# Pollution Havens? Carbon Taxes, Globalization, and the Geography of Emissions*

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**Abstract**

This paper studies the impact of national carbon taxes on $CO_2$ emissions. To do so, we run local projections on a cross-country panel dataset, matching measures of emissions of carbon dioxide with information on the introduction of carbon taxes and their implied price. Importantly, we consider both measures of *territorial* emissions — emissions emitted within a country's borders — and *consumption* emissions — emissions emitted anywhere in the world to satisfy domestic demand. We find that carbon taxes reduce territorial emissions over time, but have no significant effect on consumption emissions. Our estimates are robust to propensity-score weighting adjustments and are driven by countries which are more open to trade. Carbon taxes also lead to a modest increase in imports, suggesting that international trade may imply a negative carbon externality. Together, our findings highlight the limitations of national carbon taxes in isolation and the importance of international cooperation in reducing global emissions.

*JEL classification*: F18, F64, H23, Q58

*Key words*: carbon taxes, emissions, carbon leakage

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# 1 Introduction

Emissions of carbon dioxide ($CO_2$) are a key driver of climate change and a major threat to lives and livelihoods. While carbon emitted anywhere in the world has adverse environmental consequences for the entire planet, emissions of $CO_2$ vary widely across countries. Figure 1 shows that carbon emissions are considerably higher in some countries than others, even when taking in to account differences in population.[1] This is evident even within continents, including Europe (see Figure 2).

In response to the threat of climate change, governments around the world have introduced policies to reduce emissions of carbon, or at least slow their growth. How successful these policies have been remains an open question (Copeland, Shapiro, et al., 2022), especially as global carbon emissions continue to rise (see Figure 3). Amongst the menu of options policy makers face, carbon taxes have arguably garnered the most attention and are generally seen as an effective policy tool (Hassler et al., 2016). Skeptics, however, suggest that while carbon taxes may reduce emissions within their jurisdiction, the source of emissions may simply shift to locations in which they are not taxed, or taxed at a lower rate — known as "carbon leakage" (Copeland, Shapiro, et al., 2022).

In this paper we estimate the effects of national carbon taxes on emissions across countries and time. Importantly, we consider both measures of domestic — or, *territorial* emissions — as well as measures which also account for the emissions emitted abroad to satisfy domestic demand — or, *consumption* emissions. The difference in effects on these two types of emissions gives us an indication of whether carbon taxation spurs international carbon leakage. To further investigate this channel, we study how our estimates vary with openness to trade, as well as the impact of carbon taxes on imports.

Our estimates show that carbon taxation has a negative impact on territorial emissions over time, but no impact on consumption emissions. These results are largely driven by countries that are more open to trade, and we find some evidence that carbon taxation leads to an increase in imports. Together, these findings suggest that countries with carbon taxes

[1] Emissions patterns also vary widely when normalising aggregate emissions by GDP. While there are some differences, total emissions, emissions per capita, and emissions per unit of GDP are highly correlated across countries (see, for instance, de Silva and Tenreyro, 2021). In our analyses we control for both income and population to account for these differences.

may offset the reduction in territorial emissions by outsourcing the production of emissions, shifting their source without reducing demand for them, and contributing to carbon leakage. In turn, this implies a negative carbon externality at a global level.

Our empirical analysis is motivated by a number of stylized facts that we document in this paper. First, we show that trends in emissions vary widely across countries. In particular, emissions have been flat or falling in many advanced economies which have more stringent environmental policies, including more ambitious emissions reductions targets. In contrast, emissions have been rising in many emerging market economies, particularly in China and India. Next, we show that net imported emissions — or the difference between consumption and territorial emissions — also vary widely across countries. In particular, net imported emissions in economies with more ambitious emissions reduction targets are positive and have been growing, suggesting that emissions due to domestic demand are higher than emissions emitted within their boarders. In contrast, net emissions for many emerging market economies are negative and declining, suggesting that a large share of the emissions produced domestically are to satisfy foreign demand. A potential explanation for these patterns is that environmental policies, including carbon taxes, may be driving the sources of emissions from advanced to emerging market economies — the so-called "pollution haven" hypothesis.

Motivated by these stylized facts, we then turn to an empirical analysis of the impact of carbon taxes on emissions. We first build a panel dataset matching measures of territorial and consumption emissions with data on the timing and implied price of carbon taxes for a large sample of countries. In particular, our sample includes many emerging market and developing economies traditionally ignored in studies of emissions, and crucial for investigating the phenomenon of carbon leakage. We then estimate the dynamic effects of carbon taxation on emissions using panel local projection and controlling for all time and country-specific factors that impact emissions, as well as cross country differences in income and population.

Our estimates show that national carbon taxes have a negative, cumulative impact on territorial emissions of roughly 7% within 6 years of implementation. This corresponds to a roughly 0.1% reduction in emissions per implied USD price per ton of carbon. Our estimates of the impact of carbon taxes on consumption emissions, however, are much smaller in magnitude and are not significant at any conventional level of statistical significance, both for the implementation and implied price of taxation.

Carbon taxes are of course not randomly allocated across countries, but rather a policy tool implemented by national authorities. As such, the decision to impose a tax on carbon may be itself a function of a country's emissions. We address endogeneity concerns with our estimates in a number of ways. First, we show that trends in emissions prior to tax implementation are similar between countries that do and do not introduce carbon taxes. Second, we apply propensity score matching to our panel local projections in the form of inverse propensity score weighting (IPW) as in de Silva and Tenreyro (2021) and Jordà and A. M. Taylor (2016). IPW works, as all propensity score matching methods, by giving higher weights to observations based on their likelihood of being treated (introducing a carbon tax) inferred via select covariates. The aim of IPW is to give a higher weight to treatment and control observations which are more comparable in terms of observable characteristics. The pattern of results from our IPW estimations largely confirm the findings from our baseline model. The magnitude of our IPW estimated effects of carbon taxes on territorial emissions are nearly as large as our baseline estimates — a roughly 6% reduction within 6 years. Our IPW estimates also show no evidence of a significant effect of carbon taxes on consumption emissions.

Our findings of a significant, negative effect of carbon taxes on territorial emissions, but no effect on consumption emissions suggest that carbon taxation leads to some degree of carbon leakage. To investigate this potential mechanism further, we look to two additional analyses. First, we study how our results vary with openness to trade as countries which are more open to trade may be better able to shift emissions outside of their borders. We proceed by splitting our sample into countries with above median openness to trade (high openness to trade) and countries with below median openness to trade (low openness to trade) in each year. We then estimate our baseline model augmented with interaction terms to uncover any heterogeneous effects with trade openness. Our results suggest that there are significant differences. We find that countries with low openness to trade see a significant reduction in both territorial and consumption emissions following carbon tax implementation. In the aggregate, the effect on consumption emissions is masked by countries with high openness to trade which see no impact of carbon taxation. Second, we study how the implementation of a carbon tax affects total imports, as carbon leakage joined by a zero effect on consumption emissions should be reflected by an increase in imports. Though noisy, we find some evidence in support of this mechanism. Our estimates suggest that imports increase by 0.1% per implied US dollar price within four years after the introduction of a carbon tax.

This paper contributes to the existing literature in a number of ways. First, we add to the literature studying the effectiveness of carbon taxes. As emissions are a harmful externality of production, Pigouvian taxes following (Pigou, 1920) are typically seen as economists' preferred policy tool for reducing emissions (Baumol, 1972; Baumol and Oates, 1988; Hassler et al., 2016; Nordhaus, 1977). Notwithstanding concerns over their optimal price (Baumol and Oates, 1971), empirical evidence of the efficacy of carbon taxes is limited.[2] Studies, including Andersson (2019), de Silva and Tenreyro (2021), Känzig (2022), Kohlscheen et al. (2021), and Gilbert E. Metcalf (2019), generally find that carbon pricing via taxes or cap-and-trade systems has a negative impact on emissions. Common to all of these studies, however, is a focus on territorial emissions, rather than on the potential effects of carbon leakage. Further, most studies focus on a limited number of countries or regions. This paper fills these gaps in the literature, estimating the impact of carbon taxation on measures of both territorial and consumption emissions. We do so for a large panel of countries, including many emerging market economies, largely disregarded in the literature.

This paper also contributes to a literature linking international trade to climate change, summarized in a recent review by Copeland, Shapiro, et al. (2022). Copeland and M. S. Taylor (1994) and G. Grossman and Krueger (1993) provide the canonical models of trade and emissions, highlighting a number of channels through which international trade can affect the environment. Within this literature, the phenomenon of carbon leakage is well-defined. Simple pollution haven models, such as Copeland and M. S. Taylor (1995) and Hémous (2016), show that differences in the stringency of environmental policies can induce trade, with emissions intensive production occurring in the country with more lenient policies. Empirical evidence of carbon leakage remains limited, however. Some studies, including Aichele and Felbermayr (2012), Aichele and Felbermayr (2015), and Kellenberg (2009) argue that carbon leakage is an important and significant channel of emissions.[3] Others, including

[2] See Green (2021) and Köppl and Schratzenstaller (2022) for recent reviews.

[3] Kellenberg (2009) finds that the production of US multinational firms is higher in countries with less stringent environmental policies. Aichele and Felbermayr (2012) and Aichele and Felbermayr (2015) find that the imports of carbon emissions in countries that signed the Kyoto protocol rose following ratification.

Aldy and Pizer (2015), Branger and Quirion (2014), Levinson (2009), and Shapiro and Walker (2018), downplay the role of carbon leakage in shaping emissions trends across countries.[4] Yet most of this literature focuses on a limited number of countries or regions and few papers focus explicitly on carbon taxes as a driver of carbon leakage. To the best of our knowledge, this is the first paper to provide empirical evidence of carbon leakage from carbon taxes in a cross-country setting.

Our findings have a number of important policy implications. First, for environmental policy, our paper highlights the limitations of domestic policies and the need for international cooperation and coordination to mitigate global emissions (Ernst et al., 2023; Ferrari and Pagliari, 2021).[5] National carbon taxes will only have a meaningful impact if the production of emissions is unable to be costlessly reallocated across borders. Climate clubs, carbon border adjustments, or a global price on carbon may help to stem carbon leakage by eliminating cross-country differences in the marginal cost of emitting. Second, our results have more general macroeconomic implications via international trade. We show that carbon leakage shapes trade flows which can have implications for a broader set of economic policies.

The rest of this paper is structured as follows. Section 2 describes the data and the sample of countries considered. Section 3 presents a number of stylized facts of emissions which motivate our empirical analysis. Section 4 details the empirical model and section 5 presents our results. Section 6 concludes.

