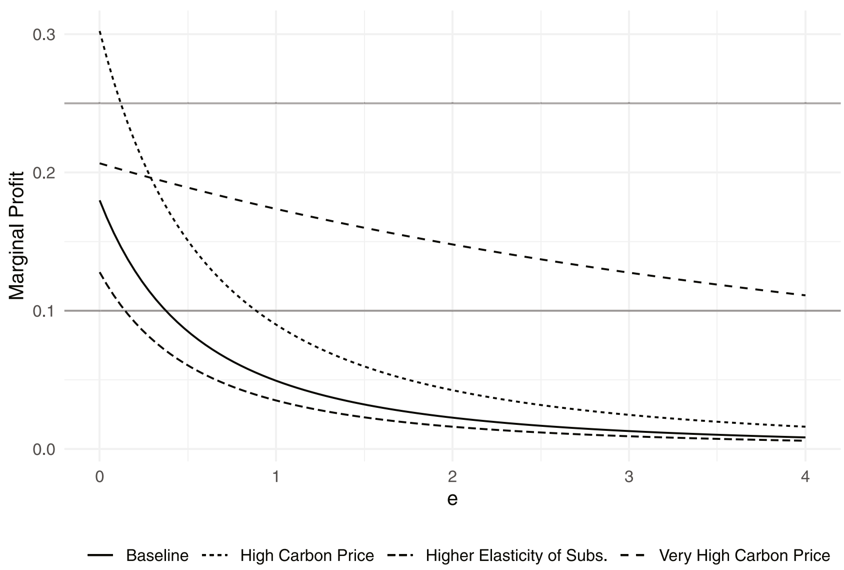

Fig. 1. Marginal profits for different parameter values.Notes: Visualization of profit equation for various parameter assumptions.

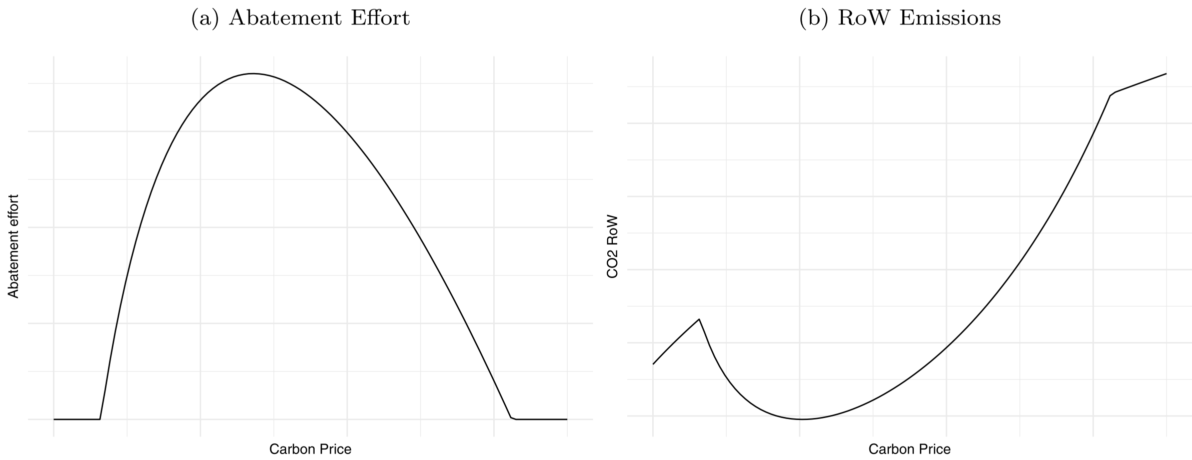

Fig. 2. Abatement and row emissions for different carbon prices.
Notes: Visualizations of the optimal amount of abatement effort and RoW emissions for different levels of EU carbon prices from simulations. Elasticity of substitution $\gamma = 2.25$. Elasticity of demand $\eta = 2$.

leakage leads to a global cost and price increase for the multinational, which in turn reduces global demand. In addition, leakage can be determined by technology spillovers if carbon pricing induces investments in carbon-mitigating technology and R&D. These technological improvements can lead to further changes and emissions reductions throughout multinational firms' production sites, irrespective of the local regulatory regime. Our model also shows that this can lead to nontrivial interactions between technological changes, the amount of carbon pricing, and RoW emissions. For instance, if carbon taxes are too low, firms might not find it profitable to engage in technological changes and only respond to carbon price increases by limited leakage. As carbon prices increase, firms will initially expand technology investments. If these spill over globally, this can lead to RoW emissions reductions (i.e. negative leakage). However, if carbon prices are even higher, increasingly less production occurs within the EU. This in turn reduces the incentive to invest in technological improvements and lead to positive leakage.

2.2. Empirical strategy

To study these issues empirically, we exploit the carbon price differential introduced by the European Union Emissions Trading System (EU ETS); i.e., we compare changes in firms regulated by the ETS with firms that are not, by running a regression of the form:

$$\Delta s_{it} = \beta_1 ETS_i + \tau X_{it} + \epsilon_{it} \quad , \tag{6}$$

where ETS_i is a dummy equal to 1 for EU ETS-regulated firms and X_{it} is vector of control variables, such as industry and time controls. As our main outcome variable, we use Δs_{it}, the first difference of the share of EU emissions in total global emissions of a firm; i.e.,

$$s_{it} = \frac{CO2_{it}^{EU}}{CO2_{it}^{EU} + CO2_{it}^{RoW}} \quad . \tag{7}$$

If carbon leakage is an issue, we would expect to find $\beta_1 < 0$ in a regression such as Eq. (6). Note that we can think of this as a conservative approach because a negative β_1 is only a necessary condition for (positive) leakage to occur. Indeed, we could have $\beta_1 < 0$ with negative leakage, whereby EU emissions reductions are simply larger in the EU but still negative in RoW. Using emissions shares as an outcome variable can also help with any remaining unobserved heterogeneity. Differencing will remove fixed heterogeneity specific to a firm. Looking at the share of emissions will remove any time-varying, firm-specific heterogeneity that is shared by all subsidiaries of a given firm.

Nevertheless, we also report below regressions where the outcome variables are the first difference of both the level of EU and of RoW emissions. Note that the EU ETS was introduced in 2005. However, as detailed in the next section, our data sample only starts in 2007. As a result, we cannot rely on a classic before-and-after design. In particular, this means that we will not capture any impact of the ETS on leakage that would have occurred at the start of the scheme. However, in Phase I of the EU ETS from 2005–2007, emissions caps were too generous and prices, as a consequence, were very low. Crucially, it was also not possible to bank permits. Hence, firms had very few incentives to either reduce or leak emissions. This changed in 2008, when caps were tightened and the banking of permits was introduced. Related studies – e.g. Colmer et al. (2020) – suggest that only this more stringent policy had any impact on emissions. Hence, if there are leakage effects we would expect to observe them from 2008 onward, which aligns with our sample period.

We estimate Eq. (6) on a variety of subsamples and with various control variables to account for concerns about both endogeneity and heterogeneity in potential leakage effects. For instance, ETS firms by definition must be located in the EU (at some point), whereas this is not the case for non-ETS firms. Moreover, ETS firms are mostly manufacturing firms or power plants. We address this issue by estimating Eq. (3) for a number of different subsets of the data. First, the sample is restricted to firms that report nonzero emissions both inside and outside the EU, although not necessarily at the same point in time. Second, we only look at firms with nonzero EU emissions in the base year (t-1). Third, we focus on firms with nonzero EU emissions in the base year (t-1) *and* nonzero non-EU emissions at some point in our sample. In addition, the previous specifications are repeated while restricting the sample to manufacturing firms. We further refine the analysis by running the regressions on a subsample of firms that belong to sectors deemed "at risk of carbon-leakage" by the European Commission (Emissions Trading Directive 2009/29/EC). Such sectors exceed certain thresholds in terms of carbon or trade intensity or both; leakage effects would be expected to be particularly strong in such sectors (see Appendix D for a list of those sectors).

