Carbon Leakage to Developing Countries*

PRELIMINARY AND INCOMPLETE -

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December 9, 2023

Abstract

How do more stringent climate policies in developed countries spill over to the developing world? Using a novel dataset that combines information on the location of multinational firms' subsidiaries with geo-referenced data, we study how multinationals change their operations and emissions in Africa in response to more stringent climate policies in Europe. We find that emissions of European multinationals at their African subsidiaries increase significantly relative to subsidiaries from less regulated firms. At the same time, European multinationals reduce their domestic investment while worldwide investment remains unchanged – consistent with the notion that these firms shift some of their operations abroad. We confirm these results at the aggregate level, documenting a significant increase in economic activity and emissions in Africa. Policies to mitigate leakage should thus balance environmental concerns against development and equity considerations.

Keywords: Carbon taxes, Carbon leakage, Inequality, Economic development

JEL classifications: F18, H23, Q52, Q54

*We thank Naomi Feldman (discussant), Juan Carlos Suárez Serrato, Martin Simmler (discussant), and Elias Papaioannou for comments and suggestions. We appreciate the helpful feedback from conference and seminar participants at the Oxford Centre for Business Taxation Annual Academic Symposium 2023 and London Business School. We thank Bihter Erbas and Mike Nuno for excellent research assistance. The authors gratefully acknowledge financial support from the Wheeler Institute for Business and Development at London Business School.

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1 Introduction

The looming climate crisis is at the top of the global policy agenda. Governments around the world started to introduce policies to reduce carbon emissions via carbon taxes, cap and trade systems, and other regulatory tools. While there is mixed early evidence on the domestic effects of such policies, an important but underexplored question concerns the global spillover effects, particularly on the developing world. A particular concern is coined carbon leakage, broadly defined as the shift of greenhouse gas emissions from one country to another because of stricter regulation. Carbon leakage poses a threat to the global objective of reducing emissions, igniting a discourse on effective strategies for its prevention. However, measures to prevent leakage may put poorer countries – which have historically contributed little to climate change and are in need of further development – at an economic disadvantage.

In this paper, we study how climate policies in developed countries spill over to the developing world through carbon leakage. Measuring leakage is challenging, however. We focus on ownership networks within multinational firms, which are a natural starting point to detect leakage. To this end, we construct a novel dataset of multinational firms headquartered in Europe, which has proven to be a global leader in climate policy, and their majority-owned subsidiaries in Africa. While data on multinational firms' consolidated emissions can be readily acquired, measures of emissions at the subsidiary level remain largely inaccessible. We overcome this challenge by geo-coding the locations of African subsidiaries and proxying their carbon footprint using geo-referenced emissions data.

Our empirical design leverages variation in the climate policy stance across European countries. While all EU countries are part of the European Emissions Trading Scheme (EU ETS), some countries have adopted a more stringent stance by complementing the carbon market with national carbon taxes. Using an event study design, contrasting African subsidiaries with parent firms subject to a tax to subsidiaries of unregulated parents, we find that subsidiary-level carbon emissions increase significantly after the introduction of a carbon tax in the parent firm home country. Focusing on parent country location does not fully capture the exposure to European carbon taxes. We thus confirm these results in a shift-share setting, where we exploit the exposure of multinational firms to European carbon taxes via their European subsidiaries. Our estimates point to significant carbon leakage effects. Increasing the exposure to European carbon taxes by one standard deviation increases emissions at African subsidiaries by more than 1 percent. Given the moderate level and limited coverage of European carbon taxes, this increase is not only statistically but also economically significant. The results are robust along a number of dimensions, including varying the grid size around the subsidiaries in Africa, as well as flexibly accounting for potential time-varying confounders using different sets of fixed effects.

Having established this new evidence on within firm carbon leakage from Europe to Africa, we aim to shed light on the mechanism. Using multinational firm and subsidiary-level financial statement data, we document evidence consistent with multinationals lowering their fixed tangible capital investment in their European home countries after the introduction of carbon taxes. On the other hand, consolidated total investment does not seem to change, pointing to an increase in investment abroad.[1] Overall, these results suggest that European multinationals shift some of their operations abroad after an increase in their carbon tax exposure – providing further indirect evidence on carbon leakage effects.

Studying carbon leakage at the firm level allows us to credibly identify potential leakage effects. However, carbon leakage is a more general problem and may also occur outside firm boundaries. To this end, we corroborate our firm-level evidence using aggregate data. We exploit the differential exposure of African countries to European carbon taxes depending on their bilateral trade linkages and the presence of multinational firms headquartered in different European countries in a panel of 48 African countries. Based on this shift-share design, we document a significant increase in aggregate emissions in African countries with greater exposure to climate policy in Europe.

In summary, our findings highlight the importance of addressing carbon leakage from developed countries to the developing world. However, any potential measures to address leakage should also take equity and development considerations into account. Specifically, our results suggests that within-multinational firm carbon leakage also comes with a reallocation of economic activity to developing countries, which likely induces growth and potentially reduces economic inequality. In our work-in-progress, we aim to directly measure local economic outcomes around carbon-leaking firm establishments in Africa to shed more light on this mechanism.

Related Literature and Contribution. The empirical literature on the economic effects of environmental policy is still sparse. Recent studies analyze the effects on local emissions and economic activity (see e.g. Metcalf, 2019; Metcalf and Stock, 2023; Känzig, 2022; Konradt and Weder di Mauro, 2021; Colmer, Martin, Muûls and Wagner, 2022; Erbertseder, Jacob, Taubenböck and Zerwer, 2023; Jacob and Zerwer, 2022). This literature documents (modest) reductions in domestic or local emissions at the aggregate and at the firm level in response to the introduction of carbon taxes in the same jurisdiction. Jacob and Zerwer (2022) exploit a sample of small Spanish firms and also document a reduction in fixed capital investment for firms located in the Valencian region after a local carbon tax was introduced. Col-

[1] Unfortunately, it is not possible to consistently use financial statement data to measure investment at the subsidiary level outside of Europe given the lack of financial reporting mandates.

lectively, this evidence suggests that firms bear at least part of higher carbon prices induced by taxes or carbon markets and that firms reduce emissions and economic activity in the regulated jurisdictions accordingly.

However, still very little is known about the potential threat of carbon leakage. This is partly because measuring carbon leakage is challenging. One strand of the literature has tried to proxy leakage by studying the carbon embodied in trade flows (Aichele and Felbermayr, 2015; Naegele and Zaklan, 2019). While looking at trade is certainly informative, imputing the carbon content of trade flows is challenging and relies on certain stringent assumptions. Another strand has used survey data on multinational firms' carbon emissions by the geographic region from the Carbon Disclosure Project (Dechezleprêtre, Gennaioli, Martin, Muûls and Stoerk, 2022; Ben-David, Jang, Kleimeier and Viehs, 2021). This is a very promising approach, as it is arguably more direct. A limitation, however, is that the survey data typically only covers a subset of large public firms and does not provide country-specific emissions by firm. Furthermore, the survey data may be subject to selection bias and measurement error.

There are two other recent studies that study potential leakage effects within firm ownership networks. Cui, Wang, Wang, Zhang and Zheng (2022) look into potential carbon leakage during the pilots of China's regional emission trading scheme. They find that carbon emissions of non-ETS firms in the same ownership network increase significantly compared to sibling firms covered by the ETS. Chen, Chen, Liu, Serrato and Xu (2021) study a prominent energy regulation affecting large Chinese manufacturers that are part of broader conglomerates. They show that regulated firms cut output and shifted some production to unregulated firms in the same conglomerate instead of improving their energy efficiency. Both studies leverage detailed administrative data on emissions within ownership networks and make significant progress on our understanding of leakage effects. We contribute to this literature by developing a new approach to directly measure leakage effects in countries where high-quality administrative data is not available. Our novel dataset is available for a representative sample of multinational firms and allows us to isolate leakage at a very granular level. While our focus is on leakage to Africa, the approach could be easily extended to study leakage to other parts of the world. Based on this approach, we provide new evidence on carbon leakage from developed to developing countries.

Outline. The paper proceeds as follows. Section 2 provides information on the policy setting and the relevant identifying variation. In Section 3, we provide more detail on our data set of multinational firms and their subsidiaries and introduce our novel approach to measure emissions at subsidiaries in developing countries. Section 4 discusses our micro evidence on leakage within multinational firms' ownership networks. Section 5 presents the macro evidence from the shift-share design. Section 6 concludes.