# 2 Data

We construct an annual panel dataset at the country level spanning the years 1991-2018. The dataset combines data on greenhouse gas emissions, carbon taxation, and trade with a broad set of country characteristics and macroeconomic variables. The sample includes 57 countries

[4] Levinson (2009) and Shapiro and Walker (2018) both find that reductions in pollution from US manufacturing over the last decades have been largely due to improvements in technology — or abatement processes — and that carbon leakage has played a smaller role. Similarly, Branger and Quirion (2014) argue that the increases in carbon-intensive imports in the US have been due to a large increase in imports from China that has been driven by other factors, including economic growth and decreasing trade costs, rather than environmental policies. Aldy and Pizer (2015) estimate the elasticity of US net imports in fuel-intensive industries to changes in US fuel prices. They then simulate the effects of a US carbon tax using their estimates, and find that carbon leakage would be minimal.

[5] Annicchiarico and Diluiso, 2019 also look at the presence of carbon taxes as a factor influencing the international transmission of shocks and policies in a DSGE model.

which together accounted for roughly 91% of global $CO_2$ emissions in 2018. Importantly, our dataset includes a relatively large number (29) of emerging and developing countries, in contrast to the bulk of the literature which largely focuses on advanced economies. A detailed overview of the data and their sources is provided in Table A1 in Appendix A. The countries included in the sample are listed in Table A2.

In our empirical analyses, we use data on emissions from the Global Carbon Project (GCP). The GCP publishes estimates of annual emissions of $CO_2$ based on long standing time series data generated by the Carbon Dioxide Information and Analysis Center and known as the CDIAC-FF. [6] The CDIAC-FF estimates emissions of $CO_2$ from the burning of fossil fuels, cement production, and gas flaring for nearly every country in the world, for some countries stretching back to the year 1751.[7] A detailed account of the data and the underlying methodologies is given in Andrew and G. Peters (2021), Friedlingstein et al. (2021), and Gilfillan and Marland (2021).[8]

Emissions data from the GCP offer the key advantage of distinguishing between *territorial* emissions — emissions emitted within a country's borders — and *consumption* emissions — emissions emitted outside of a country's borders that can be attributed to demand in the domestic economy. Conceptually, consumption emissions for country $i$ are given as the sum of territorial emissions in $i$ and the emissions emitted outside of $i$ to produce $i$'s imports (imported emissions), less emissions emitted due to the production of exports in $i$ (exported emissions).

$$\text{Consumption emissions}_i = \text{Territorial emissions}_i + (\text{Imported emissions}_i - \text{Exported emissions}_i) \tag{1}$$

In practice, consumption emissions in the GCP data are estimated by adjusting territorial emissions with estimates of net emissions transfers via international trade. Emissions are adjusted using environmentally extended input-output analysis (EEIOA) methods applied

[6] The Carbon Dioxide Information and Analysis Center (CDIAC) was originally housed at the U.S. Department of Energy's Oak Ridge National Laboratory. In 2017, the Department of Energy ceased support for the CDIAC. Since 2019, the CDIAC emissions data has continued to be generated and extended by researchers at Appalachian State University. The dataset is now commonly referred to as the CDIAC-FF.

[7] The CDIAC-FF draws on data of the consumption of fossil fuels from the United Nations Statistics Division and data from the United States Geological Survey for the production of cement. Emissions from land-use change are not included as data are not available in the necessary detail for all countries.

[8] See also https://www.globalcarbonproject.org/ and https://energy.appstate.edu/research/work-areas/cdiac-appstate

across countries.[9] The resulting allocations of emissions consider the emissions produced within supply chains and not only those contained in traded goods and services. Detailed overviews of the concepts and methods used to derive estimates of consumption emissions in the GCP data are presented in G. Peters et al. (2012) and G. P. Peters (2008).

The difference between a country's consumption emissions and territorial emissions are the net emissions imported by that country. When net imported emissions are positive, and consumption emissions are greater than territorial emissions in country $i$, country $i$ demands more emissions than what is produced within its borders. Based on these definitions, carbon leakage is reflected in an increase in net imported emissions, or a divergence in consumption and territorial emissions, due to environmental polices. This is the framework we apply when interpreting the results presented in Section 5.

Our data on carbon taxes are sourced from the World Bank's Carbon Pricing Dashboard as in Konradt and Weder di Mauro (2022), Laeven and Popov (2021), and Gilbert E Metcalf and Stock (2020). [10] These data contain information on the year of implementation of national carbon taxes around the world. In addition, the data contain estimates of the implied USD price per ton of carbon for each country and each year. On the basis of these data, we construct two policy variables. The first is a dummy variable equal to one if a country had a national carbon tax in a certain year, and zero otherwise.[11] The second is a continuous variable equal to the implied price from national carbon taxes per ton of carbon in each year in 2018 USD dollars, and zero otherwise. Importantly, the national carbon taxes in our data vary not only in their implied price, but also in the scope of emissions they cover. As such, our policy variables constitute a rough measure of carbon tax policy. Table A3 in Appendix A lists the carbon tax schemes included in our sample.

[9] See Kitzes (2013) for an overview of EEIOA.

[10] See https://carbonpricingdashboard.worldbank.org/

[11] The data from the World Bank's Carbon Pricing Dashboard also contain information on carbon taxes implemented in subnational jurisdictions, including a number of Canadian provinces and Mexican states. We exclude these carbon taxes when constructing our policy variables for a number of reasons. First, there are relatively few subnational carbon taxes. Second, the institutional background suggests that subnational carbon taxes are of secondary concern when studying national emissions patterns. In the case of Canada, most provincial carbon taxes were introduced shortly before the national carbon tax implemented in 2019. The British Columbia carbon tax introduced in 2008 is an exception, studied in Gilbert E. Metcalf (2019). Though it is Canada's third largest province, BC only accounted for a small share of Canada's total $CO_2$ emissions in 2005 (8.6%; see Environment and Climate Change Canada (2022)), due to the smaller share of fossil fuel related industries in the province. In the case of Mexico, the national carbon tax introduced in 2014 preceded the subnational carbon taxes introduced in Baja California, Tamaulipas, and Zacatecas.

Table 1 provides basic descriptive statistics of our sample in 2018. The table displays the sample mean of a number of key variables of interest in 2018. Column 1 displays the means for all countries in the sample. Column 2 displays the means for countries which had implemented a carbon tax prior to 2018 and column 3 displays the means for countries which did not. Column 4 displays the p-value from a two-sided t-test of equality of means between columns 2 and 3. The table shows that countries which implement a carbon tax tend to be somewhat smaller in population, higher income, more likely to be an advanced economy, and have lower emissions in both absolute and per capita terms. A simple t-test shows that none of the differences in sample means are significant at any conventional level of statistical significance, however.

# 3 Stylized Facts of Emissions Patterns

In this section we present a number of stylized facts describing patterns of $CO_2$ emissions across countries. The facts presented here motivate the empirical analysis which follows in Sections 4 and 5.

Our first set of stylized facts document developments in emissions over time. Figure 4 plots trends in territorial emissions of $CO_2$ between 1990-2018 for select countries from our sample. Panel 4(a) plots trends for a number of countries listed in Annex B of the Kyoto Protocol.[12] The trends show that territorial emissions in most Annex B countries have remained relatively flat or have fallen over the last three decades. Panel 4(b) plots trends for a number of major emitters not listed in Annex B of the Kyoto Protocol. The trends show that territorial emissions have increased in many non-Annex B countries, in particular in China and India. Together, the data show that (i) trends in emissions vary widely across countries and (ii) are plausibly related to the binding emissions reductions targets set by countries in the Kyoto agreement.

In terms of the total amount of emissions demanded by each country, the trends plotted in Figure 4 only tell part of the story. That's because some countries account for greater emissions than what their territorial emissions suggest, while others account for less. Figure 5 plots trends in net imported emissions — or the difference in emissions between consumption

[12]The countries listed in Annex B of the Kyoto protocol had pledged to meet binding emissions reductions targets following ratification.

and territorial emissions. A value above zero indicates that the country if a net importer of emissions, while a value below zero indicates that the country is a net exporter of emissions.

The trends in Panels 5(a) and 5(b) show that net imported emissions are positive in many Annex B countries, while they are negative in many non-Annex B countries. Further, the data show that net imported emissions have largely been rising in many Annex B countries and falling in many non-Annex B countries, in particular China and India. Together, these figures suggest that the source of global $CO_2$ emissions has shifted over the past three decades from economies with stricter environmental protection policies towards economies with more lenient policies.

# 4 Model

To estimate the dynamic effects of carbon pricing on emissions of $CO_2$, we consider the following model following the local projections method introduced by Jordà, 2005, and adapted for panel data in Jordà and A. M. Taylor, 2016,

$$\log(CO2_{i,t+h}) - \log(CO2_{i,t}) = \alpha_i^h + \delta_t^h + \varphi^h \Delta \log(CO2_{i,t}) + \beta^h \tau_{i,t} + X'_{i,t}\gamma^h + \epsilon_{it}^h \qquad (2)$$

We estimate (2) over horizons $h = 1 \ldots H$ via OLS. $\log(CO2_{i,t+h})$ is the log of carbon dioxide emissions for country $i$ in year $t+h$. The cumulative changes in log emissions on the left hand side are taken from the year of implementation as we assume that impacts will first be felt starting in the following year as taxes are typically liable with a delay. $\alpha_i^h$ are country fixed effects and $\delta_t^h$ are time fixed effects. $\tau_{i,t}$ is our main policy variable of interest capturing the taxation of carbon. $X_{i,t}$ is a vector of time-varying control variables including log GDP per capita, log GDP per capita squared, and population. We include the square of log real GDP per capita to allow for nonlinear effects of income on emissions — the so-called Environmental Kuznets curve.[13] To align our baseline model with the local projections framework advocated by Cloyne et al. (2023) that we turn to later, the covariates, $x_{i,t}$, included in $X_{i,t}$ are de-meaned and enter the vector of controls as $(x_{i,t} - \bar{x}_i)$. $\epsilon_{it}$ is the error term clustered at the country level, the level of treatment in our setting.

[13]Evidence on the existence of the Environmental Kuznets curve is mixed. Xepapadeas (2005) provides a review. Most empirical studies do tend to find evidence of a positive, but decreasing effect of income on emissions (Frankel and Rose, 2005; G. M. Grossman and Krueger, 1995; Stern, 2017).

We estimate (2) for both territorial and consumption emissions, and consider two different policy variables. The first is a dummy variable equal to one if country $i$ had a tax on carbon at any point in year $t$ and zero otherwise. The dummy variable therefore takes the value of one in the year the carbon tax was implemented, even if the tax was only implemented part way through the year. The second is a continuous variable equal to the price per ton of carbon in 2018 US dollars implied by the carbon tax. This variable takes the value of zero for countries that did not have a tax on carbon. $\beta^h$ is our main parameter of interest capturing the effect of carbon pricing on emissions at horizon $h$. Estimates of $\beta^h$ represent the cumulative percent change in emissions given a one unit increased in the policy variable, relative to the year of carbon tax implementation.