Note that firms in the EU, even within narrow sectors, are not all necessarily regulated by the EU ETS. There are sector-specific, firm-level capacity thresholds that are high enough for us to observe control firms within the same sector and within the EU, even if we restrict the sample to firms with operations within the EU.[9]

3. Data

3.1. Main dataset

In order to implement the methodology described, we construct an unbalanced panel of firms for the period 2007–2014 by combining three data sources. First, data on annual firm-level carbon emissions from the CDP, which is an NGO acting on behalf of over 600 institutional investors. The CDP asks listed companies to disclose geographically disaggregated information on carbon emissions.[10] The CDP data are unique; as far as we know, this is the only consistently available data source that tracks the geographic distribution of carbon emissions *within* multinationals. Second, we obtain data on the turnover, assets, number of employees, and sector of activity of these companies from ORBIS—one of the largest global financial firm-level databases, provided by Bureau Van Dijk under a commercial license. Finally, we use the European Union Transaction Log (EUTL) to identify companies that own at least one installation regulated under the EU ETS. Identifying which multinational company is regulated by the EU ETS is not straightforward, because of the difficulty of assigning EUTL installations to CDP multinationals based on their ownership structures. The steps required to do so and to merge the datasets are described in detail in Appendix A.

As shown in Panel (a) of Fig. 3, the number of observations in the CDP grows in the initial years of our sample and then remains above 800. The overall sample consists of 1,122 companies, 261 of which are regulated under the EU ETS.

Panel (b) in Fig. 3 displays the sectoral distribution of the companies in our sample, sorted by the number of EU ETS firms in a sector (in descending order). Sector assignment is based on the NACE Rev. 2 code of the multinational firm. As expected, the majority of EU ETS companies in the sample operate in the manufacturing and power sectors. Firms can be regulated either because they operate in an energy-intensive industry sector – such as oil, cement, aluminum – or because they generate electricity and heat.[11] As a consequence of the latter, companies that operate in virtually any sector of the economy can be subject to the EU ETS

[9] See Colmer et al. (2020) for a detailed discussion of EU ETS inclusion.

[10] The CDP has recently started to also include non-listed firms in its survey.

[11] We do not include commercial aviation, which is included in the EU ETS for flights between European airports.

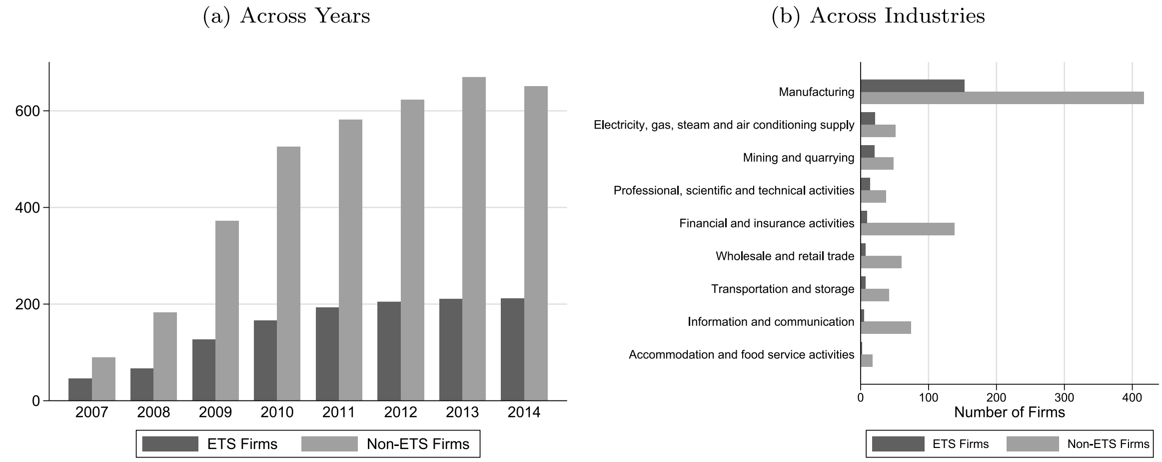

Fig. 3. Firms with positive CO_2 in the EU in the base year.

if they produce on-site large amounts of energy or heat using carbon-emitting fuels such as gas, coal, or oil. This is why our sample includes some EU ETS-regulated companies in sectors such as financial and insurance activities or retail trade: They have on-site energy production in some of their buildings.[12]

In terms of the size of regulated EU ETS companies, we focus only on multinational firms. By definition, these firms are larger in size compared with the average EU ETS-regulated company. While this limits the external validity of our findings, it is precisely large multinational firms that are most prone to leakage—so results based on our sample should give an upper bound for the effect of the EU ETS on leakage in the average EU ETS-regulated firm. The CDP offers unique data that allow us to implement our methodology. However, with non-mandatory participation in the survey, a focus on listed companies, and the self-reporting of emissions, concerns regarding selection and measurement biases might arise. Given the centrality of the data for our analysis, the next two subsections address these potential issues in detail.

3.2. Selection issues in the emissions data

We first address the selection concern by comparing multinationals that report emissions data to the CDP with those that do not out of all multinationals that are regulated under the EU ETS. To do so, we first select from ORBIS all multinational firms active in the EU and in the same sectors as those represented in the CDP dataset. We identify multinational firms through the location of their subsidiaries.[13] We then select, from those multinational firms, those that have installations that are regulated by the EU ETS as defined in the previous section. This allows us to obtain verified greenhouse gas emissions data for their European regulated installations from the EUTL. Within this dataset of all EU ETS-regulated multinational firms, we then assess whether those firms that respond to the CDP survey differ from those that do not.[14] We do so by regressing EUTL carbon emissions and each of the relevant ORBIS variables on the CDP dummy for the period 2010 to 2014. The table reports the point estimates of the CDP dummy in these regressions. In each of the eight regressions reported, we control for each firm's country and main 4-digit NACE sector, as reported by ORBIS, and include a year dummy. As shown in the first panel of Table 1, we find that regulated firms that reply to the CDP survey are larger on average. This is true in terms of emissions in the EU, revenue, assets, and employment. However, in the second panel, we consider as the dependent variable the differenced variables—i.e., the variation of these variables from $t-1$ to t. It appears that multinational firms that respond to the CDP survey are no different from others. We see no evidence of self-selection into CDP reporting by firms that would be on differential trajectories of either emissions or economic indicators. Given that our analysis is based on changes in emissions, we take Table 1 as evidence of the likely absence of a selection issue in our empirical framework.

It is also worth noting that an extensive literature studies the likelihood of companies to report their emissions in voluntary surveys. For example, some recent contributions (Reid and Toffel, 2009; Brouhle and Harrington, 2009; Matsumura et al., 2013) have shown that companies that operate in cleaner sectors are more likely to report their environmental activity. This is also true for companies that perform better than others in their sector. Reporting also increases with the proportion of firms reporting in the

12 For example, the EUTL lists Barclays Bank as having four sites in the ETS that use boilers: two in office buildings and two in data centers. Size thresholds apply to each sector for participation in the EU ETS, and in the case of combustion – i.e., boilers – any site with a thermal capacity larger than 20 MW are in principle included. This is why several hospitals are also EU ETS participants.

13 We apply an ownership threshold of 50% in defining these shareholder paths. Moreover, we only include firms that have non-missing data for revenue or total assets.

14 Due to ORBIS data availability, this comparison can only be made from 2010 onward.

Table 1
Comparison of Surveyed Multinationals.

	(1) Emissions	(2) Revenue	(3) Employees	(4) Assets
Dependent variable	ln of variable			
CDP	1.078*** (7.46)	3.176*** (44.63)	3.138*** (38.78)	3.546*** (49.96)
Observations	6,240	7,758	7,045	7,785
Dependent variable:	Δ ln of variable			
CDP	−0.0129 (−0.18)	0.0000358 (0.00)	0.00836 (0.73)	−0.00787 (−0.94)
Observations	4,873	6,113	5,348	6,139

Notes: t statistics in parentheses. Significance levels are indicated as ***p< 0.01, **p< 0.05, *p< 0.1. The Dependent variable is verified carbon emissions in the EUTL in Column 1, revenue in thousands of euros in Column 2, employees in Column 3, and assets in thousands of euros in Column 4. In the upper part of the table, the Dependent variable is the logarithm of these. In the lower part, it is the change in the logarithm from year to year. All regressions include controls for the firm's country and main 4-digit NACE sector as reported by ORBIS, and include a year dummy.

same sector. However, such issues are of less concern with the CDP data. First, while the CDP survey is not mandatory, firms have an additional incentive to participate because the CDP acts as an agent for a group of large investment firms. This setup introduces a somewhat different reputational driver: Refusal to take part could send a negative signal to potentially important investors and sources of finance for a firm (Kim and Lyon, 2011). Recent studies have shown that carbon emissions affect stock returns and firm value, with financial investors demanding a higher premium when they perceive a higher carbon risk (Matsumura et al., 2013; Bolton and Kacperczyk, 2021). Second, participating firms are given the choice to be featured in the outward-facing CDP report or only to be included in background data and confidential reports to investors. We believe that this makes positive self-selection less likely since we use the whole CDP database, which consists of both publicly available data and unpublished reports. However, for the purpose of this study, these issues would only be a concern if they vary systematically between EU ETS and non-EU ETS firms and across regions within each firm, and there seems to be no reason for that to be the case.