2 Policy Setting and Identifying Variation

The European Union (EU) is widely recognized as a global leader in climate policy due to its comprehensive and ambitious strategies to combat climate change. A key pillar of climate policy in Europe is the European Emissions Trading Scheme (ETS), which puts a cap on greenhouse gas emissions from the power sector, certain heavy-emitting industries and domestic aviation. However, the EU ETS is not the only climate policy in place. Many European countries have also enacted national carbon taxes to strengthen their climate policy stance and complement the carbon market.[2]

Table 1: Carbon Taxes in Europe

Country	Year of enactment	Tax rate in 2019 (euros per metric ton)	Share of emissions covered in 2019	Coverage-weighted tax rate in 2019
Denmark	1992	23.33	40%	9.33
Estonia	2000	1.94	3%	.06
Finland	1990	61.09	36%	21.99
France	2014	44.04	35%	15.41
Iceland	2010	29.45	29%	8.54
Ireland	2010	19.19	49%	9.4
Latvia	2004	4.39	15%	.66
Norway	1991	53.35	62%	33.08
Poland	1990	.07	4%	0.00
Portugal	2015	12.52	29%	3.63
Slovenia	1996	16.93	24%	4.06
Spain	2014	14.81	3%	.44
Sweden	1991	112.09	40%	44.84
Switzerland	2008	83.22	33%	27.46
United Kingdom	2013	19.93	23%	4.58

Notes: This table contains information in carbon taxes in Europe, in particular the year of enactment of the tax, the tax rate (in euros per ton of CO2 equivalent), the share of emissions covered by the tax, and the coverage-weighted tax rate. The tax rate and coverage are reported as of 2019.

While the EU ETS affects European countries more uniformly, carbon taxes vary significantly across countries. First, only about half of the countries in Europe have introduced a carbon tax. But also among the countries that have enacted a carbon tax, there are stark differences. Table 1 gives an overview of carbon taxes in European countries. We can see that carbon taxes tend to be the highest in Scandinavian countries and Switzerland, with tax rates in excess of 50 euros per ton of CO2 equivalent. For most other countries the rates are more moderate. The UK and France, the two largest carbon tax adopters, are in this group, with tax rates of 20 and 44 euros, respectively. Finally, some countries have enacted carbon

[2] These taxes can overlap with the ETS but generally cover sectors and industries that are not part of the carbon market.

taxes with very little bite, in particular Poland or Estonia where the rate is close to zero.

European carbon taxes have been found to lead to significant emission reductions, while the evidence on the economic impacts is less clear (see e.g. Andersson, 2019; Metcalf and Stock, 2023; Kapfhammer, 2023; Känzig and Konradt, 2023, among others). A potential explanation for these findings is that firms shift some of their emission-intensive operations abroad where climate regulation is less stringent. Developing countries in particular are a natural place for firms to reallocate their emissions, as they generally have less stringent environmental policies in place and are not expected to toughen up their regulatory stance in the foreseeable future.

Does this intuition hold up in the data? There are two complications that arise when trying to answer this question empirically. First, carbon taxes are not set in isolation. Policy makers may well take economic considerations into account when setting carbon tax rates. The variation in the climate policy stance across European countries documented above, coupled with the varying firms' exposure to these policies is what is going to help us with identification. The idea is to compare multinationals that are significantly exposed to carbon taxes to similar multinationals that are not. Second, we require data on the ownership network of multinational firms as well as a way to measure emissions at its subsidiaries, particularly in Africa and other developing countries.

3 Multinationals and Their Carbon Footprint in Developing Countries

We construct a dataset on multinational firms that contains detailed information about their ownership network and financials. Most importantly, we propose a new approach to proxy emissions at the subsidiary level that works particularly well in Africa and other developing countries.

Subsidiary Networks and Financials of Multinational Firms. To construct an ownership network of parent and subsidiary firms, we use data from the Bureau Van Dijk Orbis historic database.[3] Following previous work by De Simone and Olbert (2022), Hoopes et al. (2022), and Coppola et al. (2021), our approach allows us to identify ultimate parent companies as well as its majority-owned subsidiaries across the organizational hierarchy and across the world, including tax havens and developing countries. We briefly describe here the construction of the data set. For more information, see e.g. De Simone and Olbert (2022).

[3] In particular, we use historical snapshots of company ownership information from Orbis. The Orbis database includes detailed information on over 400 million companies worldwide. For most companies, Orbis provides ownership links for subsidiaries and shareholders.

To build the ownership tree, we first identify ultimate parents. These are defined as enterprises that either publish consolidated financial statements or that have no shareholder owning more than 50% of the company (level 0). We then identify all firms that are owned by an ultimate owner with a share exceeding 50% (level 1). In the next step we identify all firms that are owned with a share exceeding 50% by a level 1 firm, and associate these with the ultimate parent of the level 1 firm. Moreover, we identify firms that are owned by various direct parents that belong to the same ultimate parent which hold a joint share exceeding 50%. This procedure is repeated until we have constructed the full ownership tree.

The Orbis data also contains information on multinationals' financials. In particular, we use financial information from the annual consolidated financial statements filed by the multinational firms' parent entities in their headquarters countries as well as financial information from the annual subsidiary-level unconsolidated financial statements filed by the multinational firms' subsidiaries incorporated in different European countries. Fortunately, such data is available in Europe due to the financial reporting regulation requiring public and private corporations to prepare and disclose unconsolidated financial accounts (Breuer, 2021; Kim and Olbert, 2022).[4] We complement this data with ESG data from S&P Trucost, in particular data on greenhouse gas emissions reported by the multinational firms' parent entities. Note that this information is only available for a smaller sample of public firms that file voluntary or mandatory sustainability reports or disclose emissions in their annual reports. Importantly, financial information, let alone emissions data, is largely unavailable for subsidiaries in developing countries.

Measuring Subsidiary Greenhouse Gas Emissions in Developing Countries. A key challenge is thus how to measure activity and greenhouse gas emissions at a multinational's subsidiaries in developing countries. Our key idea is to proxy emissions at the subsidiaries by analyzing how emissions in the close vicinity of the subsidiary change. This approach is destined to work particularly well in Africa, where emissions are not as densely distributed as in Europe.

To this end, in a large-scale handcollection effort, we gathered information on subsidiary locations of European multinationals in Africa. To keep the number of locations manageable, we focus on a subset of firms headquartered in seven major European economies: Belgium, France, Netherlands, Germany, United Kingdom, Spain or Italy. Furthermore, we restrict our attention to firms that operate in the Mining, Quarrying, and Oil and Gas Extraction or Manufacturing sectors (NAICS codes 21, 32, 32 and 33).

For these multinational firms, we georeferenced the exact locations of all their majority-owned subsidiaries in African countries using information from Google and Google maps.[5] The top panel in Figure

[4]Data on multinationals' financial information is sourced from the Orbis Generics flatfiles as of February 2023.

[5]For some entities, Orbis provides address information, including zip codes and streets. However, this information is often

1 shows the geo-coded locations of the subsidiaries in our sample. We can see that In many countries subsidiary locations are concentrated in the capital city. For some economically more developed countries such as South Africa the spatial distribution is a bit more dispersed.

Having collected the subsidiary location data, we combine this information with spatial emissions data. We use the Emission Database for Global Atmospheric Research (EDGAR) by Crippa et al. (2022). EDGAR provides high-quality emissions data across space, at a resolution up to 0.1 degree $\times$ 0.1 degree (approximately 11 km $\times$ 11 km at the equator). The dataset is maintained jointly by the European Commission JRC Joint Research Centre and the Netherlands Environmental Assessment Agency (PBL) and is frequently used in scientific assessments, including those conducted by the Intergovernmental Panel on Climate Change (IPCC).

The emission statistics in EDGAR are estimated bottom-up from standard annual statistics of fuel, products, waste, crops, or livestock at the country level. The database then uses spatial data on population, roads, agricultural fields, and firm locations to disaggregate the national statistics at the local level. Specifically, emissions from a specific sector are attributed to a particular cell by calculating the share of the proxy associated with that sector that is located in that same cell relative to the country's total. For more details, see Janssens-Maenhout et al. (2013). We use the total emissions of all sectors, including short-cycle emissions.