# 5 Results

## 5.1 Dynamic Effects of Carbon Taxation on Emissions

Figure 6 plots the impulse response functions from equation (2) capturing the dynamic effect of carbon tax implementation on territorial and consumption emissions. Tables of the underlying estimates are available in Appendix B. The estimates in Panel 6(a) show that carbon taxation has a negative impact on territorial emissions that increases over time and is significant at the 10% level. The estimated cumulative effect stabilizes around 6 years after tax implementation and corresponds to a roughly 7% reduction in territorial emissions relative to the year of introduction. This estimate is somewhat smaller in magnitude, but comparable to those found in the literature (de Silva and Tenreyro, 2021).

The estimates plotted in Panel 6(b) depict the impulse response function of carbon taxation on consumption emissions. The figure shows that, while the estimated impact is negative, it is smaller in magnitude than the impact on territorial emissions and not significant at the 10% level. As the horizon increases, the estimated impact becomes somewhat more negative, but does not attain statistical significance at any conventional level. Comparing the results across Panels 6(a) and 6(b) suggests that the negative effect of carbon taxes on emissions disappears once we allocate emissions to the country in which demand for them occurs.

Figure 7 plots impulse response functions of territorial and consumption emissions to the implied price per ton of carbon from carbon taxation in 2018 US dollars. The estimates in

Panel 7(a) show that territorial emissions are negatively and significantly impacted by the price of carbon. The estimated impact stabilizes around 4 years after the implementation of carbon taxation and corresponds to a roughly 0.07% reduction in emissions per dollar of carbon pricing relative to emissions in the year of introduction. These estimates are comparable to those found in the literature (Kohlscheen et al., 2021). The estimates plotted in Panel 7(b) depict the impact on consumption emissions. As with the results considering the carbon tax dummy, the estimates show that the impact of the implied price of carbon on emissions is lower when we allocate emissions to the country in which demand for them occurs. The estimated impact on consumption emissions per USD price of carbon is lower than that for territorial emissions and statistically insignificant across the considered time horizon.

Together, these results show that while carbon taxation has a negative effect on the emissions emitted within a country's borders — and subject to taxation — the emissions emitted to satisfy domestic demand are unaffected. These findings suggest that carbon taxes may lead to some degree of carbon leakage as net imported emissions increase to leave consumption emissions unaffected while territorial emissions decrease.

## 5.2 Addressing Endogeneity

Carbon taxes are of course not randomly allocated across countries, but rather implemented following the decisions of national authorities. As such, there may be reason to believe that the policy variable in equation (2) is endogenous, and estimates of $\beta^h$ do not have a causal interpretation. This may be the case if carbon emissions themselves have an effect on the decision of authorities to introduce carbon taxes.

We address this concern in two ways. First, we evaluate trends in emissions prior to carbon tax implementation. Significant differences in pre-implementation, or pre-treatment, emissions trends may hint at emissions being an important determinant of the decision to introduce a carbon tax. Evidence of divergent pre-trends would cast doubt on the validity of our identifying assumption that carbon taxes are exogeneous to emissions. To study pre-trends in emissions, we estimate (2) over *backward-looking* horizons, $h = -1 \cdots - 4$. Figure 8 plots these results. Panels 8(a) and 8(b) show the backward-looking impulse response functions of territorial and consumption emissions respectively when the policy variable is the carbon tax dummy variable. Panels 8(c) and 8(d) show the analogue when the policy variable is implied price of carbon. The estimates of $\beta^h$ over the backward-looking horizons we consider are close to zero and not statistically significant in all panels of Figure 8. These results show that trends in territorial and consumption emissions were not significantly different between countries that did and did not implement carbon taxes prior to implementation. This suggests that trends in emissions were not a significant determinant of the decision to introduce carbon taxes.

In a second approach to addressing endogeneity concerns with our estimation strategy, we apply the Inverse Propensity Weighting (IPW) method to our local projections model following Jordà and A. M. Taylor, 2016. Specifically, we first estimate the following probit model

$$\bar{\tau}_i = \rho \Delta \log(CO2_i) + X_i' \theta + \nu_i \tag{3}$$

$\bar{\tau}_i$ is an indicator variable equal to one if country $i$ had a carbon tax in any year during our sample period, 1991-2018, and zero otherwise. $\Delta \log(CO2_i)$ and $X_i$ are the change in territorial emissions and the vector of controls from equation (2) in the year a carbon tax was first introduced.[14] If country $i$ did not have a carbon tax between 1991-2018, $\Delta \log(CO2_i)$ and $X_i$ are the change in territorial emissions and the vector of controls from 2018. $\nu_i$ is the error term.

We then use the estimated parameters from equation (3) to calculate predicted values — or propensity scores — for the policy variable, $\hat{\bar{\tau}}_i$. These propensity scores capture the predicted likelihood that country $i$ introduced a carbon tax during our sample period, given emissions growth and the vector of controls. With these propensity scores, we construct inverse propensity score weights for each country $i$ as follows,

$$IPW_i = \left( \frac{\bar{\tau}_i}{\hat{\bar{\tau}}_i} \right) + \left( \frac{1 - \bar{\tau}_i}{1 - \hat{\bar{\tau}}_i} \right) \tag{4}$$

IPW gives a higher weight to countries the more their chosen carbon tax policy (either introducing a carbon tax or not) diverges from that country's predicted carbon tax policy using (3).[15]

[14] With Finland and Poland we have two countries in our sample which introduced carbon taxes prior to the start of our sample period (in 1990 in both countries). For these countries, $\Delta \log(CO2_i)$ and $X_i$ are the change in territorial emissions and the vector of controls in 1991.

[15] Since we estimate panel local projections and include country fixed effects in equation (2), our propensity score weights need to be constant within country. As such, our probit model in equation (3) is run at the

Causal identification of the average treatment effect using propensity score matching methods requires the assumption that subjects have a positive probability of being either in the treatment or control groups (the "positivity" assumption). To evaluate this assumption in our setting, we plot the distribution of calculated propensity scores for countries in our sample that implement a carbon tax (the treated) and those that do not (the controls) in Figure 9. Unsurprisingly, the distribution of propensity scores for the treated lies to the right of the distribution for the control countries. The distributions, however, exhibit significant overlap suggesting that the positivity assumption is reasonably satisfied in our setting.

Figure 10 plots the IPW impulse response functions of carbon tax implementation on emissions from equation (2). Tables of the underlying estimates are available in Appendix B. The IPW estimates in Panel 10(a) show that carbon taxation is still estimated to have a negative impact on territorial emissions. The estimated impact increases in magnitude over time and is significant at the 10% level. The estimated cumulative effect stabilizes around 5 years after policy implementation and corresponds to a roughly 6% reduction in emissions — somewhat smaller in magnitude than the non-weighted estimates presented in Section 5.1. Panel 10(b) shows that the estimated impact on consumption emissions remains small in magnitude with IPW and is not significantly different from zero at conventional levels of statistical significance. Together, these results confirm the main finding that the negative impact of carbon taxation on emissions seems to disappear once emissions are allocated to the country in which demand for them occurs.

## 5.3 Does Trade Openness Matter?

One factor which may drive the results shown in Sections 5.1 and 5.2 is openness to trade. Countries that are more open to trade may be better able to shift emissions outside of their borders while leaving consumption emissions unaffected. Countries that are less open to trade may be less able to increase net imports of emissions following tax implementation and see a reduction in both territorial and consumption emissions.

To investigate this possible heterogeneity in our results, we augment our model in (2) following the state-dependent local projections framework developed by Cloyne et al. (2023). The model we consider takes the following form

country level.

$$\log(CO2_{i,t+h}) - \log(CO2_{i,t}) =$$
$$\alpha_i^h + \delta_t^h + \varphi^h \Delta \log(CO2_{i,t}) + \beta^h \tau_{i,t} + X'_{i,t}\gamma^h + \tau_{i,t}X'_{i,t}\xi^h + \mu^h TO_{i,t} + \lambda^h \tau_{i,t} TO_{i,t} + \epsilon_{it}^h \quad (5)$$

$TO_{i,t}$ is a dummy variable equal to one if country $i$ had a level of trade openness (the sum of imports and exports divided by GDP) greater than the sample median in year $t$, and zero otherwise. We label countries with above median openness to trade as "high" openness to trade countries, and countries with openness to trade at or below the median as "low" openness to trade countries. The remaining variables are defined as in equation (2). $\lambda^h$ is our parameter of interest which captures the differential impact of carbon taxation on emissions by openness to trade at horizon $h$.

The framework developed by Cloyne et al. (2023) offers a simple way of decomposing impulse response functions and resolves estimation biases often encountered in the literature on state-dependent local projections. By interacting our policy variable not only with our state of interest, but also with the other covariates included in the model, we allow for heterogeneity across multiple state dimensions, limiting potential omitted variable bias. The framework also makes clear the limitations to inference when the policy variable and the state variable of interest are jointly determined. In our setting, however, we believe that there is little cause for concern that trade openness and carbon taxes are jointly determined. Trade openness is a slow moving macroeconomic variable — not a direct policy variable — influenced to an important extent by geography (Alesina and Wacziarg, 1998). To support our assertion, we look to two exercises. First, we estimate our baseline model in (2), replacing emissions outcomes with trade openness. The estimates presented in Figure 11 show that carbon taxation has no meaningful effect on trade openness over the horizon that we consider. This suggests that, while the effect of carbon taxation on emissions may be moderated by trade openness, it does not have an indirect impact via an effect on trade openness. Second, we regress our carbon tax policy variables on trade openness, including time and country fixed effects. This exercise asks whether trade openness is a significant determinant of carbon tax policy. The results resented in Table 2 suggest it is not. Within countries, trade openness has neither a significant impact on the propensity to implement carbon taxes nor on their implied price.

Figure 12 plots the main results of our estimates of equation (5) where the policy variable is a dummy variable equal to one if a country has a carbon tax and zero otherwise. The blue circles plot point estimates of the effect of carbon taxation on emissions for countries with low openness to trade. The red squares plot estimated effects for countries with high openness to trade.[16] The impulse responses plotted in panel 12(a) show that both high and low openness to trade countries see a similar reduction in territorial emissions following carbon tax implementation. The estimated effect is somewhat less for countries that are more open to trade, yet this difference is not significant at the 10% level (see Figure B1 in Appendix B). Panel 12(b) plots estimated effects on consumption emissions. Starting around 4 years after the introduction of a carbon tax, the impulse response functions diverge for countries with high and low openness to trade. Low openness to trade countries exhibit a significant, negative effect of carbon taxation on consumption emissions, in line with the estimated impact on territorial emissions. High openness to trade countries, however, exhibit no significant impact of carbon taxation on consumption emissions. These differences are significant at the 10% level starting 6 years after the introduction of a carbon tax (see Figure B1 in Appendix B). To the extent that countries more open to trade are easier able to offset reductions in territorial emissions via international trade, our results suggest that trade may act as a conduit for carbon leakage across borders following the implementation of carbon taxes.