3.3. Consistency of the CDP emissions data

Since the CDP emissions data originate from a survey, there could be concerns about the consistency of the quality of responses, both across firms and over time, and the lack of verification of survey answers. Lack of consistency could imply that the emissions data might not contain enough signal to detect a leakage effect because of noise. Carbon reporting is a recent development, and different reporting methodologies currently coexist. While the CDP recommends the use of a particular reporting protocol (the Greenhouse Gas Protocol, jointly convened by World Business Council for Sustainable Development and World Resources Institute), multinationals are allowed to follow different reporting methodologies (Bellassen and Stephan, 2015). To assess the consistency of the outcome data, we use the CDP emissions data for the European subsidiaries of EU ETS multinationals and correlate it to the verified emissions data obtained from the EUTL. This comparison is invariably coarse, because multinationals may operate both regulated and unregulated installations, so that a perfect correspondence cannot be expected. Nevertheless, we expect to find a clear and significant relationship between the two. To do this, we use the verified emissions for each EUTL installation that belongs to a multinational firm and aggregate them at the multinational level. We weight the emissions by the percentage of shares the multinational owns in a subsidiary. To illustrate: A multinational that owns 50% of all shares of a subsidiary would be assigned 50% of that subsidiary's emissions. This weighting strategy corresponds to the guidelines in the Climate Change Reporting Framework used by the CDP survey, which instructs multinationals to weight greenhouse gas emissions in joint ventures by ownership percentage. For this analysis, we compute the correlation of these verified emissions to the emissions data reported in the CDP survey. We do so by aggregating emissions to the European level for each multinational.

Fig. 4 shows that there is a strong correlation of 0.88 and a slope coefficient of close to 1. In other words, the CO_2 emissions reported in the CDP survey are an accurate reflection of the underlying reality, as reported in EUTL data verified by third-party auditors.[15] The correlation is also statistically significant: While there are some obvious outliers, possibly due to practical carbon accounting errors, a linear regression of reported emissions on verified emissions with cluster-robust standard errors, where multinationals are the units of clustering, yields a t-statistic of 13.71. We interpret this as an additional indication that the quality of the CDP data is sufficient for our analysis.

There is still substantial noise in the CDP data, but this is to be expected for the following reasons: (i) the matching process between CDP companies and EU ETS-regulated installations is inevitably an approximation; (ii) not all companies report greenhouse gas emissions alike and they must be consistently applying existing guidelines; and (iii) in a limited number of cases, multinationals

[15] The reason to assess the consistency in levels rather than in changes is twofold: To directly illustrate the measure we use in the robustness check for treatment assignment in Section 5.1, and because a correlation in levels is a more demanding consistency check than a correlation in the rate of change.

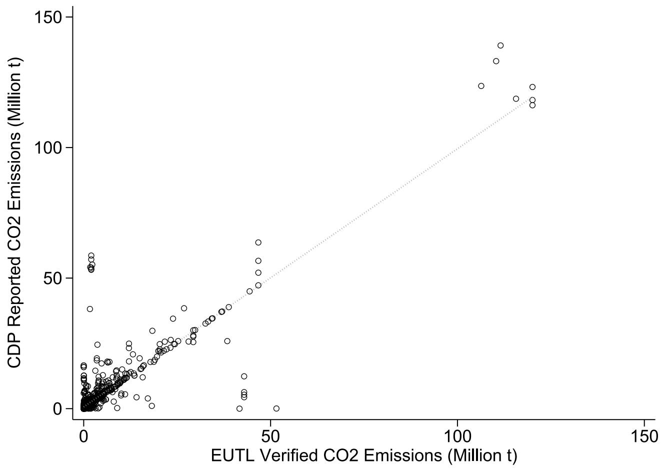

Fig. 4. Consistency of CDP-reported CO_2 emissions data.Note: Corr: 0.88; Coeff: 0.99; t-stat: 13.71 (cluster-robust SEs).

Table 2
Descriptive statistics.

	(1) Mean	(2) Stand. Dev.	(3) N. firms	(4) Obs.	(5) Source
CO_2 Emissions within Europe (Million t CO_2e)	1.26	9.86	1,122	4,924	CDP
CO_2 Emissions outside Europe (Million t CO_2e)	3.07	12.37	1,122	4,924	CDP
Share of CO_2 Emissions within Europe	34%	39%	1,122	3,802	CDP
Δ Share of EU emissions	−0.01	0.09	1,122	3,802	CDP
Operating Revenue (Million euros)	12940.85	24503.95	1,113	4,889	ORBIS
Total Assets (Million euros)	55180.93	198541.37	1,106	4,850	ORBIS
Employees (in Thousands)	44.11	94.28	1,000	4,430	ORBIS
EU ETS Price (euros/tCO_2)	10.07	3.39	1,122	4,924	EU ETS
Climate Laws, Institutions, and Measures Index (CLIMI)	0.30	0.16	1,122	4,924	EBRD

only report total European emissions in the CDP survey – rather than emissions broken down by countries – which makes it difficult to compare emissions on a like-for-like basis.

Finally, we find below in Section 5.4.1 that by using the carbon emissions reported in the CDP survey to estimate the emissions reduction induced by the EU ETS, we obtain estimates of the same order of magnitude as those found by Colmer et al. (2020) who use administrative French data, and by Dechezleprêtre et al. (2020), who use administrative data from France, the Netherlands, Norway, and the United Kingdom. This provides additional evidence that the CDP emissions data are consistent with administrative data, which can be considered more reliable. In light of these considerations, we now present the results of our analysis.

4. Main results

The sample resulting from our data collection and compilation is described in Table 2 and consists of 1,122 multinational companies.[16] The average share of CO_2 emissions within Europe across our sample is 34%.

In Table 3, we compare ETS and non-ETS companies using simple t-tests. Not surprisingly, ETS firms emit more in both European and non-European countries. They are on average characterized by a higher turnover, a higher number of employees, and higher assets. About 60% of the emissions of ETS firms tend to be located in Europe. A look at the full firm-level distribution of the share of emissions in Europe, shown in Fig. 5, demonstrates the large overlap across both groups of multinationals; this suggests that the non-ETS firms in our sample are in fact a relevant control group. The figure depicts our preferred sample, which includes only non-ETS multinationals that report positive emissions in the European Union in the CDP survey.

Fig. 6 separately displays the share of CO_2 emissions in Europe over the period 2007–2014 for the full sample of ETS and non-ETS firms respectively. It is consistent with the evidence presented in Table 3, showing that ETS firms generate a larger share of emissions in Europe than non-ETS firms. From 2007 to 2009, the share of European CO_2 emissions grows slightly for both ETS and non-ETS firms. It then remains fairly constant afterward for both groups of multinationals. The gap between the two types of firms then remains stable over the period 2007–2014. If anything, we observe that non-EU ETS firms increase their share of emissions in Europe over time, while the share remains stable for EU ETS firms.

[16] There are 9 firms for which there is no operating revenue data available in ORBIS, 16 firms for which total assets are missing, and slightly more than 100 firms for which employment is missing.

Table 3
ETS vs. Non-ETS Firms.