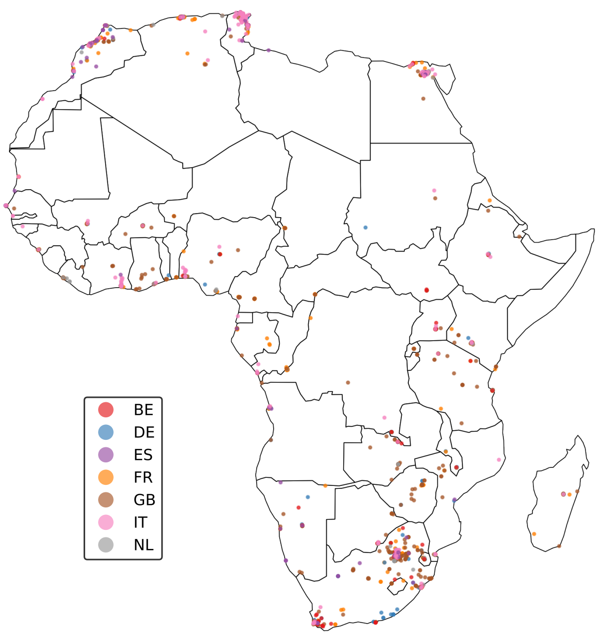
The bottom panel in Figure 1 visualizes the distribution in estimated emissions (total tons of CO2) from the EDGAR database across the African continent at the 0.1 $\times$ 0.1 grid cell level for the year 2015. We can see that emissions vary a lot both within and across countries. Generally, emissions are higher in densely populated areas. Emissions are particularly high in Nigeria and parts of South Africa and Egypt.

Equipped with the spatial emissions data, we are able to proxy emissions around the subsidiaries of European multinationals. The measurement, however, crucially hinges upon the quality of the emissions data. Therefore, we perform a number of validations checks (see Appendix B.1). First, we study how well the EDGAR data aligns with emissions data from other sources at the country level. Specifically, we compare annual changes in EDGAR CO2 emission proxies to the same annual changes in CO2 emissions data from the Worldbank. The two series are very highly correlated, with a correlation coefficient above 75 percent even after controlling for changes in GDP. This is reassuring, but for our purposes we are also interested in how accurate the emissions data is across space. To this end, we correlate the EDGAR emissions data with nighttime luminosity data at the grid-cell level. We would expect these two series to be positively correlated, to the extent that higher luminosity is a proxy for higher economic activity

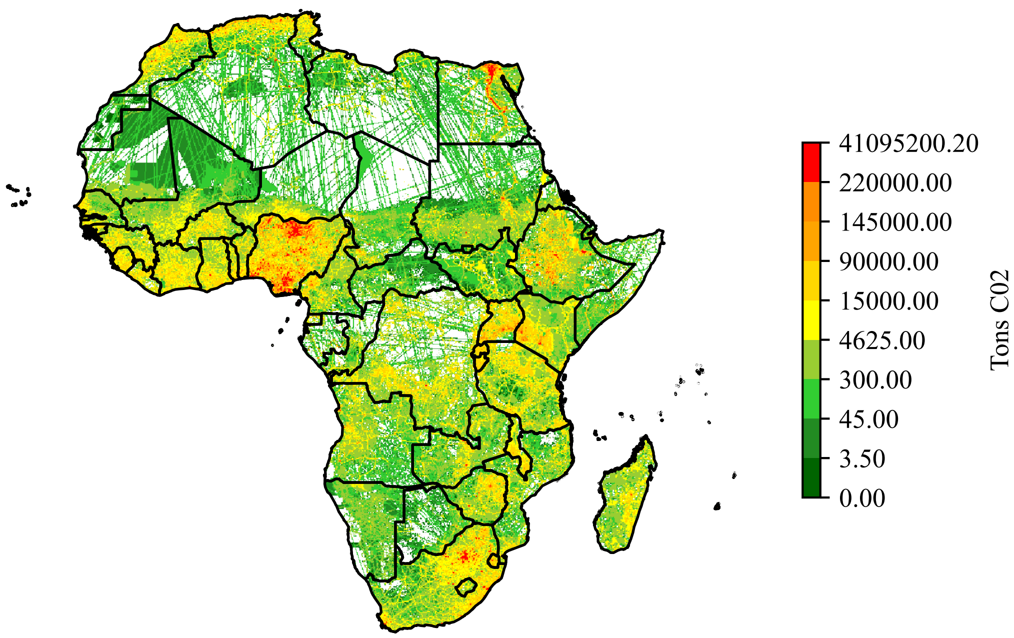
missing and less reliable and not as accurate as handcollecting the location data, in particular in the case of developing countries.

Figure 1: Proxying Emissions at African Subsidiaries

(i) Subsidiary locations



(ii) CO2 Emissions Across Africa



Notes: This figure illustrates how we measure emissions at African subsidiaries. Panel (i) shows the geographical distribution of the subsidiary locations in our dataset. The color indicates the country where the ultimate parent of the subsidiary has their headquarter (Belgium, Germany, Spain, France, Great Britain or the Netherlands). Panel (ii) shows the geographical distribution of CO2 emissions in Africa at the 0.1 $\times$ 0.1 grid cell level based on data from EDGAR v7.0 for the year 2015. The values correspond to the sum of CO2 emissions excluding short-cycle emissions.

which in turn is associated with higher emissions. This is indeed what we find. The correlation between the two measures approximately 67 percent.

Sample Selection and Summary Statistics. We focus our analysis on the period from 2010 to 2019. We start the sample thus after the global financial crisis and stop before the outbreak of the Covid-19 pandemic, to avoid any confounding effects of these large shocks.

Table 2: SUMMARY STATISTICS

	Obs.	Mean	Median	Min	Max	SD
Panel A	Emissions around Firms' African Subsidiary Locations					
ln(CO2) [Grid Size: 0.10 × 0.10]	25,272	13.17	13.45	9.35	15.58	1.34
ln(CO2) [Grid Size: 0.25 × 0.25]	27,909	12.99	13.28	9.54	15.16	1.29
Panel B	Firms' European Subsidiary-Country-level Data					
Total Assets (USD m)	32,057	2906.82	28.95	-41.92	794226.28	23133.28
ln(Total Assets)	31,551	17.40	17.23	9.97	24.91	2.94
Fixed Tan. Assets (USD m)	32,057	142.70	1.38	-235.28	60001.09	1380.42
ln(Fixed Tan. Assets)	28,124	14.58	14.79	6.75	21.59	3.29
Panel C	Consolidated Firm Data					
Total Assets (Cons., USD m)	4,714	14610.74	822.61	0.00	610008.24	46158.77
ln(Total Assets (Cons.))	4,713	20.64	20.53	15.05	26.27	2.56
Fixed Tan. Assets (Cons., USD m)	4,705	3458.40	155.99	0.00	142705.00	12830.68
ln(Fixed Tan. Assets (Cons.))	4,627	18.78	18.93	9.41	25.03	3.08
Scope 1 GHG/1m Total Assets (Cons.)	1,786	0.04	0.01	0.00	0.86	0.11
Scope 2 GHG/1m Total Assets (Cons.)	1,786	0.02	0.01	0.00	0.28	0.04
Panel D	African Country-level Data					
CO2 Country	473	56.31	18.38	0.57	601.95	112.51
ln(CO2 Country)	473	2.91	2.91	-0.57	6.40	1.52
ln(GDP)	473	23.40	23.24	20.54	26.96	1.52
GDP Growth	473	4.14	4.39	-50.34	86.83	6.58
ln(Exports)	473	22.17	22.25	18.29	25.71	1.59
ln(Population)	473	16.05	16.34	11.38	19.13	1.55

Notes: This table presents summary statistics for the variables used in the different regression samples throughout the analyses. In the different panels, variables and samples are categorized based on the level of the unit of observation for the sample period 2010-2021. Panel A shows statistics for grid cell-level emissions from the EDGAR database. Panel B shows statistics for multinational firms' aggregated subsidiary financial data in European countries. Panel C shows statistics for multinational firms' consolidated financial data and reported Greenhouse Gas emissions from the Trucost database. Panel D shows aggregate data at the country level.

In Table 2 we report some summary statistics for the main variables in our analysis over the sample of interest. Panel A shows statistics regarding the emissions at African subsidiary locations. Panel B displays information on total and fixed tangible assets for multinational firms' European subsidiary countries. To construct these variables, we sum up the unconsolidated assets of all subsidiaries in a given country and year owned by the same multinational. Panel D shows statistics for equivalent asset variables based on multinational firm's consolidated financial statements. Thus, these variables capture firm's total worldwide assets in a given year. We also show the total Scope 1 and 2 greenhouse gas emissions, scaled by firms' consolidated total assets, for the subset of publicly listed firms reporting these data and covered in the Trucost database. Panel D shows summary statistics of variables at the African country level. We document a large heterogeneity in the country-level of CO2 emissions, with small countries like Comoros or the Seychelles emitting less than one million tons of CO2 per year.