### 5.4 Dynamic Effects of Carbon Taxation on Imports

The results presented in the previous sections suggest that carbon taxes may lead to some degree of carbon leakage. Over time, carbon taxes reduce the production of territorial emissions yet have no impact on consumption emissions. This implies that the production of emissions is reallocated across borders following the introduction of carbon taxes. These findings are driven in particular by countries which are more open to trade suggesting that trade may play a role in facilitating carbon leakage. Further evidence of carbon leakage via international trade may be found by looking at the impact of carbon taxes on imports. A positive impact of carbon taxes on imports might be a further indication of net imported emissions offsetting

[16]The effects for low openness to trade countries are captured by estimates of the parameter $\beta^h$ over the horizons $h = 1 \dots H$ from the model in equation (5). The effects for high openness to trade countries are captured by the sum of the estimates $\beta^h$ and $\lambda^h$. Both series of estimates are surrounded by 90% confidence intervals represented by the solid lines of the same colour. Full sets of estimates are presented in Table B5 in Appendix B while Figure B1 plots estimates of $\beta^h$ and $\lambda^h$ separately.

reductions in territorial emissions. Indeed, the literature offers some evidence of this effect (Broner et al., 2012; Ederington and Minier, 2003). To investigate this channel further, we estimate (2), replacing emissions of $CO_2$ with total real imports of goods in 2018 US dollars.

Figure 13 plots estimates of the dynamic effects of carbon taxation on imports. The estimates plotted in Panel 13(a) show the estimated effects for the carbon dummy policy variable. The results, while noisy, provide some evidence that carbon taxes lead to an increase in imports. The cumulative impact of carbon taxes on imports is found to increase over time, yet the estimates are imprecise. Only 8 years after the introduction of carbon taxes is the estimated effect significant at the 10% level. The point estimate suggests that carbon taxation leads to a cumulative increase in imports of around 26% after 8 years. This amounts to an average annual increase in imports of roughly 3.25% compared to the year the carbon tax was introduced.

Panel 13(b) shows the estimated dynamic effects of the carbon price policy variable on real total imports. The results paint a similar picture to those in Panel 13(a). Namely, the price of carbon is associated with an increase in imports over time, yet the estimated impulse response function is not statistically significant at any conventional level of significance. In terms of magnitude, the point estimates stabilize around 5 years after the introduction of carbon taxes and suggest that imports are estimated to rise by just over 0.1% per implied US dollar price of carbon. The imprecise nature of our estimates is perhaps not surprising, given the course nature of international trade statistics. Our data on imports only capture the value of goods imported, and ignore the emissions contained within these. Studying the impacts of carbon taxes on the emissions contents of imports, and imports by origin seems like a fruitful path for future research.

# 6 Conclusions

The threat of climate change has led to the introduction of national carbon taxes in an effort to mitigate emissions of $CO_2$. Yet the efficacy of carbon taxes remains unclear, particularly when the production of emissions can be shifted across borders to locations where they are not subject to taxation, or taxed at a lower rate. This paper estimates the effects of national carbon taxes on emissions. Importantly, we estimate the impact on country level emissions measures which take into account foreign emissions emitted to satisfy domestic demand. We find that, over time, carbon taxes reduce emissions emitted within a country's borders but have no significant effect on total emissions attributed to domestic demand. These results are driven by countries that are more open to trade. We also find some evidence that carbon taxation leads to an increase in imports. Together, our results suggest that international trade may act as a conduit for reallocating the production of emissions away from carbon taxation — known as carbon leakage.

This paper has a number of important policy implications. For environmental policies aimed at mitigating global emissions, our findings suggest that national carbon taxes will only have a meaningful impact in reducing global emissions if emissions cannot be costlessly shifted across borders. Our results highlight the need for international cooperation and coordination to increase the marginal cost of emitting — regardless of location. Climate clubs, carbon border adjustments, or a global price on carbon could help to stem international carbon leakage from national carbon taxes. Our results also highlight some of the lesser-known side effects of carbon taxes, including potential effects on trade flows which carry implications for a broader set of economic policies. When designing effective environmental policies, policy makers should look to consider these effects while seeking to mitigate carbon leakage.

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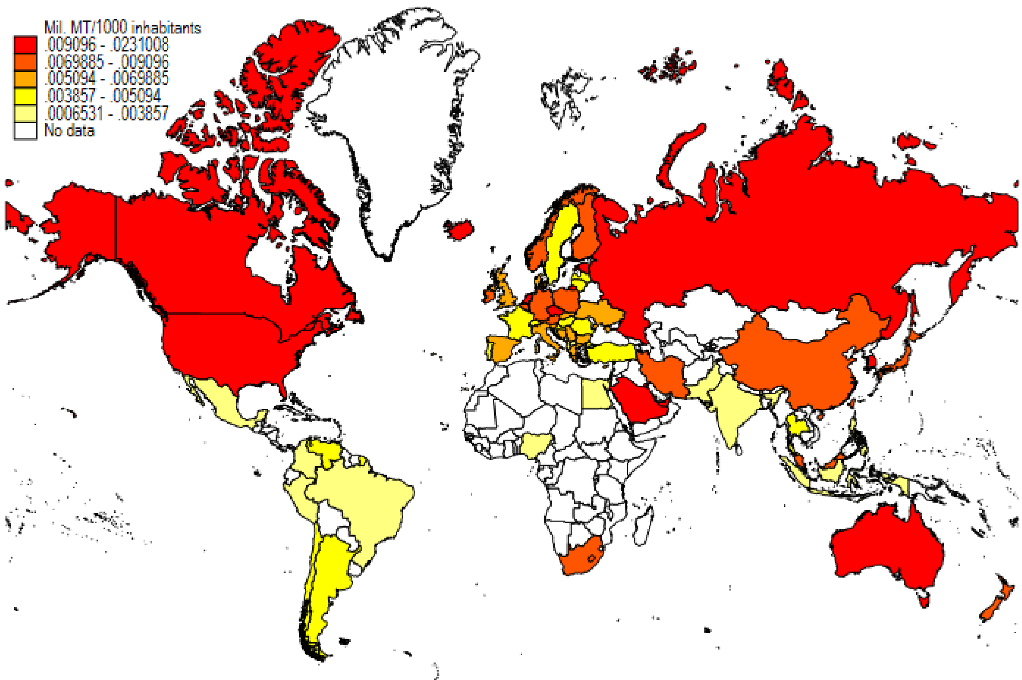
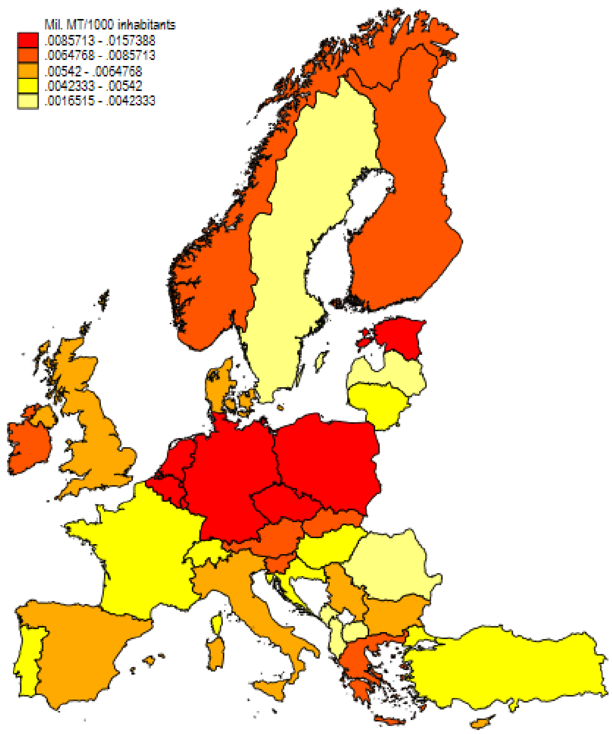
Figure 1: Carbon Dioxide ($CO_2$) Emissions per capita, 2018



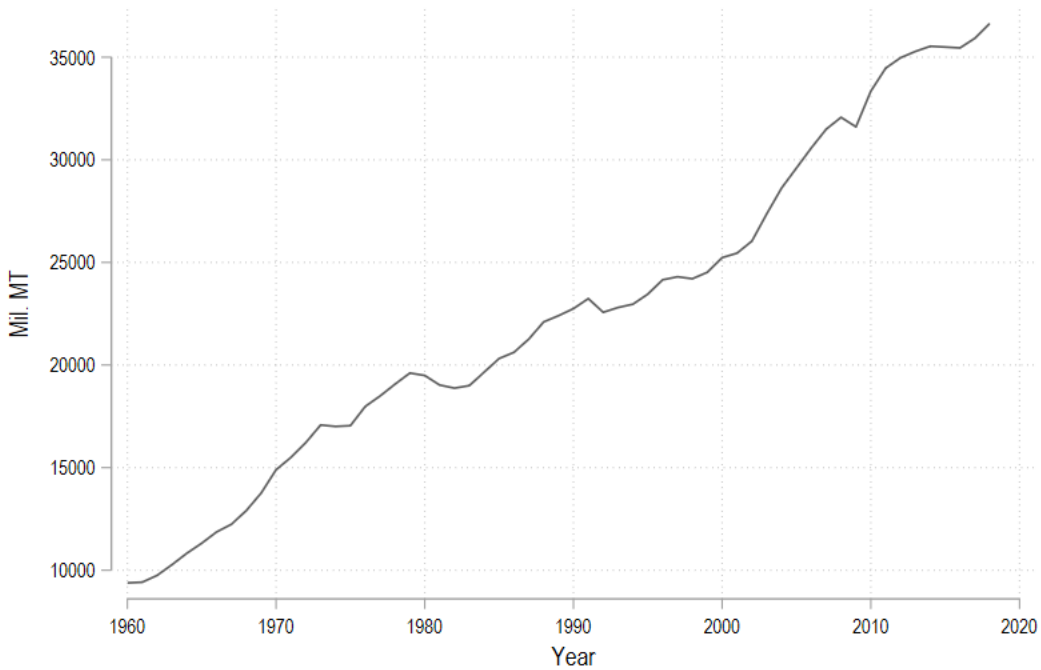

Notes: This figure depicts total territorial emissions of carbon dioxide per capita. Countries with missing data are coloured white. Data on emissions are sourced from the Global Carbon Project. Data on population are sourced from the World Bank.

Figure 2: Carbon Dioxide ($CO_2$) Emissions per capita, 2018




Notes: This figure depicts total territorial emissions of carbon dioxide per capita. Countries with missing data are coloured white. Data on emissions are sourced from the Global Carbon Project. Data on population are sourced from the World Bank.