	ETS Firms	Non-ETS Firms	Difference
Panel A: All Firms (N = 1,122)	238	884	
CO_2 Emissions within Europe	5.68	0.07	5.61***
(Million tons CO_2e)	(20.82)	(0.46)	[0.00]
CO_2 Emissions outside Europe	4.34	2.72	1.61*
(Million tons CO_2e)	(12)	(12.45)	[0.07]
Share of CO_2 Emissions within Europe	53.47%	28.3%	25.16%***
	(0.36)	(0.37)	[0.00]
Δ Share of EU emissions	−0.7%	−0.9%	−0.1%
	(0.08)	(0.09)	[0.82]
Operating Revenue	25,683.52	9,474.84	16,208.68***
(Million euros)	(37,364.24)	(18,142.07)	[0.00]
Total Assets	65,353.97	52,421.34	12,932.63
(Million euros)	(200,098.8)	(198,142.61)	[0.37]
Employees	64.19	38.34	25.84***
(in Thousands)	(84.31)	(96.23)	[0.00]
Climate Laws, Institutions, and Measures Index	0.24	0.30	−0.06***
(CLIMI)	(0.16)	(0.16)	[0.00]
Panel B: Manufacturing Firms (N = 571)	154	417	
CO_2 Emissions within Europe	1.72	0.02	1.69***
(Million tons CO_2e)	(6.34)	(0.18)	[0.00]
CO_2 Emissions outside Europe	2.93	1.26	1.66***
(Million tons CO_2e)	(9.84)	(5.73)	[0.01]
Share of CO_2 Emissions within Europe	48.85%	22.25%	26.59%***
	(0.34)	(0.32)	[0.00]
Δ Share of EU emissions	−0.2%	−0.5%	0.3%
	(0.09)	(0.11)	[0.74]
Operating Revenue	24,099.02	7,331.53	16,767.48***
(Million euros)	(35,754.96)	(12,192.53)	[0.00]
Total Assets	36,028.31	9,024.81	27,003.49***
(Million euros)	(60,873.86)	(14,050.55)	[0.00]
Employees	65.05	27.29	37.76***
(in Thousands)	(79.40)	(41.50)	[0.00]
Climate Laws, Institutions, and Measures Index	0.27	0.34	−0.06***
(CLIMI)	(0.15)	(0.13)	[0.00]
Panel C: Man. Firms at Risk of Carbon Leakage (N = 444)	114	330	
CO_2 Emissions within Europe	1.54	0.03	1.51***
(Million tons CO_2e)	(3.63)	(0.21)	[0.00]
CO_2 Emissions outside Europe	2.8	1.37	1.43***
(Million tons CO_2e)	(7.59)	(6.13)	[0.04]
Share of CO_2 Emissions within Europe	50.35%	20.7%	29.65%***
	(0.34)	(0.3)	[0.00]
Δ Share of EU emissions	0.1%	−0.4%	0.6%
	(0.09)	(0.11)	[0.55]
Operating Revenue	20,547.37	7,749.52	12,797.85***
(Million euros)	(32,122.19)	(13,032.47)	[0.00]
Total Assets	31,059.39	9,453.2	21,606.19***
(Million euros)	(59,035.29)	(145,909.78)	[0.00]
Employees	54.50	28.20	26.3***
(in Thousands)	(66.66)	(43.08)	[0.00]
Climate Laws, Institutions, and Measures Index	0.28	0.34	−0.06***
(CLIMI)	(0.15)	(0.13)	[0.00]

NOTES: Means and standard deviations are reported in parentheses. The p-value for the difference is reported in square brackets in Column (3) and taken from a two-sided t-test with equal variances. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$. Firms at risk of carbon leakage are CDP companies operating in sectors deemed at risk of carbon leakage by the European Commission. Manufacturing firms are firms coded as "C-Manufacturing" in the NACE Rev. 2 Main Section classification. The number of firms N in Panels A-C refers to the total number of firms in the sample. Not all firms report all firm-level characteristics. Sample is restricted to firms that reported positive emissions in Europe when they first reported in the CDP.

Turning to the results relative to the share of EU emissions, Table 4 reports the estimates of Eq. (3) with the dependent variable being the change in the share of EU emissions. Panel A reports the results for all firms in our sample, Panel B restricts the sample to manufacturing firms only, and Panel C presents the results for firms in sectors considered at risk of carbon leakage by the European Commission.

Moving through the columns of Table 4, we impose different restrictions regarding the regional presence of firms. Column 1 includes all firms. In Column 2, we only include companies that report positive emissions in *both* the EU and the RoW, although not

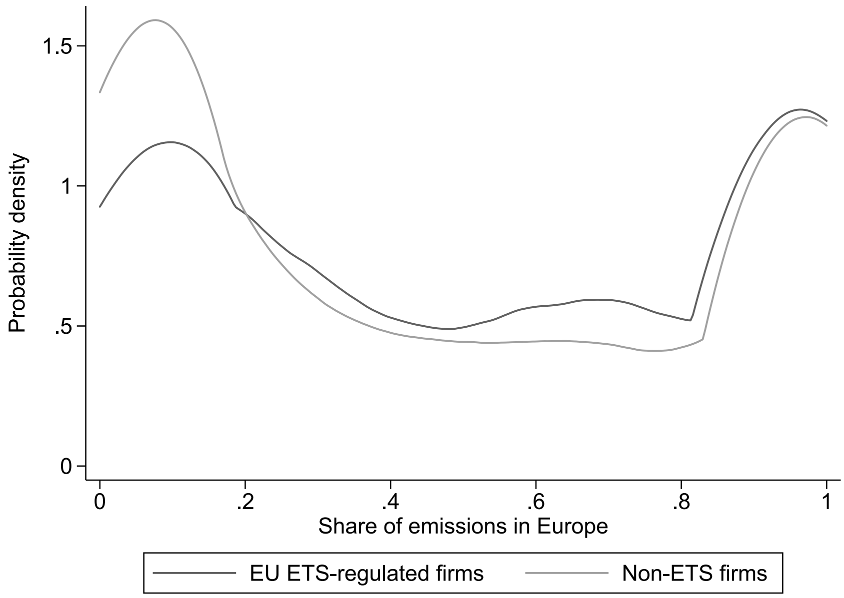

Fig. 5. Comparability of treated and control firms.

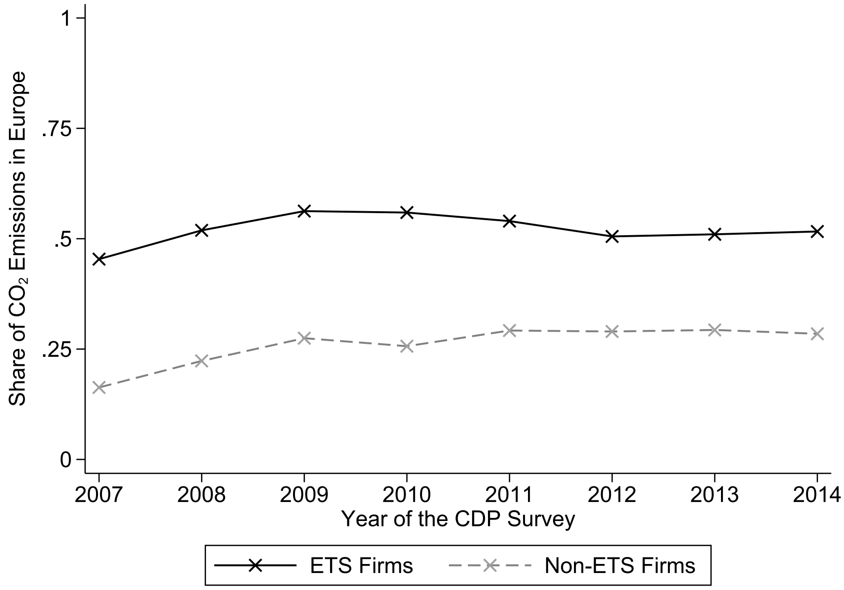

Fig. 6. Share of CO_2 emissions in Europe for ETS and non-ETS firms.

necessarily at the same time. Column 3 includes only observations from companies with positive EU emissions in the first period for which the company answered the CDP survey. Finally, Column 4 includes firms with positive EU emissions in the first period *and* nonzero emissions in the RoW at some point over the sample. The subsamples created by cycling through both the panels and columns of Table 4 serve two purposes. First, by restricting the sample to manufacturing firms or firms with nonzero EU emissions in their first year, we render the control group of non-ETS firms more similar to firms regulated by the ETS.[17] Secondly, by focusing on sectors supposedly at risk of carbon leakage or firms with both EU *and* RoW emissions, we investigate the potential heterogeneity of leakage effects between firms. Specifically, we would expect leakage effects to be more severe in groups deemed at risk of carbon leakage by the European Commission.