4 Searching for Carbon Leaks to Developing Countries

How does stricter environmental regulation of European firms affect emissions at their subsidiaries in Africa? As we discussed, carbon taxes not only incentivize multinational firms to reduce their emissions in their home country, they may also offshore pollution-intensive activities to countries where there is no or little regulation. To shed light on this channel, we conduct two main empirical exercises: a simple event study analysis to motivate our approach and a shift-share design that leverages the exposure of European multinationals' to European carbon taxes.

4.1 A Motivating Event Study Analysis

To motivate our empirical design, we first perform a simple event study analysis. We consider three countries that have relatively recently implemented a carbon tax: the UK, which has introduced the carbon price floor in 2013, France, and Spain, which have both introduced a carbon tax in 2014. The idea is then to compare subsidiaries that are owned by a French or British parents to subsidiaries that are owned by a multinational headquartered in a country with no carbon tax in place. Specifically, we use parent firms in Germany, the Netherlands, Belgium and Italy as the relevant control group.

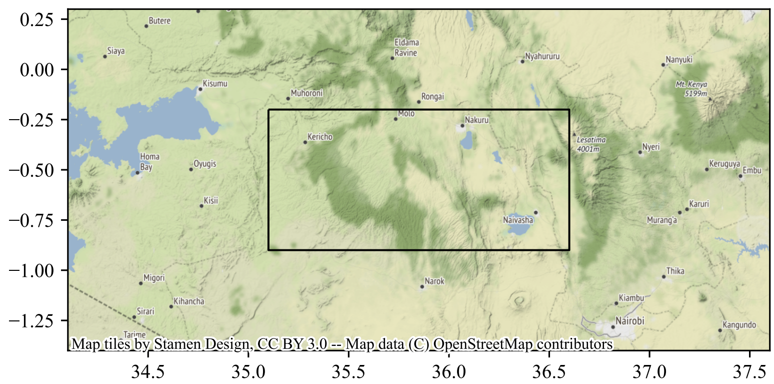
The implicit assumption underpinning this approach is that multinational firms maintain a significant portion of their business operations, including production activities and employment, in their home countries and are thus affected by the tax.

Figure 2 illustrates our differences-in-differences design with a simple example. Displayed are two subsidiaries in Kenya that are relatively close to each other. Importantly, however, one is owned by a UK while the other subsidiary belongs to a German multinational. The top panel shows the area on the map under consideration, while the bottom panel zooms in and displays the change in emissions from 2012 to 2016 across space. The green dot shows the location of the British and the blue dot shows the location of the German subsidiary. The black square around the firm is of size 0.25×0.25 degrees (approximately

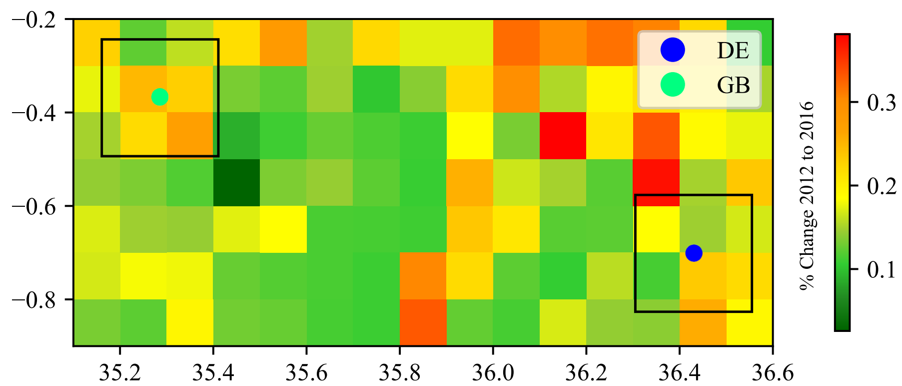
27.5km × 27.5 km). We can see that the UK subsidiary, whose parent has become subject to a carbon tax, displays a stronger increase in emissions than the German subsidiary. This evidence is consistent with carbon leakage effects. Of course, this represent but one example. Do we observe these leakage effects be observed more systematically across a wider range of cases?

Figure 2: An Example of Two Subsidiaries in Kenya

(i) Zoom Area



(ii) CO_2 Emissions Around DE and GB Subsidiary



Notes: This figure illustrates the mechanism of carbon leakage. Panel (i) shows a map of Kenya where the black box highlights the region that we zoom into in panel (ii). Panel (ii) shows subsidiaries of a a German and a UK multinational firm. The black bounding box is of size 0.25 × 0.25. Cell colour indicates the percentage change in CO2 emissions from 2012 to 2016.

To formally examine the effect of European carbon taxes on emissions of European-owned subsidiaries in Africa, we consider the following event-study regression framework:

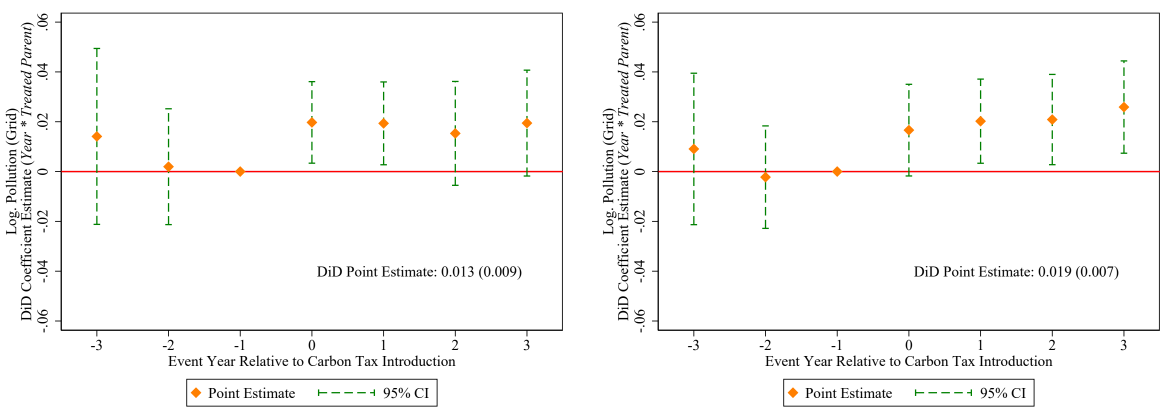
$$\ln(\text{CO2}_{s(i)t}) = \alpha_s + \delta_t + \sum_{r \neq -1} \beta_t \times \mathbf{1}\left[r = t\right] \times \text{Treat}_s(i) + \epsilon_{st}, \tag{1}$$

where $\ln(\text{CO2}_{s(i)t})$ is the log-level of pollution at time t at subsidiary s owned by parent firm i. We include subsidiary (i.e. grid-cell) fixed effects, α_s, and year fixed effects, δ_t. $\text{Treat}_s(i)$ is a binary treatment indicator equal to one if the subsidiary is owned by a multinational firm headquartered in a country that introduced a carbon tax in our sample period. For inference, we use Conley spatial HAC standard errors to account for spatial dependence in a linearly decreasing manner up to 500km (Conley, 1999). Of interest are the coefficients β_t over time, where the relative event years r measure the distance to the year of the carbon tax introduction in the respective multinational firm headquarters country. Coefficients on β_t should be insignificant before treatment to ensure parallel trends.

Figure 3 shows the results of the event study regression. We can see that after the introduction of a carbon tax in the parent country of a multinational firm, CO_2 emissions at its African subsidiaries increase significantly. Reassuringly, we find little evidence for pre-trends. The point estimates in the pre-period are relatively close to zero and not statistically significant. The results are also robust to varying the grid size around the subsidiaries. Using a grid size of 0.1×0.1 or 0.25×0.25 yields largely comparable results, even though the coefficients are slightly larger and more precisely estimated for the larger grid size. In terms of magnitudes, our estimates suggest that emissions around African subsidiaries affected by European carbon taxes through their ownership by a multinational firm located in a carbon tax country increase by approximately 2 percent more than those of less affected subsidiaries. This is a non-negligible effect, especially when considering that the introduced carbon tax rates were at relatively moderate levels.