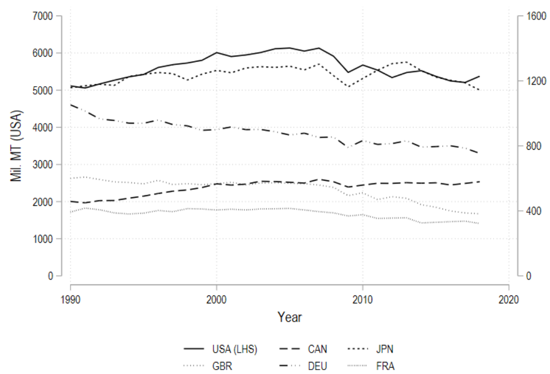
Figure 3: Global Carbon Dioxide ($CO_2$) Emissions, 1960-2018



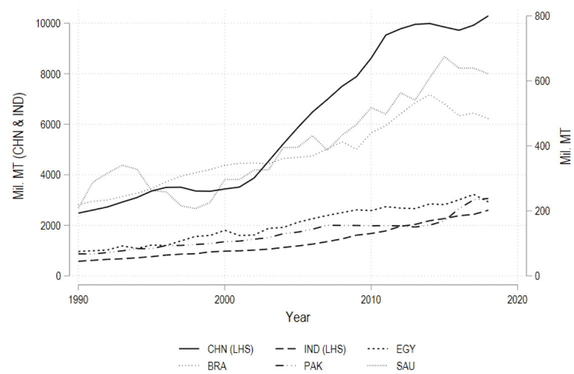

Notes: This figure depicts total global emissions of carbon dioxide in millions of metric tons. Data on emissions are sourced from the Global Carbon Project.

Figure 4: Trends in Territorial $CO_2$ Emissions, 1990-2018

(a) Annex B Countries




(b) Non-Annex B Countries

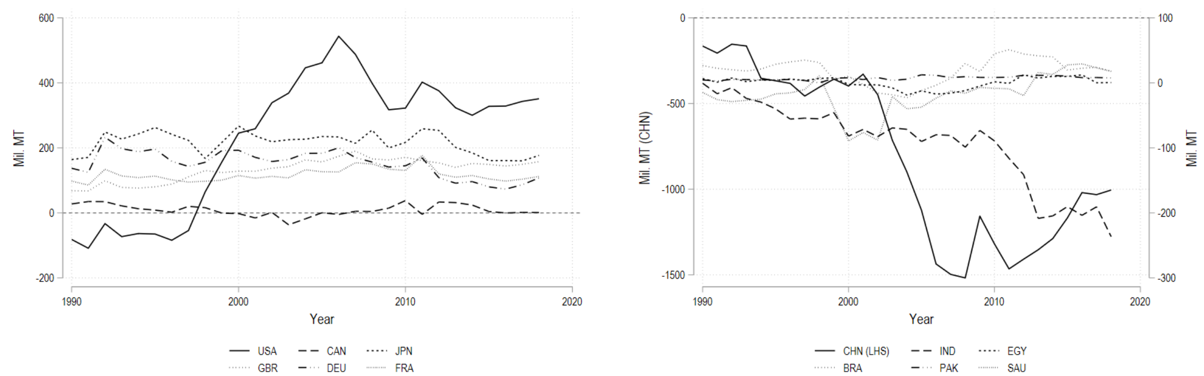



This figure plots trends in territorial emissions of $CO_2$ between 1990-2018. Panel 4(a): territorial emissions for select countries listed in Annex B of the Kyoto Protocol. Panel 4(b): territorial emissions for select countries not listed in Annex B of the Kyoto Protocol. Canada and Japan both withdrew from the Kyoto agreement, but not until 2011 which is why we assign them to the "Annex B" group.

Figure 5: Trends in Net $CO_2$ Emissions, 1990-2018

(a) Annex B Countries

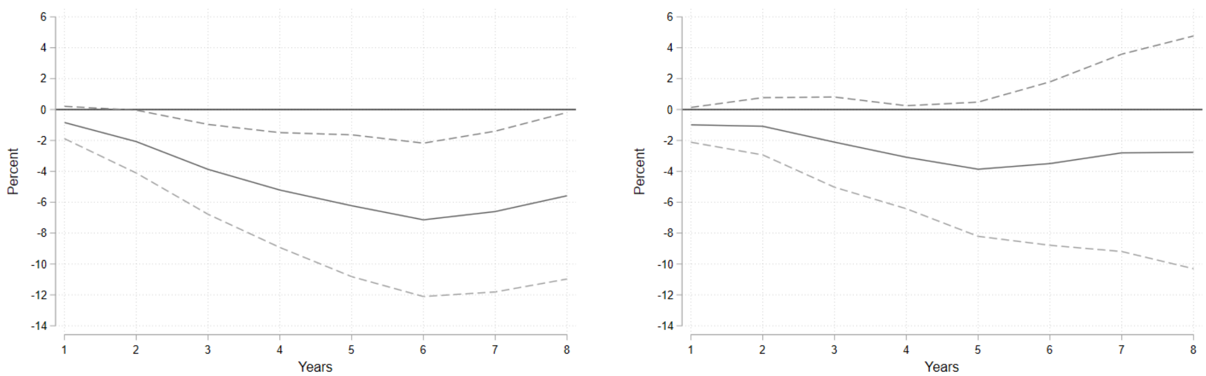
(b) Non-Annex B Countries




This figure plots trends in net imported emissions of $CO_2$ between 1990-2018. Panel 4(a): net imported emissions for select countries listed in Annex B of the Kyoto Protocol. Panel 4(b): net imported emissions for select countries not listed in Annex B of the Kyoto Protocol. Canada and Japan both withdrew from the Kyoto agreement, but not until 2011 which is why we assign them to the "Annex B" group. Net imported emissions are defined as the difference between consumption emissions and territorial emissions. A value above zero indicates that emissions accounted for by domestic demand were higher than those produced within the country.

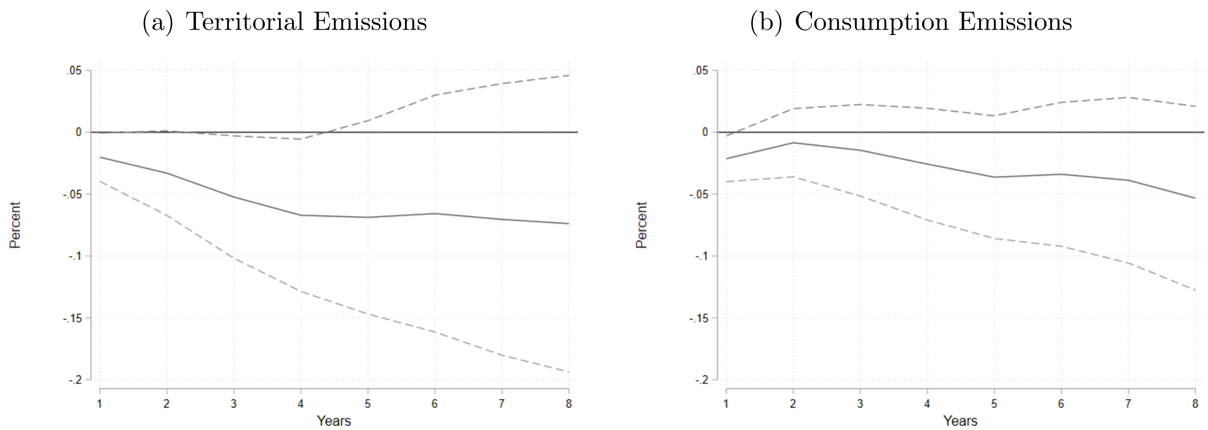
Figure 6: Dynamic Effects of Carbon Taxation on Emissions

(a) Territorial Emissions (b) Consumption Emissions




Notes: This figure plots impulse response functions capturing the dynamic effects of carbon tax implementation on territorial (a) and consumption (b) emissions from model (2) estimated via OLS. The distinction between territorial and consumption emissions is described in detail in Section 2. The solid line plots estimates of $\beta^h$ for each horizon where the policy variable, $\tau_{i,t}$, is a dummy variable equal to one if a country has a carbon tax in a particular year and zero otherwise. The dashed lines represent 90% confidence intervals where the standard errors have been clustered at the country level (the level of treatment). The sample consists of 57 countries between the years 1991-2018 as described in Section 2.

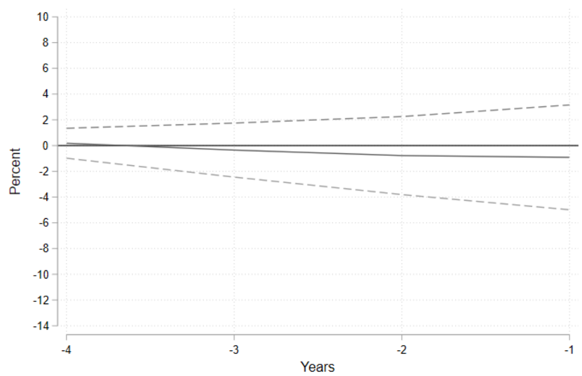
Figure 7: Dynamic Effects of Carbon Tax Prices on Emissions



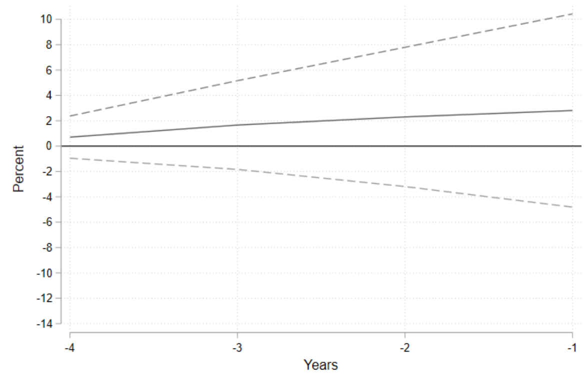

Notes: This figure plots impulse response functions capturing the dynamic effects of carbon tax implementation on territorial (a) and consumption (b) emissions from model (2) estimated via OLS. The distinction between territorial and consumption emissions is described in detail in Section 2. The solid line plots estimates of $\beta^h$ for each horizon where the policy variable, $\tau_{i,t}$, is equal to the implied price of one ton of carbon in 2018 US dollars from carbon taxation in a country in a particular year and zero otherwise. The dashed lines represent 90% confidence intervals where the standard errors have been clustered at the country level (the level of treatment). The sample consists of 57 countries between the years 1991-2018 as described in Section 2.