[17] A company can only be regulated by the EU ETS if its installations emit within the EU.

Table 4
Regressions of the Share of Emissions in EU.

Dependent variable:	Δ Share of EU emissions			
	(1)	(2)	(3)	(4)
Sample composition:	All	EU>0 RoW>0 any	EU>0 in t = 1	EU>0 in t = 1 RoW>0 any
Panel A: All Firms				
ETS	−0.00379	0.000934	0.00429	0.00396
	(−0.84)	(−0.15)	(0.71)	(0.58)
Observations	3,802	2,589	2,441	2,134
Number of firms	1,122	676	683	568
R^2	0.00481	0.00871	0.00922	0.0128
Panel B: Manufacturing Firms				
ETS	−0.00179	0.000155	0.00407	0.00451
	(−0.28)	(0.02)	(0.49)	(0.50)
Observations	2,007	1,496	1,305	1,196
Number of firms	571	388	360	318
R^2	0.00743	0.0113	0.0129	0.0143
Panel C: Manufacturing Firms at Risk of Carbon Leakage				
ETS	0.00136	0.00294	0.00644	0.00657
	(0.17)	(0.30)	(0.59)	(0.56)
Observations	1,147	830	706	656
Number of firms	328	220	201	180
R^2	0.00736	0.0108	0.0118	0.0129

Notes: t statistics in parentheses. Significance levels are indicated as ***p< 0.01, **p< 0.05, *p< 0.1. Column 1 includes all firms in the sample. Column 2, firms that have positive emissions in both the EU and RoW in some year. Column 3, firms with positive EU emissions in the first period for which the company answered the CDP survey (t = 1). Column 4, with positive EU emissions in t = 1 and nonzero RoW emissions at some point over the sample.

Looking at the different point estimates, we see that the coefficients on the ETS indicator are insignificant throughout Table 4. Furthermore, it is estimated to be remarkably close to 0, compared with the −0.09 average decrease in the share of CO_2 emissions in Europe for EU ETS firms. The point estimate is slightly positive for all subsamples, but we can never reject the hypothesis that it is equal to zero. The highest positive coefficient estimate – though still insignificant and small – in all panels is in Column 4–i.e., for companies that report positive CO_2 emissions in an EU ETS-regulated country in the first period and positive CO_2 emissions in RoW at some point. This is the group of firms for which a leakage effect would be most expected. Therefore we do not find any evidence of a leakage effect, which would be characterized by a negative and statistically significant coefficient.[18]

In the other columns we find that our point estimate is positive, but it is not statistically significant at the 10% level. It is instructive, however, to ask what a positive coefficient would imply, hypothetically speaking. Two possible explanations spring to mind. First, as discussed in more detail in Section 2.1, there might be offsetting region-specific productivity shocks that are much stronger than the carbon price shocks implied by the ETS. Second, we have to bear in mind that the European Commission is classifying sectors at risk of leakage in order to target risk-mitigating policy measures; specifically, sectors "at risk" are receiving freely allocated emissions permits. Hence, a positive effect could imply that this policy is particularly successful, to an extent that borders on reverse leakage.

5. Extensions and robustness

In this section, we present a range of robustness checks and extensions that together support our finding of no leakage.

5.1. Robustness to treatment assignment

We first address the potential measurement error in treatment assignment. Since we match firm-level data from the CDP dataset to EU ETS installations via ORBIS to obtain treatment status, there is likely to be some amount of noise that this process introduces for treatment assignment. The mis-assignment of treated installations to multinationals will bias our estimates toward zero.

To rule out measurement error on treatment assignment as an explanation for our null result, we re-estimate the treatment effect of our preferred specification from Table 4, Panel A, Column 2 using different subsamples. We exploit the fact that, as described in Fig. 4, Section 3.3, we have constructed a measure of the consistency between the CDP and EUTL emissions for each firm. We can assume that if reported emissions from both datasets are similar, there was less noise in the matching process of assigning EU ETS

[18] We provide further discussion of the magnitude of these findings in Section 5.4.

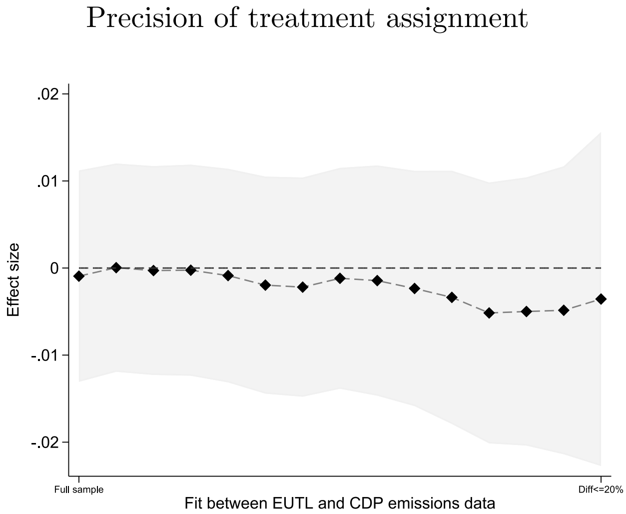

Fig. 7. Robustness of estimated effect size.
Note: The figure reports the effect size for the specification in Table 4, Panel A, Column (2). Each data point represents the specification for a different subsample based on the fit between the CDP and EUTL emissions data.

installations to CDP multinationals. We therefore run the regression with 15 samples, reducing in each step the accepted difference in reported emissions and, as such, restricting the sample. This allows us to study how the estimated effect size changes with the quality of the match. If measurement error on treatment is a concern, the effect size would change as we increasingly restrict the subsample.

Fig. 7, Panel (a) shows that this is not the case. Instead, the point estimate for the effect size is remarkably stable for all subsamples, starting from the full sample (the leftmost observation) all the way to the most restricted subsample, which only considers observations for which CDP and EUTL emissions differ by at most 20%.[19] This means that the mis-assigned treatment status is unlikely to explain the null result of no carbon leakage as a result of the EU ETS.

5.2. Robustness to heterogeneous treatment effects

As an additional robustness check, we run the same specification, but this time we restrict the sample based on the share of total emissions firms emit outside the EU when they enter the CDP survey for the first time. The results are shown in the right panel of Fig. 8. Starting with the whole sample on the y-axis, each point further to the right represents the estimated effect for a smaller sample, which we restrict it all the way down to firms that do not have more than 10% of their emissions in the EU—i.e., 90% of their emissions occur outside the EU. The effect remains insignificant.

This robustness check aims to evaluate whether the impact of the ETS might be different for firms that emit a smaller share in the EU. These could be expected to leak their emissions more easily, since they would already have a significant share of their activities in unregulated regions. Recall that in our main specification we only include firms with positive emissions in the EU in the first year they enter the CDP survey, since only these firms could experience leakage. This robustness check, therefore, is a refinement of the main specification.

5.3. Climate policy stringency in non-European jurisdictions

To further explore the heterogeneity of our results, we consider whether the stringency of climate policies in non-EU regions in which multinationals operate might affect the impact of the EU ETS on those firms' carbon leakage. In particular, companies that face a less stringent climate policy in other regions of operation might have a higher incentive to displace emissions outside of Europe in response to the EU ETS. We use the EBRD's Climate Laws, Institutions and Measures Index (CLIMI), which measures the stringency of climate policy regulation in each country. First, we compute an average CLIMI for different regions in the world by weighting the CLIMI of each country within a given region with its GDP levels in the initial period. As shown in Appendix B, this regional measure displays significant variation: Europe is the region with the most stringent climate regulation, while the regions corresponding to the former USSR and North America score at the bottom of our weighted index. Oceania's and Asia's CLIMIs are close to the world average, driven by Australia and China in their respective region. Both countries increased their policy efforts to tackle climate change at the end of our sample period (before Australia abolished its carbon tax in 2014). Based on these regional

[19] Confidence intervals, in light gray, widen as expected due to the reduced sample size.