Figure 3: European Carbon Tax Introductions and LOCAL CO_2 Emissions in Africa

(i) Grid Size: 0.1 **(ii)** Grid Size: 0.25



Notes: This figure displays the results from the event study model (1), estimating the effect of the introduction of a carbon tax in a multinational's home country on CO_2 emissions at its African subsidiaries. The coefficient from the corresponding differences-in-differences model is also reported. The dependent variable is the log of CO_2 emitted in grid cells around the firm location based on data from EDGAR. In panel (i), we include the EDGAR cell which has the center inside a 0.1×0.1 cell around the firm. In panel (ii), we include the EDGAR cells which have their center inside a 0.25×0.25 cell around the firm. The sample consists of 20,608 and 22,765 subsidiary grid cell-year observations respectively. These subsidiaries are majority-owned by 659 unique multinational firms headquartered in Belgium, France, Great Britain, Germany, Netherlands, Italy, or Spain. We exclude observations when the sample subsidiaries are less than 10km apart from each other. The specifications include grid-cell (unit of observation) and year fixed effects. 95% confidence intervals are reported based on Conley spatial HAC standard errors.

To gauge to overall impact, we also run a difference-in-differences specification which estimates the difference in the change of local emissions between treated and control subsidiary-locations over the entire sample period. We also report these estimates in Figure 3. Consistent with the event-study evidence our estimates suggest that carbon subsidiary-level emissions increased by up to 2 percent following the introduction of a carbon tax in parent firm's home country.

4.2 A Shift-share Design based on the Exposure to European Carbon Taxes

In the previous section, we have seen tentative evidence for carbon leakage based on a simple and transparent event study design. However, it does not take the full exposure of European multinationals to carbon taxes into account. In particular, it fails to account for multinationals that have significant exposure to carbon taxes in European countries other than their home country. For instance, "treated" multinationals may be subject to other carbon taxes via their subsidiary network in Europe. More importantly, "untreated" multinationals may also be exposed to carbon taxes in other European countries to the extent they have operations there. The latter concern in particular may attenuate our estimates.

A new exposure measure. To more comprehensively measure a multinational firms' exposure to European carbon taxes, we proxy to what extent a multinational is exposed to carbon taxes via its operations in European countries that have adopted such taxes. The exposure measure is computed as follows.

First, we measure the extent to which a multinational operates in a given European country. We do this by looking at unconsolidated total or fixed tangible assets in the country of interest relative to the total value of assets in European countries:

$$w_{id} = \left(\sum_{t=2007}^{2009} \frac{\text{Assets}_{idt}}{\sum_{k \in K} \text{Assets}_{ikt}} \right) /3 \tag{2}$$

We interpret w_{it} as the exposure weight of multinational firm m to regulations in country d in Europe at time t. To mitigate the concern that this exposure may change in response to changes in regulation, we measure the weight as an average over the three years prior to our sample.[6]

Using these exposure weights, the firm-specific carbon tax exposure measure then takes the form:

$$Z_{it} = \sum_{d \in K} w_{id} \times \text{ctax}_{dt}, \tag{3}$$

where ctax_{dt} is the carbon tax in European country d and w_{md} are the exposure weights computed as described above. We express the carbon tax in real coverage-weighted terms, i.e. deflating them using the relevant GDP deflator and weighting by the country-specific emission coverage of the tax as in Metcalf

[6]Orbis provides subsidiary ownership information from 2007, allowing us to use data from three pre-sample period years.

and Stock (2023).

Shift-share design. Based on this exposure measure, we can estimate the impact of European carbon taxes on local CO2 emissions around multinational firms' African subsidiaries for the years using the following specification:

$$\ln(\text{CO2}_{s(i)t}) = \alpha_s + \delta_t + \beta Z_{it} + \epsilon_{s(i)t}, \tag{4}$$

where $\ln(\text{CO2}_{s(i)t})$ is again the log-level of pollution at time t around subsidiary s located owned by multinational firm i. In the simplest specification, we again just include subsidiary and year fixed effects. However, we can also include other fixed effects such as country by year fixed effects to control more flexibly for potential confounding factors.

This design leverages variation in the overall exposure of multinationals to European carbon taxes. It exploits a multinational firm's pre-determined exposure to different European countries's environmental policies based on the subsidiary-level assets located in a given country and time-series variation in countries' carbon taxes which then affect multinational firms differentially conditional on their exposure.

Table 3 reports the results. We can see that multinationals with higher exposure to European carbon taxes increase their emissions at African subsidiaries by relatively more. These effects are highly statistically significant and robust along a number of dimensions. In particular, the results are robust to the exposure measure used: using unconsolidated total or fixed tangible assets to measure exposure produces very similar results, albeit the effects are a bit larger when we focus on fixed tangible asset exposure. The results are also robust to using different grid sizes. In terms of magnitudes, an increase in a multinational's carbon tax exposure by one standard deviation leads to an increase in emissions at its African subsidiaries by 0.8 to 1.4 percent (as the standard deviation of the exposure measure is approximately 11.5).

Threats to Identification. As we have seen above, our results are robust along a number of dimensions, including the grid size and definition of carbon tax exposure. In all our specifications, we have also included subsidiary and year fixed effects to control for time-invariant subsidiary specific characteristics, which also spans characteristics of its parent company, as well as global trends.

A potential concern with regards to identifcation relates to time-varying confounding factors. These could come in the form of varying trends across African countries. For instance, British multinationals may have more subsidiaries in their former colonies. While the selection of subsidary locations is

Table 3: Firm-Level Exposure to European Carbon Taxes and Local CO2 Pollution in Africa

	(1)	(2)	(3)	(4)
Panel A	ln(CO2)			
Grid Size:	0.1×0.1	0.1×0.1	0.25×0.25	0.25×0.25
Carbon Tax Exp. (TA)	0.0007**		0.0007**	
	(0.0004)		(0.0003)	
Carbon Tax Exp. (FTanA)		0.0012***		0.0012***
		(0.0005)		(0.0004)
Obs.	15,665	15,094	17,264	16,663
Adj. R2	0.001	0.002	0.001	0.003
Subsidiary FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Panel B	ln(CO2)			
Grid Size:	0.1×0.1	0.1×0.1	0.1×0.1	0.1×0.1
Carbon Tax Exp. (TA)	0.0007**	0.0007*	0.0007**	0.0010**
	(0.0004)	(0.0004)	(0.0003)	(0.0004)
Obs.	15,665	15,665	15,665	1,112
Adj. R2	0.001	0.001	0.001	0.009
Subsidiary FE	Yes	Yes	Yes	Yes
Year FE				
Industry × Year FE	Yes	Yes	No	No
Parent Country Controls	No	Yes	No	No
African Region × Year FE	No	No	Yes	
Country × Year FE	No	No	No	Yes

Notes: The dependent variable is logarithm of the mean level of CO2 emitted in grid cells around the firm location based on data from EDGAR. Columns 1 and 2 of Panel A and all Columns in Panel B include grid cells that have their center inside a cell around the subsidiary location of 0.1×0.1 degrees. Columns 3 and 4 of Panel A use 0.25×0.25 degrees. GPS coordinates are in longitude and latitude based on the World Geodetic System 1984. The independent variable *Carbon Tax Exp.* is akin to a shift-share instrument measuring a firms' exposure to European countries' carbon taxes. The weight is constructed as a multinational firms' share of total European unconsolidated assets in a given European country (for details see equation 4). *Carbon Tax Exp. (TA)* and *Carbon Tax Exp. (FTanA)* refer to the exposure measures based on multinational firms' unconsolidated total or fixed tangible assets, respectively, in European countries as explained in equation 3. In Europe, we include the former EU 28 member countries (EU27 + Great Britain). The shift is the level of the carbon tax in a European country. *Parent Country Controls* refer to the multinational firm's headquarter country's natural logarithms of GDP and population as well as the ratio of net FDI outflows to GDP. Standard errors account for spatial dependence in a linearly decreasing manner up to 500km (as discussed by Conley, 1999). * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Data Source: CO2 emissions are taken from EDGAR. The multinational firm unconsolidated asset data and corporate ownership panel data are from the BvD Orbis Generics flatfiles update as of February 2023. Carbon tax data are from the carbon pricing dashboard of the World Bank. Macroeconomic variables are based on data from the World Bank.

controlled for by our subsidiary fixed effects, this could still pose a threat to identification if the development in these countries differs systematically from other African countries over time. Similarly, varying trends in European countries could be of a concern, as European multinationals may be unequally exposed to the business cycle in countries that have adopted a carbon tax relative to countries that have not. Furthermore, even within the same country, they may be differentially affected by industry-specific developments.