Figure 8: Evaluating Pre-trends in Emissions

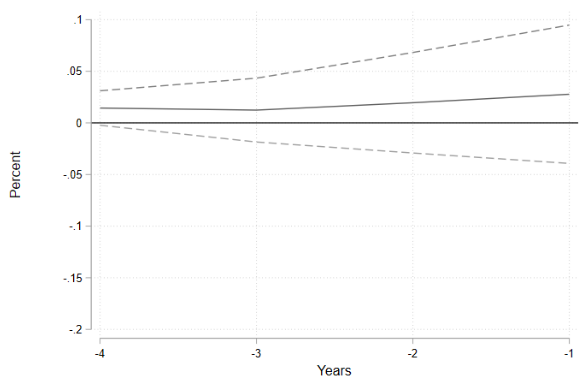
(a) Territorial Emissions, Tax Dummy



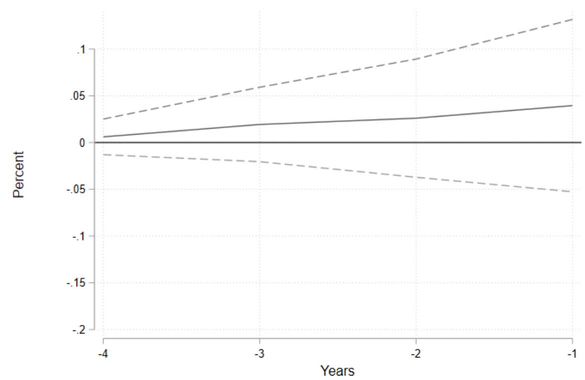

(b) Consumption Emissions, Tax Dummy




(c) Territorial Emissions, Tax Rate

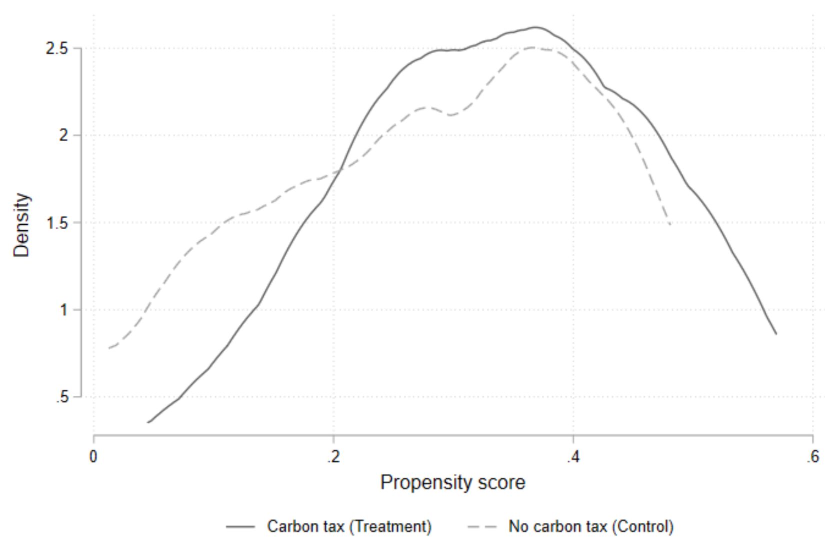



(d) Consumption Emissions, Tax Rate




Notes: This figure plots backward-looking impulse response functions over a period of four years. Plotted are estimates of $\beta^h$ from model (2) for horizons $h = -1 \cdots - 4$ estimated via OLS. Panels (a) and (b) show the pre-trends in territorial and consumption emissions respectively for the carbon taxation dummy policy variable. (c) and (d) show the analogue for the carbon price policy variable. The distinction between territorial and consumption emissions is described in detail in Section 2. The dashed lines represent 90% confidence intervals where the standard errors have been clustered at the country level (the level of treatment). The sample consists of 57 countries between the years 1991-2018 as described in Section 2.

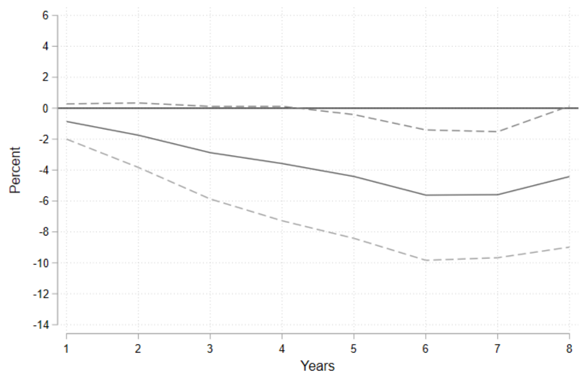
Figure 9: Distributions of Propensity Scores for Treated and Controls



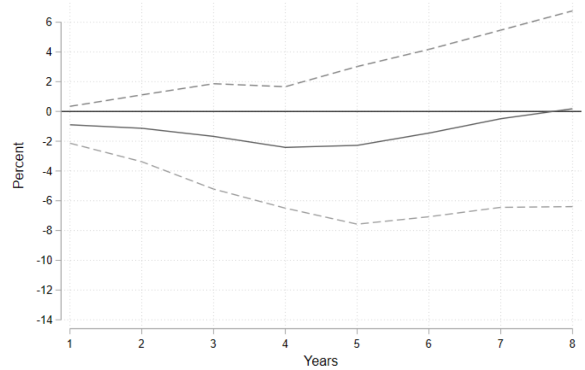

Notes: This figure plots the distributions of calculated propensity scores for countries in our sample that implemented a carbon tax (the treated) and those that did not (controls). The propensity scores are estimated via the probit model in (3).

Figure 10: Dynamic Effects of Carbon Taxation on Emissions using Inverse Propensity Score Weighting

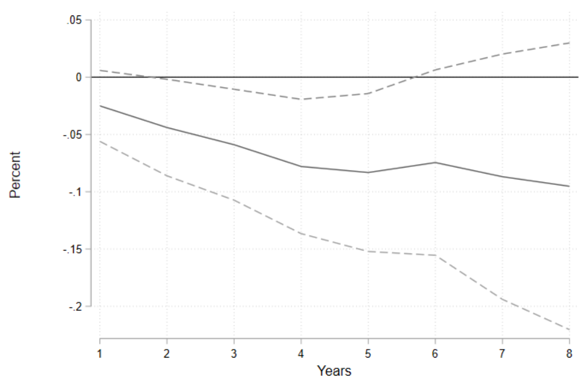
(a) Territorial Emissions, Tax Dummy



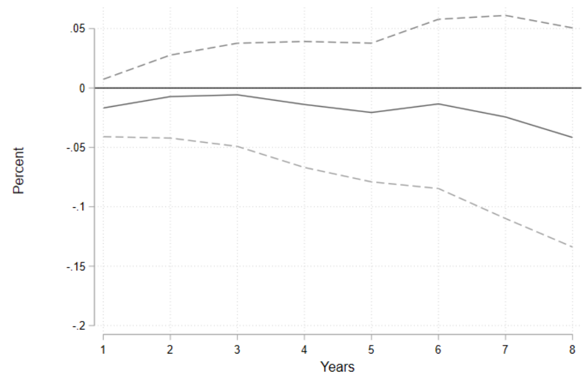

(b) Consumption Emissions, Tax Dummy




(c) Territorial Emissions, Tax Rate

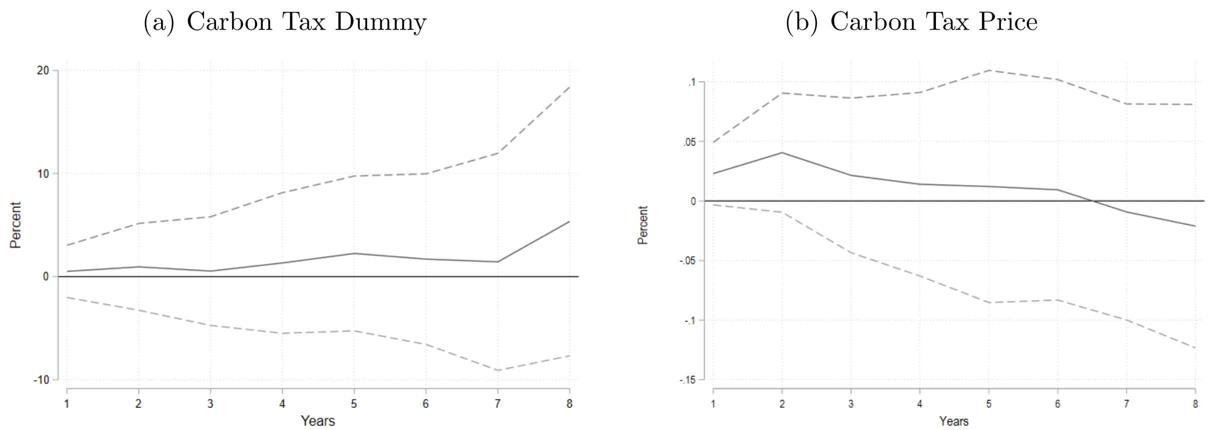



(d) Consumption Emissions, Tax Rate




Notes: This figure plots impulse response functions capturing the dynamic effects of carbon tax implementation on emissions from model (2) estimated via OLS using the IPW method outlined in Section 5.2. Panels (a) and (c) display the estimated effects of carbon tax implementation and carbon tax implied prices on territorial emissions. Panels (b) and (d) display the estimated effects of carbon tax implementation and carbon tax implied prices on consumption emissions. The distinction between territorial and consumption emissions is described in detail in Section 2. The solid line plots estimates of $\beta^h$ for each horizon where the policy variable, $\tau_{i,t}$, is either a dummy variable equal to one if a country has a carbon tax in a particular year and zero otherwise, or equal to the implied price of one ton of carbon in 2018 US dollars from carbon taxation in a country in a particular year and zero otherwise. The dashed lines represent 90% confidence intervals where the standard errors have been clustered at the country level (the level of treatment). The sample consists of 57 countries between the years 1991-2018 as described in Section 2.

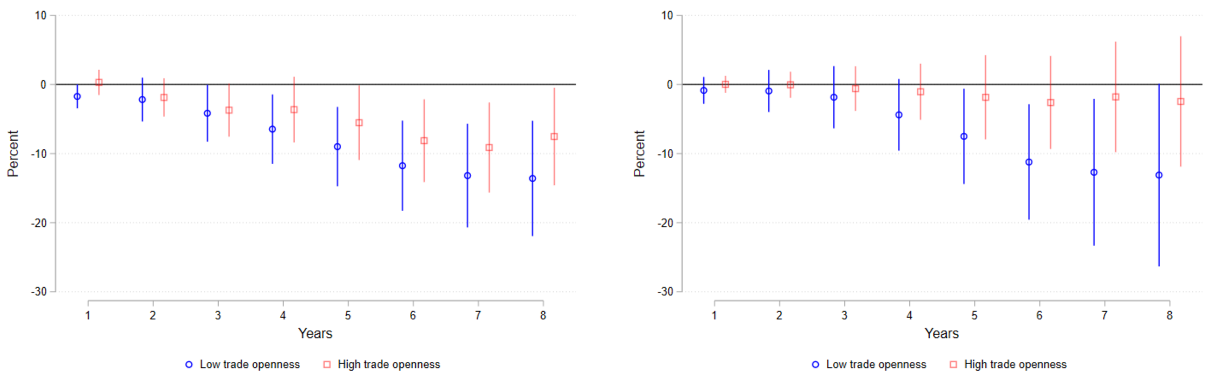
Figure 11: Dynamic Effect of Carbon Taxation and Pricing on Trade Openness




Notes: This figure plots impulse response functions capturing the dynamic effects of carbon tax implementation (a) and carbon tax prices (b) on trade openness from model (2) estimated via OLS. The solid line plots estimates of $\beta^h$ for each horizon. In panel (a) $\tau_{i,t}$ is a dummy variable equal to one if a country has a carbon tax in a particular year and zero otherwise. In panel (b) $\tau_{i,t}$ is equal to the implied price of one ton of carbon in 2018 US dollars from carbon taxation in a country in a particular year and zero otherwise. The dashed lines represent 90% confidence intervals where the standard errors have been clustered at the country level (the level of treatment). The sample consists of 57 countries between the years 1991-2018 as described in Section 2.