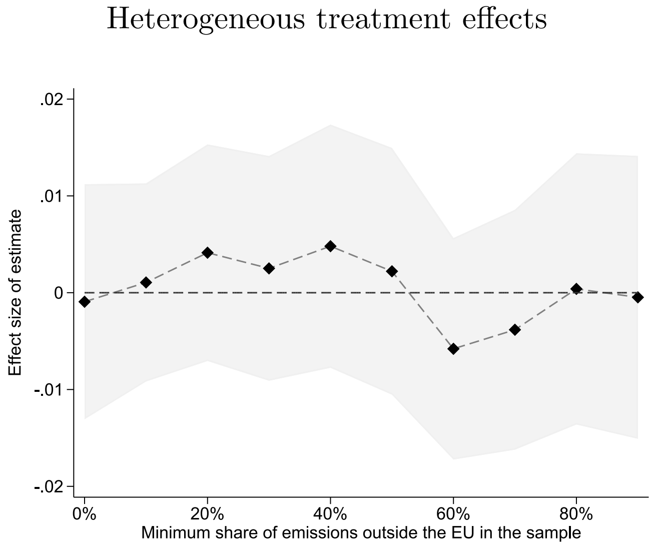

Fig. 8. Robustness of estimated effect size.
Note: The figure reports the effect size for the specification in Table 4, Panel A, Column (2). Each data point represents the specification for a different subsample based on the minimum share of emissions of the firm outside the EU when it first entered the CDP survey.

CLIMI indices, we construct a company-specific CLIMI Index. We weigh the CLIMIs of non-European world regions in which the company operates. The weight used for each region is computed as the share of the company's emissions in that region in the first year for which geographically disaggregated emissions are reported for the firm.[20] Each firm's specific measure captures the extent to which the individual company is exposed to a stringent regulation outside Europe. In this section, we explore whether the share of EU emissions is influenced by the climate stringency companies face outside the EU in regions they are active in, depending on whether they are EU ETS-regulated companies. We test this hypothesis by estimating an augmented version of Eq. (6):

$$\begin{aligned}\Delta s_{it} = {} & \beta_1 ETS_i \times LowReg_i + \beta_2 ETS_i + \beta_3 LowReg_i \\ & + \tau X_{it} + \epsilon_{it},\end{aligned} \tag{8}$$

where $LowReg_i$ is a dummy equal to one if the company-specific weighted CLIMI is below the median of the sample distribution, which indicates companies that are exposed to a less stringent climate policy outside Europe. $ETS_i \times LowReg_i$ is the interaction between the ETS dummy and the Low Regulation dummy. A significant coefficient on the interaction term would indicate the presence of heterogeneous effects of the EU ETS on companies that are more or less exposed to stringent climate regulation outside Europe. X_{it}, as in Eq. (6), includes industry and time controls.

Table 5 reports the results of this exercise, in which we estimate this specification for different subsamples. Column 1 presents results for the whole sample of firms emitting outside the EU, Column 2 focuses on the manufacturing sector, and Column 3 narrows the sample to firms that are in the manufacturing sector and in a sector defined as at risk of carbon leakage. We find that being active in non-EU regions with less stringent climate policy does not increase the likelihood of reducing the share of EU emissions; the coefficient is negative but not statistically significant at conventional levels.

5.4. On the power of the null result

In our main results, we do not find a significant difference in EU emissions share trends between ETS and non-ETS firms. We conclude that we cannot reject the hypothesis that there is no carbon leakage due to the EU ETS.

Naturally, such a null result raises a question: what are the chances of detecting leakage in our data, if leakage was actually occurring? In other words, what is the statistical power of our approach? To gauge this, we pursue three approaches in this section: First, we compare our findings for Europe based on the CDP data with findings from administrative emissions data. Second, we calculate the maximum amount of emissions leakage we cannot reject statistically. Third, we explore the substantial variation in the price of EU ETS allowances through time over our sample period to estimate how sensitive leakage might be to price. All three lines of inquiry point toward a strong null result.

[20] The share is computed only relative to the emissions each company produces outside Europe.

Table 5
Regressions of the Share of Emissions in EU–Climate Stringency.

Dependent variable:	Δ Share of EU emissions		
	(1)	(2)	(3)
Sample composition:	All	Manufacturing	Manufacturing + at Risk of CL
$ETS \times LowRegulation$	−0.00335	−0.0118	−0.0232
	(−0.29)	(−0.71)	(−1.13)
ETS	0.00576	0.0166	0.0269
	(0.57)	(1.14)	(1.48)
$LowRegulation$	0.0420***	0.0541***	0.0598***
	(5.87)	(4.67)	(4.00)
ln (Revenue)	0.0106*	0.0216	0.0178
	(1.83)	(1.39)	(1.16)
ln (Assets)	−0.00659	−0.0223*	−0.0186
	(−1.54)	(−1.66)	(−1.56)
ln (Employment)	−0.00198	0.00260	−0.000129
	(−0.76)	(0.56)	(−0.02)
Observations	2,393	1,433	793
Number of firms	623	371	210
R^2	0.0249	0.0305	0.0255

Notes: t statistics in parentheses. Significance levels are indicated as ***p<0.01, **p<0.05, *p<0.1. Only firms that have positive emissions in both EU and RoW in some year are included. Columns 1, 2, and 3's samples are, respectively, equivalent to Panels A, B, and C of Table 4 Column 2 but add balance sheet controls.

5.4.1. Regressions of the level of emissions

In a first robustness analysis to challenge our null result, we establish whether trends in emissions levels differ across regulated and unregulated firms in three jurisdictions: the EU, RoW, and the world–i.e., the EU and RoW combined. In Table 6, we report regressions of changes in the level of EU, RoW, and global emissions on an ETS treatment indicator—i.e., as in Eq. (6) but with outcome variables being first differences of levels of emissions rather than $s_{i,t}$. This reveals a significantly lower emissions trend for EU emissions of regulated EU ETS multinationals. These effects are economically meaningful; e.g., in Column 1, where we report results for our full sample, we find average reductions of 8.7% (calculated as 0.515/5.948). This result is quantitatively similar to the findings of Colmer et al. (2020) and Dechezleprêtre et al. (2020). On the other hand, despite finding such strong CO_2 reductions of emissions within the EU, Panel B shows that we find no significant effects on RoW emissions of EU ETS-regulated multinationals. If the EU emissions reductions we measure were to leak, we would expect to find equivalent increases in RoW emissions—but the point estimates are 5 to 20 times smaller in absolute magnitude across columns. Taken together, the first and second panels provide an additional piece of evidence against carbon leakage being driven by the EU ETS. Finally, when looking at global emissions in the third panel, we do not find significant reductions. However, the point estimates are close to the EU emissions estimates, which reflects the relatively large EU share in emissions of multinationals in our sample. On balance, this suggests that multinationals behave as if EU and RoW were fairly independent jurisdictions rather than substitutes, as the carbon leakage hypothesis would have suggested. When looking at global emissions with noise from RoW emissions added, we find the same quantitative effect with a higher statistical error. These results are highly consistent with the idea that the substitution of emissions between Europe and the rest of the world has not been occurring.

5.4.2. An upper bound for leakage

As a sensitivity analysis, we explore an extreme case: We measure the highest leakage effect we cannot statistically reject and compare the amount of implied leakage with aggregate emissions reductions of EU ETS-regulated multinationals. As reported in the previous subsection, these firms reduced their emissions in Europe. Given this result, can we attribute a share of these reductions to carbon leakage? In our empirical strategy, as specified in Eq. (6), we would have concluded that leakage had occurred if $\beta_1 < 0$. Here, we revisit our main results from Table 4. For each specification reported in the table, we compute the largest value c such that the hypothesis test of $H0 : \beta_1 <= -c$; $H1 : \beta_1 > -c$ would be inconclusive. Hence, we seek the smallest threshold, $-c$, that we cannot reject at a significance level of 5%; i.e., the biggest leakage effect that our data cannot statistically rule out, or the lower boundary of a 90% confidence interval of our estimate of β_1 in Eq. (6). We report those lower-bound EU ETS (upper-bound leakage) effect estimates in Table 7, along with our original point estimates. We find that we cannot reject EU ETS leakage effect estimates of between $\hat{\beta}_1^c = -0.0127$ and $\hat{\beta}_1^c = -0.00755$ (which imply that the EU share would decline by between 1.27 and 0.755 percentage points more in ETS firms).