In Panel B of Table 3 we address these potential concerns by examining the robustness of our results subject to the inclusion of different sets of fixed effects. We can see that the results are robust to including industry by year fixed effects. As can be seen from the first column, the inclusion of these fixed effects leaves the estimated coefficients virtually unchanged. To account for different trends in the parent country, we also try to control for a selection of macroeconomic variables in these countries. The results turn again out to be robust. To address the concern of varying trends across African regions, we include African region by time fixed effects. The point estimate is again unchanged. Finally, in our most restrictive specification, we include country by year fixed effects, which yields again very similar results. Overall, these results illustrate that our finding of carbon leakage effects within multinational firm networks is very robust and survives when controlling flexibly for potential time-varying confounders.

A final concern relates to the fact that our subsidiary locations are in certain parts of Africa quite concentrated, for instance because of the presence of industrial parks (see the top panel of Figure 1). This could again attenuate our estimates if treated and control (or more and less exposed) subsidiaries are located in close vicinity. To mitigate this concern, we exclude subsidiaries that are less than 7km apart from each other (the 90th percentile distance) apart from each other. Note that our the results are robust if we increase this threshold or if we do not drop any locations all together. These findings suggest that our results are not confounded by overlapping locations.

4.3 Within-firm Mechanisms

After documenting evidence consistent with multinational firms increasing emissions at African subsidiaries after the introduction of carbon tax in their European home countries on carbon emissions abroad, our aim is to shed more light on the within-firm mechanism to corroborate our findings. To this end, we exploit multinational firms' consolidated and subsidiary-level unconsolidated financial reporting data. We examine both investment in European countries and consolidated investment and overall emissions of multinationals affected by carbon taxes in our sample. Specifically, we focus on those multinationals that own the African subsidiaries included in our difference-in-difference specification in Section 4.1.

To this end, we estimate a specification akin to (4) for our sample of European subsidiaries. As outcomes, we look at fixed tangible assets, total assets and the number of employees. Furthermore, we compare the effect for subsidiaries that are located in European countries that have implemented a carbon tax to subsidiaries located in European countries that have no such tax in place.

Table 4: Firm-Level Exposure to European Carbon Taxes and Corporate Investment in Europe

	(1)	(2)	(3)	(4)	(5)	(6)
	All EU 28		Carbon Tax Countries		No Carbon Tax Countries	
Panel A	ln(Fixed Tan. Assets)					
Carbon Tax Exp. (FTanA)	-0.0037*	-0.0040*	-0.0042*	-0.0055**	-0.0031	-0.0022
	(0.0020)	(0.0024)	(0.0024)	(0.0024)	(0.0039)	(0.0040)
Obs.	41,539	41,528	23,809	23,806	17,730	17,722
Adj. R2	0.925	0.926	0.927	0.927	0.923	0.924
Panel B	ln(Total Assets)					
Carbon Tax Exp. (FTanA)	-0.0020	-0.0012	0.0004	-0.0014	-0.0010	-0.0011
	(0.0029)	(0.0027)	(0.0039)	(0.0043)	(0.0027)	(0.0025)
Obs.	71,618	71,606	45,307	45,305	26,311	26,301
Adj. R2	0.909	0.910	0.911	0.912	0.904	0.905
Panel C	ln(Employees)					
Carbon Tax Exp. (FTanA)	-0.0020**	-0.0018*	-0.0032**	-0.0027*	-0.0006	-0.0008
	(0.0010)	(0.0010)	(0.0015)	(0.0014)	(0.0012)	(0.0012)
Obs.	42,922	42,908	21,137	21,135	21,785	21,773
Adj. R2	0.949	0.950	0.947	0.948	0.951	0.951
Sub. FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes		Yes		Yes	
Year × Country FE		Yes		Yes		Yes

Notes: The dependent variable is logarithm of the the sample firms' subsidiary-level unconsolidated fixed tangible assets (Panel A), total assets (Panel B), or the number of employees (Panel C). Columns 1 and 2 include observations from subsidiaries in all former EU 28 (i.e., EU 27 and the Great Britain) countries, Columns 3 and 4 from EU 28 countries with carbon taxes in place during the sample period, and Columns 5 and 6 from EU 28 countries without carbon taxes in place during the sample period. The independent variable *Carbon Tax Exp.* is akin to a shift-share instrument measuring a firms' exposure to European countries' carbon taxes. The weight is constructed as a multinational firms' share of total European unconsolidated fixed tangible assets. The shift is the level of the carbon tax in a European country. For details, see equations 3 and 4. Standard errors are clustered at the multinational firm level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Data Source: The multinational firm unconsolidated subsidiary-level financial data and corporate ownership panel data are from the BvD Orbis Generics flatfiles update as of February 2023.

The results are shown in Table 4. We can see that subsidiaries of multinationals with a greater exposure to European carbon taxes reduce their fixed tangible assets in Europe significantly. Interestingly, this effect appears to be driven by a strong reduction of subsidiaries that are themselves located in carbon tax countries. This suggests that in response to an increase in the exposure to European carbon taxes, multinationals reduce their operations, particularly in countries that are directly affected by the regulation. The effect on total assets also tends to be negative but not significant. This is perhaps not too surprising, as total assets may also include assets that are not directly linked to the company's primary operational activities. On the other hand, fixed tangible assets are generally closely tied to the core operational activities of a business. Finally, we also document a significant fall in the number of employees of more exposed firms, which is again concentrated in countries that are directly affected by the regulation.

How do these results look at the consolidated level? Table 5 shows the results for the consolidated activity measures. We can see that the effects are largely insignificant. Coupled with the evidence on the fall in activity at European subsidiaries, this provides further, indirect evidence on carbon leakage. Some of the firms' operations are relocated outside Europe, leading to a fall in activity in Europe that is however not visible at the consolidated level. Coupled with our direct evidence from Section , this provides a strong case for the presence of carbon leakage in the context of European carbon taxes.

Table 5: Firm-Level Exposure to European Carbon Taxes and Consolidated Multinational Firm Activity

	Activity		
	ln(Fixed Tan. Assets)	ln(Total Assets)	ln(Employees)
Carbon Tax Exp. (FTanA)	0.0005	-0.0012	0.0006
	(0.0031)	(0.0019)	(0.0023)
Obs.	1,775	1,781	1,727
Adj. R2	0.949	0.984	0.968
Firm FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

Notes: The dependent variable is logarithm of the multinational firms' consolidated fixed tangible assets (Column 1), total assets (Column 2), or the number of employees (Column 3) for our main firms with consolisated financial data in Orbis. The independent variable *Carbon Tax Exp.* is akin to a shift-share instrument measuring a firms' exposure to European countries' carbon taxes. The weight is constructed as a multinational firms' share of total European unconsolidated fixed tangible assets. The shift is the level of the carbon tax in a European country. For details, see equations 3 and 4. Standard errors are clustered at the multinational firm level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.
Data Source: The multinational firm consolidated and subsidiary-level unconsolidated financial data and corporate ownership panel data are from the BvD Orbis Generics flatfiles update as of February 2023.

5 Carbon Leaks at the Macro Level

We have seen strong evidence for carbon leakage at the firm level. However, carbon leakage effects are not bound within firms. A natural question is thus: are these leakage effects also present at the macro level?

To this end, we estimate the impact of European carbon taxes on African emissions at the country level. We exploit the fact that African countries are exposed differently to European carbon taxes depending on how much they export to a country with a higher or lower carbon tax. The idea is that in a country with a relatively higher tax on CO2 emissions, it is costlier to produce carbon intensive commodities and, as a consequence, these commodities will be increasingly imported from abroad. This might happen either due to outsourcing or offshoring of production.

We construct a panel of 49 African countries, featuring data on different macro indicators such as GDP or populations and emissions.[7] The macro variables are from the World Bank while we source the emissions data again from EDGAR. To construct the exposure to European carbon taxes, we have collected data on European imports from African countries from Eurostat.[8]

An aggregate exposure measure. We employ again a shift-share design and construct the exposure measure in the following way:

$$w_{id} = \left(\sum_{t=1999}^{2009} \frac{\mathrm{EX}_{idt}}{\sum_{k \in K} \mathrm{EX}_{ikt}} \right) / 11, \tag{5}$$

where w_{it} is the exposure weight of country i in Africa to the carbon tax of country d in Europe at time t. It is calculated by dividing EX_{idt}, the value of exports of i to d at time t by the total value of exports of country i at time t to the set of European countries K we use. To mitigate the concern that this exposure may change in response to changes in regulation, we measure the weight as an average over eleven years prior to our sample.