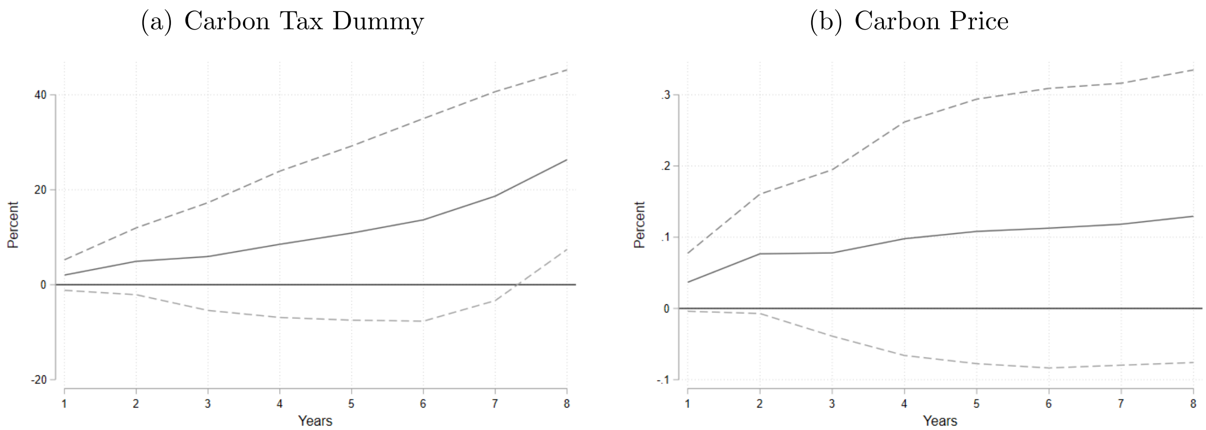
Figure 12: Dynamic Effects of Carbon Taxation on Emissions by Openness to Trade

(a) Territorial Emissions (b) Consumption Emissions




Notes: This figure plots impulse response functions capturing the dynamic effects of carbon tax implementation on territorial (a) and consumption (b) emissions by the level of trade openness. The blue circles plot point estimates of the effect for countries with low openness to trade (estimates of $\beta^h$ from the model in equation (5) estimated using OLS). The red squares plot point estimates of the effect for countries with high openness to trade (the sum of the estimates $\beta^h$ and $\lambda^h$ from (5)). High openness to trade countries are defined as those with above median openness to trade in a particular year. The policy variable, $\tau_{i,t}$, is a dummy variable equal to one if a country has a carbon tax in a particular year and zero otherwise. Both series of estimates are surrounded by 90% confidence intervals represented by the solid lines of the same colour. Standard errors are clustered at the country level (the level of treatment). The distinction between territorial and consumption emissions is described in detail in Section 2. The sample consists of 57 countries between the years 1991-2018 as described in Section 2.

Figure 13: Dynamic Effects of Carbon Taxation and Prices on Imports




Notes: This figure plots impulse response functions capturing the dynamic effects of carbon tax implementation (a) and pricing (b) on imports estimated via OLS. The solid line plots estimates of $\beta^h$ for each horizon where the policy variable, $\tau_{i,t}$, is a dummy variable equal to one if a country has a carbon tax in a particular year and zero otherwise (a), or the implied price of one ton of carbon in 2018 US dollars from carbon taxation in a country in a particular year and zero otherwise (b). The dashed lines represent 90% confidence intervals where the standard errors have been clustered at the country level (the level of treatment). The sample consists of 57 countries between the years 1991-2018 as described in Section 2.

Table 1: Descriptive Statistics, 2018

| | All | $CO_2$ Tax | No $CO_2$ Tax | p-value |
|---|---|---|---|---|
| Population (mil.) | 101.87 | 39.78 | 128.26 | .24 |
| GDP per capita (thsd. 2015 USD) | 26.98 | 33.49 | 24.22 | .17 |
| Share advanced economies | .49 | .65 | .43 | .13 |
| $CO_2$ Emissions (metric tons) | 566.23 | 220.99 | 712.95 | .27 |
| $CO_2$ Emissions per capita (metric tons) | 7.24 | 5.67 | 7.9 | .11 |
| N | 57 | 17 | 40 | . |

Notes: This table displays descriptive statistics of the sample in 2018. Population is given in millions and is sourced from the Penn World Tables. GDP per capita is given in thousands of 2015 USD and is sourced from the World Bank's World Development Indicators. We classify countries as either advanced economies or emerging and developing economies according to the classification used in the IMF's 2021 World Economic Outlook. Data on emissions of $CO_2$ are sourced from the Global Carbon Project as described in Section 2.

Table 2: Impact of Trade Openness on Carbon Taxation

| | (1)<br>=1 if Carbon Tax | (2)<br>Carbon Tax Rate |
|---|---|---|
| Trade openness | 0.002 | -0.490 |
| | (0.078) | (3.028) |
| Country FE | Yes | Yes |
| Time FE | Yes | Yes |
| Countries | 57 | 57 |
| R-squared | .1426854 | .075674 |
| N | 1557 | 1557 |

Standard errors in parentheses

$^{*}$ $p < 0.1$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$

Notes: This table shows the results of OLS regressions regressing our carbon tax policy variables on trade openness. The outcome variable in column 1 is a dummy variable equal to one if a country has a carbon tax in a particular year and zero otherwise. The outcome variable in column 2 is equal to the implied price of one ton of carbon in 2018 US dollars from carbon taxation in a country in a particular year and zero otherwise. Standard errors are clustered at the country level (the level of treatment). The sample consists of 57 countries between the years 1991-2018 as described in Section 2.

# A Data

Table A1: Data Overview

| Variable | Source | Notes |
|---|---|---|
| Territorial $CO_2$ emissions | Global Carbon Project | Carbon dioxide emissions from the use of coal, oil and gas (combustion and industrial processes), the process of gas flaring and the manufacture of cement attributed to the country in which they physically occur. See Andrew and G. Peters (2021) for more information. |
| Consumption $CO_2$ emissions | Global Carbon Project | Carbon dioxide emissions from the use of coal, oil and gas (combustion and industrial processes), the process of gas flaring and the manufacture of cement occurring anywhere in the world attributed to the country in which goods and services are consumed. See Andrew and G. Peters (2021) for more information. |
| Real GDP per capita | World Bank WDI | GDP in constant prices divided by population. |
| Population | World Bank WDI | Population in millions. |
| Imports | IMF DOTS | Total goods imports in US dollars. |
| Trade openness | IMF DOTS & World Bank WDI | Sum of total exports and imports divided by GDP. |
| Carbon tax dummy | World Bank Carbon Pricing Dashboard | Dummy variable equal to one if a country has a carbon tax in a particular year and zero otherwise. |
| Carbon price | World Bank Carbon Pricing Dashboard | 2018 USD price per ton of carbon implied by carbon taxation in each country in each year. |

Notes: IMF DOTS = IMF Direction of Trade Statistics. World Bank WDI = World Bank World Development Indicators.

Table A2: Countries Included in the Sample

| Advanced Economies | Emerging and Developing Economies |
|---|---|
| Australia | Albania |
| Austria | Argentina |
| Belgium | Brazil |
| Canada | Bulgaria |
| Cyprus | Chile |
| Czech Republic | China |
| Denmark | Colombia |
| Finland | Croatia |
| France | Egypt |
| Germany | Hungary |
| Greece | India |
| Ireland | Indonesia |
| Israel | Iran |
| Italy | Kuwait |
| Japan | Malaysia |
| Luxembourg | Mexico |
| Netherlands | Nigeria |
| New Zealand | Pakistan |
| Portugal | Peru |
| Singapore | Philippines |
| Slovakia | Poland |
| Slovenia | Romania |
| South Korea | Russia |
| Spain | Saudi Arabia |
| Sweden | South Africa |
| Switzerland | Thailand |
| United Kingdom | Turkey |
| United States | Ukraine |
| | United Arab Emirates |

Notes: We classify countries as either advanced economies or emerging and developing economies according to the classification used in the IMF's 2021 World Economic Outlook.

Table A3: Carbon Tax Schemes Included in the Sample

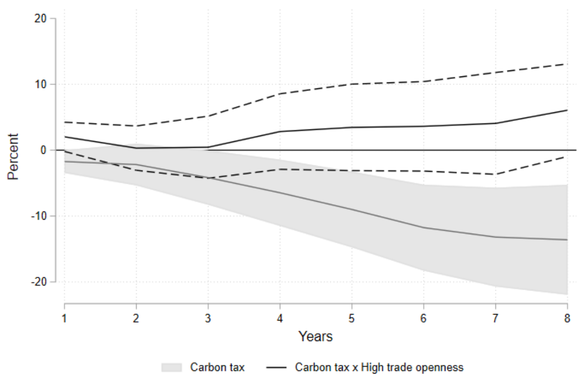
| Country | Year $CO_2$ Tax Implemented | Mean implied price per ton of $CO_2$ (2018 USD) |
|---|---|---|
| Finland | 1990 | $ 36.52 |
| Poland | 1990 | $ 0.09 |
| Sweden | 1991 | $ 120.75 |
| Denmark | 1992 | $ 25.29 |
| Slovenia | 1996 | $ 19.45 |
| Switzerland | 2008 | $ 56.73 |
| Ireland | 2010 | $ 24.58 |
| Ukraine | 2011 | $ 0.02 |
| Japan | 2012 | $ 2.05 |
| United Kingdom | 2013 | $ 21.30 |
| France | 2014 | $ 28.90 |
| Mexico | 2014 | $ 3.22 |
| Spain | 2014 | $ 24.86 |
| Portugal | 2015 | $ 7.58 |
| Chile | 2017 | $ 5.06 |
| Colombia | 2017 | $ 5.40 |
| Argentina | 2018 | $ 10.00 |

Notes: This table shows the date of $CO_2$ tax implementation and the mean implied price per ton of $CO_2$ of the countries in our sample that had a carbon tax during the period, 1991-2018. The data is sourced from the World Bank's Carbon Pricing Dashboard. The mean price per ton of $CO_2$ is calculated only for those years that the country had a carbon tax and is given in 2018 US dollars.