To get a sense of the environmental magnitude of this result, we compute a counterfactual level of emissions that would be implied by these effects over our sample period. First, for firm i in year t, we compute the counterfactual share of EU emissions, $s_{it}^{EU,CF}$ as: $s_{it}^{EU,CF} = s_{it}^{EU} - \hat{\beta}^c ETS_i \times (t - t_0)$, where t_0 is the start of our sample period (2008), and ETS_i indicates whether the firm is regulated by the EU ETS. For this exercise, we assume the only thing that changes as a consequence of leakage is the amount of emissions in the EU vs RoW, but the total amount of emissions, $CO2_{it}$, is unchanged in the counterfactual. This is a strong assumption, made as part of our extreme counterfactual exercise: Drops in emissions in Europe for reasons other than relocation

Table 6
Regressions of emissions levels.

	(1)	(2)	(3)	(4)
Sample composition:	All	EU>0 RoW>0 any	EU>0 in t = 1	EU>0 in t = 1 RoW>0 any
Dependent variable	Δ Emissions EU			
ETS	−0.515*	−0.414**	−0.424**	−0.488**
	(−1.85)	(−2.51)	(−2.40)	(−2.50)
Average for ETS firms	5.948	5.761	6.383	6.196
Dependent variable	Δ Emissions RoW			
ETS	0.107	0.0232	0.0797	0.0975
	(0.56)	(0.16)	(0.59)	(0.63)
Average for ETS firms	4.925	6.043	5.273	6.072
Dependent variable	Δ Emissions Global			
ETS	−0.408	−0.391	−0.344	−0.390
	(−1.06)	(−1.63)	(−1.43)	(−1.43)
Average for ETS firms	10.87	11.80	11.66	12.27
Observations	3,802	2,589	2,441	2,134
Firms	1,122	676	683	568

Notes: t statistics in parentheses. Significance levels are indicated as ***p< 0.01, **p< 0.05, *p< 0.1. Column 1 includes all firms in the sample. Column 2, firms that have positive emissions in both EU and RoW in some year. Column 3, firms with positive EU emissions in the first period for which the company answered the CDP survey (t = 1). Column 4, with positive EU emissions in t = 1 and nonzero RoW emissions at some point over the sample.

Table 7
Counterfactual calculations.

Dependent variable	Δ Share of EU Emissions			
	(1)	(2)	(3)	(4)
Sample composition	All	EU>0 RoW>0 any	EU>0 in t = 1	EU>0 in t = 1 RoW>0 any
ETS point estimate	−0.00379	0.000934	0.00429	0.00396
	(−0.84)	(−0.15)	(0.71)	(0.58)
ETS lower bound estimate	−0.0127	−0.0131	−0.00755	−0.00945
Upper bound leakage share in reductions 2008–2014	13.63%	14.40%	6.41%	8.77%

Notes: t statistics in parentheses. Significance levels are indicated as ***p< 0.01, **p< 0.05, *p< 0.1. Column 1 includes all firms in the sample. Column 2, firms that have positive emissions in both EU and RoW in some year. Column 3, firms with positive EU emissions in the first period for which the company answered the CDP survey (t = 1). Column 4, with positive EU emissions in t = 1 and nonzero RoW emissions at some point over the sample.

are also counted as carbon leakage, even when those had no impact on RoW emissions. This means that $s_{it}^{EU,CF} = \frac{CO2_{it}^{EU,CF}}{CO2_{it}}$, hence $CO2_{it}^{EU,CF} = s_{it}^{EU,CF} \times CO2_{it}$. We therefore estimate the amount leaked from Europe as

$$l_{it}^{EU} = CO2_{it}^{EU,CF} - CO2_{it}^{EU}. \tag{9}$$

To assess whether leakage is high or low, we compare this to an estimate of the total amount of emissions reductions by EU ETS multinationals over the same period, $\Delta CO2_t$.[21] As a result, we measure an indicator of leakage as the share of EU emissions reductions by multinationals that can be attributed to leakage:

$$leak_t = \frac{\Sigma_{i \in ETS} l_{it}^{EU}}{\Delta CO2_t} \tag{10}$$

In the last row of Table 7, we report this leakage indicator for the last year of our sample, 2014, in each of our specifications. Against this background, our analysis reveals that we cannot reject that up to 14.4% of the reductions made between 2008 and 2014 might have been the result of leakage. For the most policy-relevant subset of multinationals—the subsample of firms that initially report positive CO_2 emissions in the EU—this figure is 6.4%. We conclude that our results provide strong evidence that EU ETS-regulated multinationals achieve equally substantial global emissions reductions.

[21] For internal consistency, we rely on an estimate based on our sample. We discuss below how our sample relates to official data on emissions reductions. We define δ as the average annual change of EU emissions by ETS multinationals over the sample period: $\delta = \frac{1}{\sum_{i \in ETS} T_i} \sum_{i \in ETS} \sum_{t \in 2008--2014} \left(CO2_{it}^{EU} - CO2_{it-1}^{EU} \right)$, where T_i is the number of years a multinational i is in the sample. We consequently estimate aggregate emissions reductions over the sample period as $\Delta CO2_t = \delta \times (t - t_0) \times \#\{ETS\}$, where #{ETS is the number of ETS firms in the sample.

Table 8
Regressions of EU Share on Price.

Dependent variable	Δ Share of EU Emissions			
	(1)	(2)	(3)	(4)
$Price \times ETS$	−0.00118	0.00228	−0.00498**	−0.00383
	(−0.87)	(0.47)	(−2.62)	(−0.54)
$Price^2 \times ETS$		−0.000135		−0.0000468
		(−0.68)		(−0.16)
$Price \times ETS \times LowRegulation$			0.00736***	0.0125*
			(3.89)	(1.78)
$Price^2 \times ETS \times LowRegulation$				−0.000196
				(−0.70)
Observations	2,441	2,441	2,441	2,441
Firms	683	683	683	683

Notes: t statistics in parentheses. Significance levels are indicated as ***p< 0.01, **p< 0.05, *p< 0.1. Only firms with positive EU emissions in the first period for which the company answered the CDP survey (t = 1) are included. All regressions include company fixed and time fixed effects. The price variable is lagged by one period.

5.4.3. Price response

In a third sensitivity analysis on the null result, we consider the spot price on the EU ETS. The central driver of emissions reductions in a carbon market is the allowance price. While the EU ETS might not have had much impact on leakage in the past, it might have had some, since the cap was further reduced—for instance, through the market stability reserve—and therefore prices increased beyond 2008–2014 levels. Granted, the observed spot price is not necessarily the relevant price, as emissions are likely highly complementary to fixed investment, which is guided by long-term price expectations that could diverge. Moreover, what matters for carbon leakage is fundamentally the price difference between the EU ETS and that of the rest of the world, which depends on policy action in non-EU countries. Still, at least since EU ETS Phase II, when permit banking was introduced (2008), the spot price should be indicative of long-term price expectations. Moreover, during our sample period spot prices moved considerably, from €24 per ton of CO_2 in 2008 to only €4 in 2013. So it is reasonable to examine any potential linkage between observed prices and emissions. While €24 might still be lower than future price expectations, a sixfold change makes for a fairly wide range in which a differential response would become visible.

For this exploratory analysis, we run regressions of the change in the share of EU emissions at the company level on interactions between the EU ETS spot price and the regulated status of a multinational: EU ETS-regulated or not. In the most general case we allow for quadratic price effects and we allow for different effects between firms with and without low regulation exposure; i.e., our most general regressions is of the form:

$$\begin{aligned}\Delta s_{it} = {} & \beta_1 ETS_i \times Price_{t-1} + \beta_1^2 ETS_i \times Price_{t-1}^2 \\ & + \beta_1 ETS_i \times Price_{t-1} \times LowReg_i \\ & + \beta_1^2 ETS_i \times Price_{t-1}^2 \times LowReg_i \\ & + \tau X_{it} + \epsilon_{it}\end{aligned} \tag{11}$$

The quadratic effects are a simple way to allow for the possibility that there are threshold effects: i.e., firms only respond if price exceed a certain threshold. We use lagged prices as we assume that changes in emissions will require some investment and therefore occur with at least one period delay. Also note that all (ETS) firms face the same price in a given year. Hence, this is effectively a regression to check whether there is any variation in the strength of the effect over time and, specifically, if there might have been an effect in years where prices were the highest.