To validate the instrument and to connect the macroeconomic analysis to our firm-level tests in Section 4.1, we also calculate an alternative exposure weight using the share of multinational firm subsidiaries operating in an African country i and headquartered in the respective European country d. For this exercise, we exploit the full sample of multinational firms with ownership data in the Orbis database.

Using these exposure weights, the shift-share instrument then takes the form:

$$Z_{it} = \sum_{d \in K} w_{id} \times \mathrm{ctax}_{dt}, \tag{6}$$

where ctax_{dt} is the carbon tax in European country d that is weighted by w_{id}. We can then estimate the impact of European carbon taxes on CO2 emissions in Africa for the years 2010 to 2019 in the following way:

$$\ln(\mathrm{CO2}_{it}) = \alpha_i + \delta_t + \mathbf{X}_{it}\theta + \beta Z_{it} + \epsilon_{it} \tag{7}$$

Here, $\mathrm{CO2}_{it}$ is the level of emissions of country i at time t as measured in tons of CO2, α_i are

[7]We do not include Western Sahara due to lack of data. Moreover, we exclude Sudan and South Sudan as it the latter country gained independence during our sample period.

[8]We focus on SITC-codes 2, Crude Materials, Inedible, Except Fuels, 3, Mineral Fuels, Lubric. And Related Mtrls., 5, Chemicals And Related Products, N.E.S., 6, Manufactured Goods Classif. By Material, 7, Machinery And Transport Equipment, and 8, Miscellaneous Manufactured Articles, as these are the most relevant for our question.

country fixed effects, δ_t are year fixed effects, $\boldsymbol{X}_{it}$ are a vector of control variables,[9] Z_{it} is the shift-share instrument, and ϵ_{it} is the error term.We are interested in the coefficient β which tells us how responsive emissions in Africa are to carbon taxation in Europe.

Table 6: Shift Share Regressions

	(1)	(2)	(3)	(4)
		ln(CO2 Country)		
Carbon Tax Exp. (Trade)	0.010**	0.010*		
	(0.005)	(0.005)		
Carbon Tax Exp. (Firms)			0.008*	0.010*
			(0.005)	(0.005)
ln(GDP)	0.296*	0.242	0.322*	0.257
	(0.175)	(0.183)	(0.171)	(0.177)
GDP Growth	0.000	-0.000	0.000	-0.000
	(0.001)	(0.001)	(0.001)	(0.001)
ln(Exports)	0.048*	0.068**	0.039	0.061**
	(0.026)	(0.027)	(0.025)	(0.027)
ln(Population)	0.384	0.648	0.262	0.593
	(0.483)	(0.555)	(0.492)	(0.518)
Obs.	473	473	473	473
Adj. R2	0.998	0.998	0.998	0.998
Country FE	Yes	Yes	Yes	Yes
Year FE	Yes		Yes	
Year × Region FE		Yes		Yes

Notes: The dependent variable is the natural logarithm of the level of total CO2 emissions in a country based on data from EDGAR. The sample consists of 49 African countries in the period 2010-2019. For our independent variable, we use a shift-share instrument where the weight is constructed as either the share of exports of an African country to a European country or the share of multinational firm subsidiaries operating in an African country that have their headquarter in a European country (for details see equation 5). In Europe, we include the EU27 + Great Britain. The shift is the level of the carbon tax in a European country. Standard errors are clustered at the country level. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. *Data Source*: CO2 emissions are taken from EDGAR. The trade shares are taken from Eurostat and the level of the carbon tax from the carbon pricing dashboard of the World Bank. Control variables are based on data from the World Bank.

Table 6 shows the results. The coefficient of the shift-share instrument is significant in all specifications. In column (1) and (3) we simply use a year fixed effect, and in column (2) to (4) we use a region-year fixed effect, where regions are defined as Northern, Western, Middle, Eastern or Southern Africa. In terms of economic magnitudes, we document that a unit increase in the level of the shift-share instrument increases pollution in a country by around 1%. The standard deviation of the instrument based on trade shares is around 2.2, it is around 3.9 based on firm shares. The magnitudes are thus comparable

[9]We include African country-level GDP Growth and the natural logarithms of GDP, Exports and Population. A concern with including controls for economic activity is that this activity could also be directly effected by European carbon taxes through Carbon leakage, leading to a bad controls issue. To mitigate this concern, we also estimate the regression without control variables. We obtain qualitatively similar results, but the coefficients are measured less precisely.

to what we estimate at the firm level. To give two examples for the case where we use trade shares - the instrument increased from 0.2 in 2013 to 3.1 in 2017 for Algeria; for Kenya, it increased from 1.01 to 2.7 over the same time period. This is to say that changes in the level of taxation do have a meaningful impact on CO2 emissions in Africa.

6 Conclusion

In this paper, we study the complex relationship between climate policies in developed countries and their spillover effects on the developing world. Specifically, we look into potential carbon leakage effects from Europe to Africa. Europe has introduced different policies to mitigate climate change, including the carbon market and national carbon taxes, providing interesting policy variation.

We document substantial leakage within multinational European firms' ownership networks. We find that subsidiary-level carbon emissions increase significantly when a parent becomes more exposed to European carbon taxes, indicating notable within-firm carbon leakage from Europe to Africa. We corroborate these findings using indirect evidence from consolidated financial data. In particular, we show that while multinationals that are more exposed to European carbon taxes reduce their operations in Europe, activity at the consolidated level remains largely unchanged – consistent with the existence of carbon leakage effects. We confirm these results at the macro level, where we document a significant increase in aggregate African emissions after an increase in the exposure to European carbon taxes. Our future work will aim to measure local economic outcomes in Africa, providing a deeper understanding of the mechanism and broader effects of carbon leakage. Our results will be crucial for policymakers to be able to design climate policies that are effective, equitable, and sensitive to the diverse needs of our global economy.

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Appendix

Carbon Leakage to Developing Countries

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This version: December 9, 2023

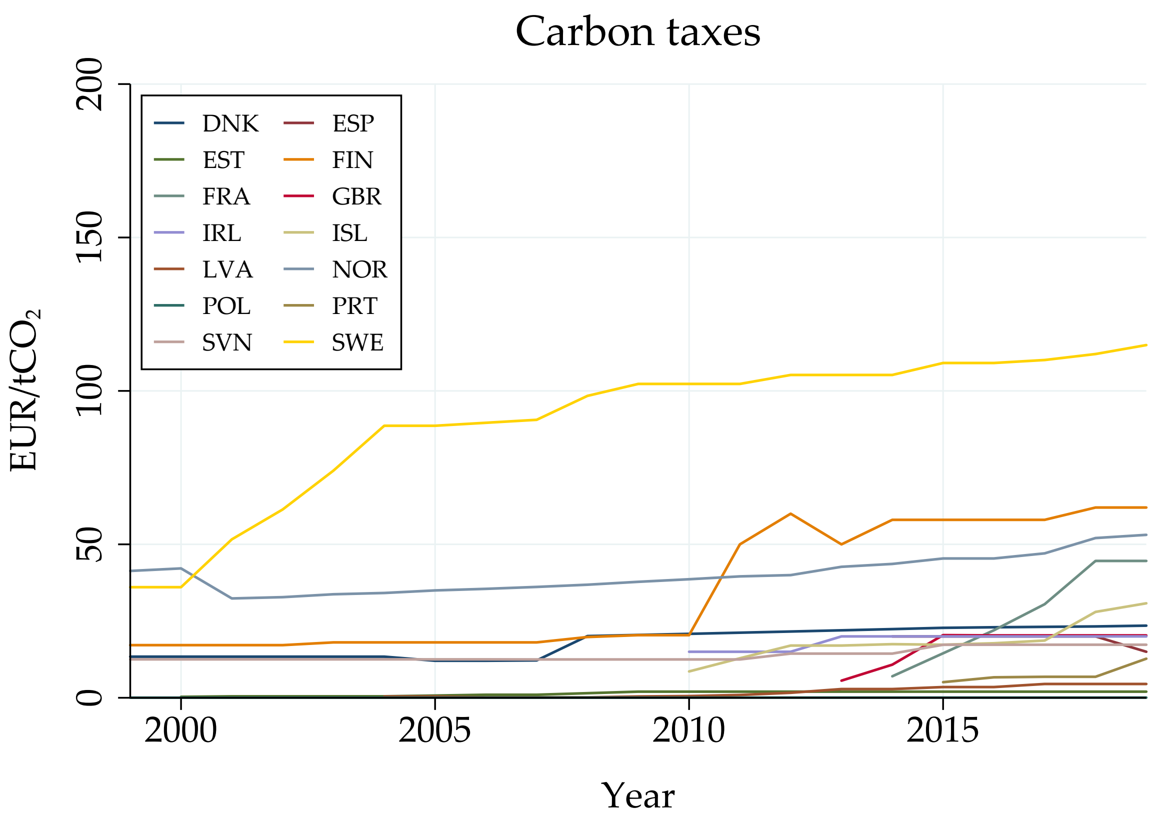
Table of Contents:

A Institutional Details

A.1 Carbon Taxes

Carbon taxes were first enacted in Europe with Finland leading the way in 1990. Following an early wave of carbon tax enactments primarily in the Nordic countries, more countries enacted carbon taxes and currently sixteen European countries have carbon taxes in place. Data on carbon taxes are available from the Worldbank. For more information, see also Metcalf and Stock (2023) and Konradt and Weder di Mauro (2021). Figure A-1 shows the evolution of carbon taxes in Europe. Importantly, not all European countries enacted a carbon tax and for the countries that have introduced one, there is a lot of heterogeneity in the timing. This variation is crucial for our event study and shift-share designs.

Figure A-1: Carbon taxes in Europe



Notes: This figure shows European carbon taxes in real 2018 euros. Data is taken from the carbon pricing dashboard of the World Bank.

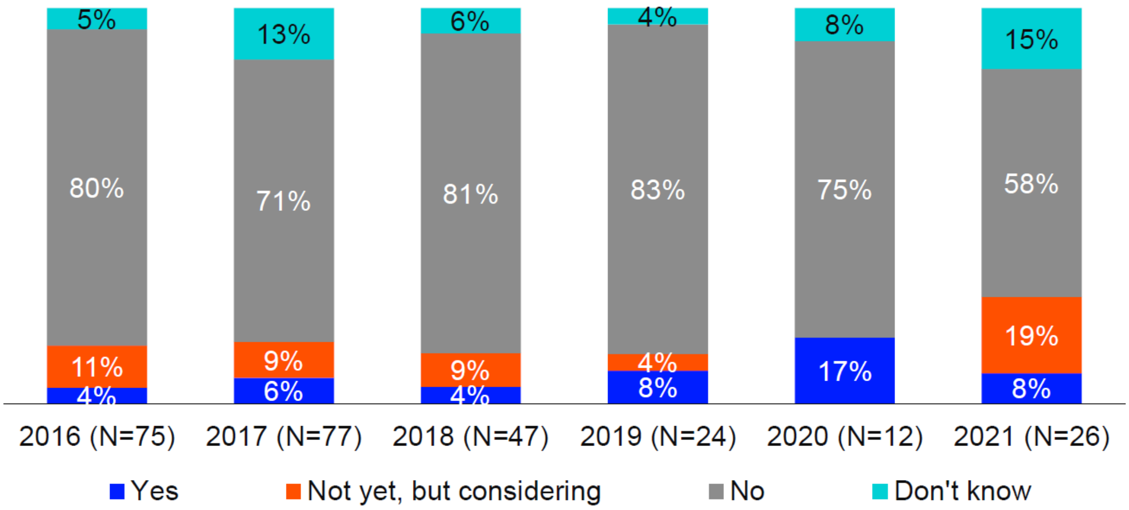
A.2 Carbon Leakage

As motivating evidence for the presence of carbon leakage we below present results from a survey conducted by Refinitiv. Clearly, offshoring business as a reaction to an increase in the price of emitting carbon is a consideration for firm executives.

Figure A-2: CARBON LEAKAGE: SURVEY EVIDENCE

Figure 1.9. Location effect

"Has your company moved operations/investments outside the EU ETS because of carbon costs?"*



* Until 2019 this question read: "Has your company moved production/activity outside the EU ETS because of carbon costs?"

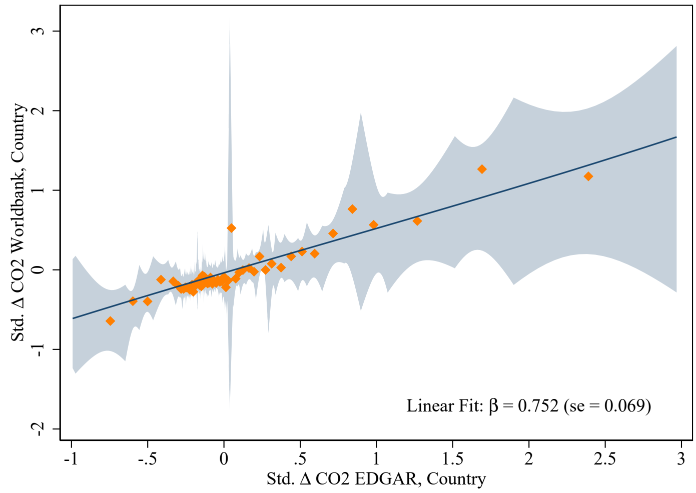
Source: Refinitiv

B Data - Details and Validation

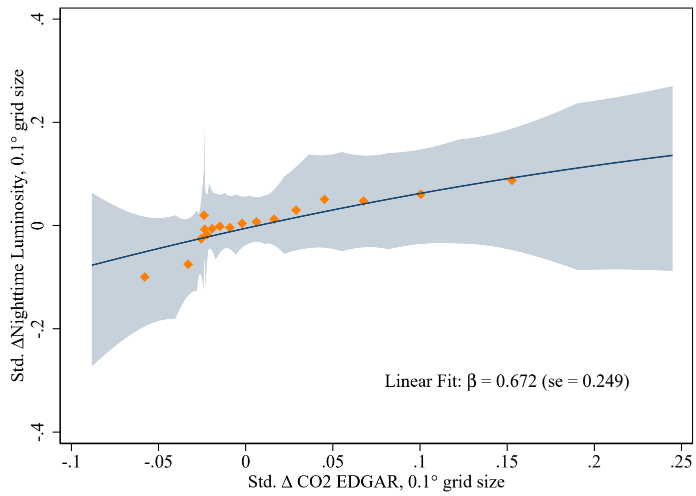
B.1 Validation of EDGAR CO2 Emissions Data

Figure A-3: VALIDATION OF EDGAR CO2 EMISSIONS DATA

(i) Correlation between EDGAR and Worldbank CO2 data at the Country Level



(ii) Correlation between EDGAR CO2 Emissions and Nighttime Luminosity at the Grid-Cell Level



Notes: This figure presents a binscatter plot illustrating the relationship between CO2 emission data from EDGAR and CO2 emission data from the Worldbank (Panel (i)) or measures of nighttime luminoisty (Panel (ii). We implement a binscatter least squares estimations with robust inference using the methodology proposed in Cattaneo et al. (2023). We use canonical binscatter options with a piecewise constant, adding the sample average of the standardized change in *CO2 EDGAR* within each bin to the grid of evaluation points. The number of bins is selected via the data-driven procedure described in Cattaneo et al. (2023). The shaded area represents a 95% confidence band, calculated using first-order polynomials. A third-order polynomial fit of the regression function is added to the binned scatter plot. We also report the results of a linear fixed effects regressions within the graph. In Panel (i), we regress the standardized annual change in country-level values in *CO2 EDGAR* on the standardized annual change in *CO2 Worldbank*, controlling for changes in the natural logarithm of country-level GDP and country and year fixed effects. Standard errors are clustered at the country-year level. We use a sample of 52 African countries with non-missing emissions data in both datasets from 1991-2019. In Panel (ii), we proceed analogously but use CO2 EDGAR emissions data at the 0.1×0.1 grid-size level for Sub-Saharan Africa (as in our main tests discussed in Section 4.1). we regress the standardized annual change in grid-cell-level values in *CO2 EDGAR* the standardized annual change in the same grid-cell-level nighttime luminosity measured by US Air Force Defense Meteorological Satellite Program (DMSP). We control for grid-cell and country-year fixed effects, and we drop observations with a standardized annual change of more than 1 standard deviation to mitigate the influence of extreme outliers likely reflecting measurement noise. Standard errors are clustered at the country-year level. We use a sample of approximately 30,000 unique grid cells in 51 Sub-Saharan African countries with non-missing information in both datasets from 2010-2019 as in our main tests.