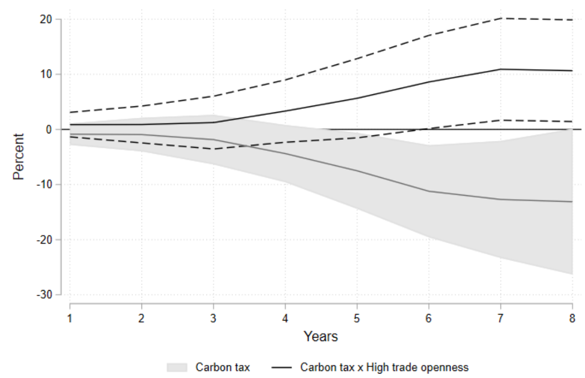
# B Additional Figures and Tables

Figure B1: Dynamic Interaction Effect of Carbon Taxation on Emissions by Openness to Trade

(a) Territorial Emissions




(b) Consumption Emissions




Notes: This figure plots impulse response functions capturing the dynamic interaction effects of carbon tax implementation on territorial (1(a)) and consumption (1(b)) emissions by the level of trade openness. The grey area plots the 90% confidence intervals surrounding estimates of $\beta^h$ from the model in equation (5) estimated using OLS. The solid line plots estimates of $\lambda^h$ from (5) surrounded by 90% confidence intervals represented by the dashed lines. Standard errors are clustered at the country level (the level of treatment). The distinction between territorial and consumption emissions is described in detail in Section 2. The solid line plots estimates of $\lambda^h$ for each horizon where the policy variable, $\tau_{i,t}$, is a dummy variable equal to one if a country has a carbon tax in a particular year and zero otherwise. The sample consists of 57 countries between the years 1991-2018 as described in Section 2.

Table B1: Dynamic Effects of Carbon Taxation and Pricing on Territorial Emissions

| | (1) Log territorial emissions | (2) Log territorial emissions | (3) Log territorial emissions | (4) Log territorial emissions | (5) Log territorial emissions | (6) Log territorial emissions |
|---|---|---|---|---|---|---|
| = 1 if Carbon Tax | -0.008 | -0.039** | -0.071** | | | |
| | (0.006) | (0.018) | (0.030) | | | |
| Carbon Tax Rate | | | | -0.000* | -0.001* | -0.001 |
| | | | | (0.000) | (0.000) | (0.001) |
| Log GDP per capita | 0.086 | 0.057 | 0.003 | 0.083 | 0.053 | -0.001 |
| | (0.089) | (0.189) | (0.298) | (0.090) | (0.190) | (0.301) |
| Log GDP per capita $^2$ | -0.006 | -0.006 | -0.009 | -0.006 | -0.006 | -0.009 |
| | (0.006) | (0.012) | (0.018) | (0.006) | (0.012) | (0.018) |
| Log population | -0.063*** | -0.128** | -0.181 | -0.062*** | -0.123** | -0.175 |
| | (0.023) | (0.058) | (0.110) | (0.023) | (0.057) | (0.110) |
| Country FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Time FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Horizon | 1 | 3 | 6 | 1 | 3 | 6 |
| Countries | 57 | 57 | 57 | 57 | 57 | 57 |
| R-squared | .0649 | .134 | .21 | .0651 | .132 | .208 |
| N | 1596 | 1539 | 1368 | 1596 | 1539 | 1368 |

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B2: Dynamic Effects of Carbon Taxation and Pricing on Consumption Emissions

| | (1) Log consumption emissions | (2) Log consumption emissions | (3) Log consumption emissions | (4) Log consumption emissions | (5) Log consumption emissions | (6) Log consumption emissions |
|---|---|---|---|---|---|---|
| = 1 if Carbon Tax | -0.010 | -0.021 | -0.035 | | | |
| | (0.007) | (0.018) | (0.032) | | | |
| Carbon Tax Rate | | | | -0.000* | -0.000 | -0.000 |
| | | | | (0.000) | (0.000) | (0.000) |
| Log GDP per capita | 0.092 | 0.176 | 0.321 | 0.089 | 0.176 | 0.319 |
| | (0.068) | (0.167) | (0.293) | (0.068) | (0.169) | (0.295) |
| Log GDP per capita $^2$ | -0.005 | -0.012 | -0.025 | -0.005 | -0.012 | -0.025 |
| | (0.004) | (0.011) | (0.019) | (0.004) | (0.011) | (0.019) |
| Log population | -0.057** | -0.102 | -0.087 | -0.056** | -0.099 | -0.085 |
| | (0.026) | (0.079) | (0.192) | (0.025) | (0.078) | (0.191) |
| Country FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Time FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Horizon | 1 | 3 | 6 | 1 | 3 | 6 |
| Countries | 57 | 57 | 57 | 57 | 57 | 57 |
| R-squared | .111 | .149 | .216 | .112 | .149 | .216 |
| N | 1596 | 1482 | 1311 | 1596 | 1482 | 1311 |

Standard errors in parentheses

$^{*}$ $p < 0.1$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$

Table B3: Dynamic Effects of Carbon Taxation and Pricing on Territorial Emissions with Inverse Propensity Weighting

| | (1) Log territorial emissions | (2) Log territorial emissions | (3) Log territorial emissions | (4) Log territorial emissions | (5) Log territorial emissions | (6) Log territorial emissions |
|---|---|---|---|---|---|---|
| = 1 if Carbon Tax | -0.009 | -0.029 | -0.056** | | | |
| | (0.007) | (0.018) | (0.026) | | | |
| Carbon Tax Rate | | | | -0.000 | -0.001* | -0.001 |
| | | | | (0.000) | (0.000) | (0.000) |
| Log GDP per capita | -0.016 | -0.222 | -0.329 | -0.022 | -0.230 | -0.332 |
| | (0.074) | (0.198) | (0.270) | (0.076) | (0.200) | (0.273) |
| Log GDP per capita $^2$ | 0.000 | 0.012 | 0.013 | 0.001 | 0.013 | 0.013 |
| | (0.004) | (0.013) | (0.017) | (0.004) | (0.013) | (0.017) |
| Log population | -0.069*** | -0.183** | -0.170* | -0.069*** | -0.180** | -0.164* |
| | (0.020) | (0.075) | (0.091) | (0.019) | (0.074) | (0.090) |
| Country FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Time FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Horizon | 1 | 3 | 6 | 1 | 3 | 6 |
| Countries | 57 | 57 | 57 | 57 | 57 | 57 |
| R-squared | .127 | .197 | .206 | .127 | .197 | .204 |
| N | 1596 | 1539 | 1368 | 1596 | 1539 | 1368 |

Standard errors in parentheses
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B4: Dynamic Effects of Carbon Taxation and Pricing on Consumption Emissions with Inverse Propensity Weighting

| | (1)<br>Log consumption emissions | (2)<br>Log consumption emissions | (3)<br>Log consumption emissions | (4)<br>Log consumption emissions | (5)<br>Log consumption emissions | (6)<br>Log consumption emissions |
|---|---|---|---|---|---|---|
| = 1 if Carbon Tax | -0.009 | -0.017 | -0.015 | | | |
| | (0.008) | (0.022) | (0.034) | | | |
| Carbon Tax Rate | | | | -0.000 | -0.000 | -0.000 |
| | | | | (0.000) | (0.000) | (0.000) |
| Log GDP per capita | 0.137*** | 0.315*** | 0.493** | 0.135*** | 0.320*** | 0.494** |
| | (0.032) | (0.080) | (0.194) | (0.033) | (0.084) | (0.196) |
| Log GDP per capita $^2$ | -0.008*** | -0.022*** | -0.037*** | -0.008*** | -0.022*** | -0.037*** |
| | (0.002) | (0.004) | (0.011) | (0.002) | (0.005) | (0.011) |
| Log population | -0.073*** | -0.131* | -0.074 | -0.072*** | -0.127* | -0.072 |
| | (0.022) | (0.071) | (0.170) | (0.021) | (0.070) | (0.170) |
| Country FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Time FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Horizon | 1 | 3 | 6 | 1 | 3 | 6 |
| Countries | 57 | 57 | 57 | 57 | 57 | 57 |
| R-squared | .18 | .23 | .29 | .18 | .23 | .29 |
| N | 1596 | 1482 | 1311 | 1596 | 1482 | 1311 |

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B5: Dynamic Effect of Carbon Taxation on Territorial and Consumption Emissions by Openness to Trade

| | (1)<br>Log territorial emissions | (2)<br>Log territorial emissions | (3)<br>Log territorial emissions | (4)<br>Log consumption emissions | (5)<br>Log consumption emissions | (6)<br>Log consumption emissions |
|---|---|---|---|---|---|---|
| = 1 if Carbon Tax | -0.017 | -0.042 | -0.118*** | -0.009 | -0.018 | -0.112** |
| | (0.010) | (0.025) | (0.040) | (0.012) | (0.027) | (0.051) |
| High trade openness | 0.000 | -0.009 | -0.019 | -0.002 | 0.009 | 0.005 |
| | (0.013) | (0.027) | (0.041) | (0.018) | (0.027) | (0.043) |
| = 1 if Carbon Tax × High trade openness | 0.020 | 0.005 | 0.036 | 0.009 | 0.012 | 0.086* |
| | (0.013) | (0.029) | (0.041) | (0.014) | (0.029) | (0.051) |
| Country FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Time FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Horizon | 1 | 3 | 6 | 1 | 3 | 6 |
| Countries | 57 | 57 | 57 | 57 | 57 | 57 |
| R-squared | .0662 | .135 | .218 | .079 | .118 | .198 |
| N | 1596 | 1539 | 1368 | 1596 | 1482 | 1311 |

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table B6: Dynamic Effects of Carbon Taxation and Pricing on Imports

| | (1) Log imports | (2) Log imports | (3) Log imports | (4) Log imports | (5) Log imports | (6) Log imports |
|---|---|---|---|---|---|---|
| = 1 if Carbon Tax | 0.020 | 0.059 | 0.137 | | | |
| | (0.020) | (0.069) | (0.130) | | | |
| Carbon Tax Rate | | | | 0.000 | 0.001 | 0.001 |
| | | | | (0.000) | (0.001) | (0.001) |
| Log GDP per capita | 0.129 | 0.536$^{**}$ | 0.890$^{**}$ | 0.134 | 0.543$^{**}$ | 0.895$^{**}$ |
| | (0.092) | (0.238) | (0.442) | (0.091) | (0.238) | (0.440) |
| Log GDP per capita $^2$ | -0.008 | -0.037$^{**}$ | -0.071$^{**}$ | -0.008 | -0.038$^{**}$ | -0.072$^{**}$ |
| | (0.006) | (0.016) | (0.029) | (0.006) | (0.016) | (0.029) |
| Log population | -0.011 | -0.039 | 0.105 | -0.013 | -0.044 | 0.100 |
| | (0.032) | (0.091) | (0.266) | (0.032) | (0.092) | (0.266) |
| Country FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Time FE | Yes | Yes | Yes | Yes | Yes | Yes |
| Horizon | 1 | 3 | 6 | 1 | 3 | 6 |
| Countries | 57 | 57 | 57 | 57 | 57 | 57 |
| R-squared | .48 | .518 | .622 | .48 | .518 | .621 |
| N | 1558 | 1444 | 1273 | 1558 | 1444 | 1273 |

Standard errors in parentheses

$^{*}$ $p < 0.1$, $^{**}$ $p < 0.05$, $^{***}$ $p < 0.01$