Table 8 reports fixed-effects regressions of the EU emissions share on lagged EU ETS permit spot prices.[22] In Column 1, we find that the price effect is negative—as would be expected—although not significant. In Column 2, we introduce a quadratic price term and find point estimates consistent, though not significant, with carbon leakage effects occurring at higher prices only. In Column 3, we explore whether price effects differ for firms more exposed to low-regulation regions abroad (i.e., the CLIMI index). We would expect a stronger impact of higher prices on the carbon leakage for such firms. Interestingly, we find the contrary: Firms that are more exposed to regions with less stringent climate regulation display *less* of a carbon leakage effect. In Column 4, we include controls for differential regulation exposure and for a nonlinear price response simultaneously. This indicates no carbon leakage, even for multinationals that are already present in jurisdictions with low regulatory pressure on CO_2 emissions.

In Table 9 we also consider the different components of the share of emissions separately. This reveals the presence of a nonlinear price effect for both EU and RoW emissions, and of the CLIMI effect—i.e., heterogeneity in the response of low-regulation-exposed firms—derives entirely from RoW emissions.

[22] For simplicity, all regressions are based on the sample of firms with nonzero EU emissions in the first period we observe them—i.e., corresponding to Column 3 in Table 4. We find the same broad results irrespective of the sample, and these additional results are available on request.

Table 9
Regressions of Emissions on ETS Price.

Sample composition:	(1) EU>0 in t = 1	(2) EU>0 in t = 1	(3) EU>0 in t = 1	(4) EU>0 in t = 1
Dependent variable	Δ Emissions EU			
$Price \times ETS$	−0.188	0.637*	−0.0730	0.603**
	(−1.47)	(1.87)	(−1.14)	(2.62)
$Price^2 \times ETS$		−0.0322*		−0.0266**
		(−1.79)		(−2.71)
$Price \times ETS \times LowRegulation$			−0.222	0.0506
			(−0.92)	(0.08)
$Price^2 \times ETS \times LowRegulation$				−0.0102
				(−0.32)
Minimum Price for Reductions		9.895		8.892
Dependent variable	Δ Emissions RoW			
$Price \times ETS$	0.00128	0.218*	0.108*	0.330**
	(0.02)	(1.76)	(1.74)	(2.07)
$Price^2 \times ETS$		−0.00844		−0.00871*
		(−1.55)		(−1.71)
$Price \times ETS \times LowRegulation$			−0.206**	−0.236
			(−2.14)	(−1.10)
$Price^2 \times ETS \times LowRegulation$				0.00119
				(0.13)
Minimum Price for Reductions		12.89		6.289
Dependent variable	Δ Emissions Global			
$Price \times ETS$	−0.186	0.854**	0.0348	0.933**
	(−1.11)	(2.05)	(0.33)	(2.82)
$Price^2 \times ETS$		−0.0406*		−0.0353**
		(−1.85)		(−2.76)
$Price \times ETS \times LowRegulation$			−0.428	−0.185
			(−1.34)	(−0.24)
$Price^2 \times ETS \times LowRegulation$				−0.00896
				(−0.23)
Minimum Price for Reductions		10.52		8.450
Observations	2,441	2,441	2,441	2,441

NOTES: t statistics in parentheses. Significance levels are indicated as ***p< 0.01, **p< 0.05, *p< 0.1. Only firms with positive EU emissions in the first period for which the company answered the CDP survey (t = 1) are included. All regressions include company fixed and time fixed effects. The price variable is lagged by one period.

We have to be careful in reading too much into these results given that most coefficients are estimated with low precision, limited variation in the price variable, and the clear challenges to identification. However, for discussion purposes, we can still attempt to find an explanation for the results that is consistent with the emerging evidence: Our evidence would be compatible with the following interpretations. First, our results are consistent with price threshold effects: Firms will only respond with carbon reductions if the price exceeds a minimum threshold; e.g., for EU emissions this would be at a carbon price of € 9.9 when the marginal price effect turns negative. Second, the EU ETS leads to negative leakage effects, with emissions also being reduced outside the EU at higher prices. This negative leakage effect is stronger for firms more active in low-regulation countries because, presumably, marginal abatement costs are relatively lower there due to a lack of regulations. In Fig. 9, we summarize this evidence by plotting the implied carbon-abatement functions. If carbon leakage as a result of the EU ETS were to occur, the non-EU emissions curves would be upward sloping in the EU ETS allowance spot price. However, the data indicate the opposite: All curves are downward sloping, which implies that higher carbon prices in the EU ETS are associated with fewer emissions, both in the EU and abroad. However, the magnitude of the response differs: As is to be expected, domestic EU emissions respond the most. RoW emissions in firms primarily active in low-regulation countries and RoW emissions for firms in high-regulation regions respond more slowly, and only at higher price levels.

On balance, the three extensions appear to confirm our main null result: The EU ETS has not led to carbon leakage within multinational firms.

6. Conclusion

This paper uses a unique dataset on within-firm carbon emissions to study the distribution of carbon emissions of multinational firms across countries and over time. We focus on the concern that EU climate policy, particularly its flagship EU Emissions Trading System, could lead to carbon leakage—i.e., firms could re-locate polluting activities to non-EU locations in response to being subjected to the EU ETS. Using both exploratory data analysis and regression analysis, and looking at a wide range of subsamples

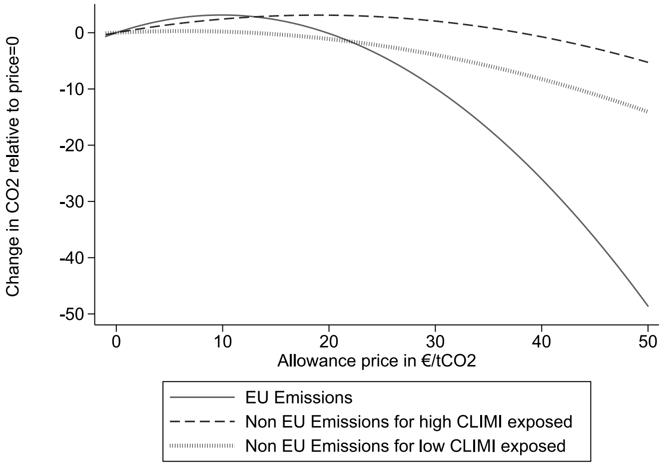

Fig. 9. Counterfactual carbon response to the EU ETS allowance price.
Note: The figure visualizes the quadratic price response functions estimated in Table 9.

and specifications, we cannot find any evidence in our data for carbon leakage. Our estimation strategy cannot necessarily reveal the causal effect of the EU ETS on leakage, since we cannot rule out that region-specific productivity shocks might confound the effects of the EU ETS. However, our results suggest that carbon leakage due to the EU ETS is unlikely to have been an economically meaningful concern until 2014.

Why are the effects of the EU ETS on carbon leakage so small that they cannot, at least so far, be statistically detected? The evidence presented here is based on multinational companies that would be expected to be the first to react to unilateral climate change regulations by shifting production and emissions to less-regulated jurisdictions. A first possibility is that the EU ETS, by widely allocating emissions permits to carbon-intensive and trade-exposed industries for free, is successfully preventing leakage effects. In this vein, Martin et al. (2014b) argue that the European Commission has been handing out free permits more generously than necessary. A second possibility is that the statistically insignificant effects identified thus far simply reflect the lack of stringency of the EU ETS. The price of carbon in the European market has fluctuated between 0 and 30 euros per ton since its introduction, spending most of the time in the lower range of this interval. While regulation that does not lead to carbon leakage should be favored, it is likely that the threats posed by climate change will require more stringent regulations going forward than the EU ETS experience analyzed here, and are therefore more likely to lead to leakage. However, the regulatory gap could also narrow in the future, with emerging economies such as China implementing more stringent climate policy. At present, we can conclude that modest differences in climate policy stringency across countries do not seem to induce carbon leakage, even among multinational companies that can easily shift production and emissions across jurisdictions. An important question for future research is to understand how large these differences can be before carbon leakage starts becoming an issue (and in which sectors), and how climate policies should be adjusted as other countries' regulations evolve.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jeem.2021.102601. Additional detail on the construction of the dataset, descriptive statistics, and sensitivity analyses.

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