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The Effect of Carbon Pricing on Firm Emissions: Evidence from the Swedish CO_2 Tax

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Sweden was one of the first countries to introduce a carbon tax back in 1991. We assemble a unique data set tracking CO_2 emissions from Swedish manufacturing firms over 26 years to estimate the impact of carbon pricing on firm-level emission intensities. We estimate an emission-to-pricing elasticity of around two, with substantial heterogeneity across subsectors and firms, where higher abatement costs and tighter financial constraints are associated with lower elasticities. A simple calibration suggests that 2015 CO_2 emissions from Swedish manufacturing would have been roughly 30% higher without carbon pricing. (*JEL* H23, Q54, Q58, G32)

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Anthropogenic climate change is one of the most pressing issues of our time, representing a massive market failure in need of urgent policy intervention (Stern 2008). Many economists have argued the most important policy tool to combat climate change is to price CO_2 emissions through a global carbon tax (e.g., Nordhaus 1993; Golosov et al. 2014; Rockström et al. 2017; Sterner et al. 2019), ideally in combination with subsidies for green innovation (e.g., Acemoglu et al. 2016; Aghion et al. 2016). While there is still no agreement on a global carbon tax, many countries around the world have implemented local or regional carbon pricing schemes (World Bank 2022). Despite the risk of carbon leakage, Conte, Desmet, and Rossi-Hansberg (2022) argue that such unilateral schemes, if properly designed, can still be effective.

Until just a few years ago, there was little evidence on whether existing carbon pricing schemes had actually reduced firm CO_2 emissions (Burke et al. 2016; Martin, Muûls, and Wagner 2016). While the literature has grown over the last few years, the evidence on the effectiveness of carbon pricing is still mixed (see Rafaty, Dolphin, and Pretis 2021; Timilsina 2022; Green 2021, for recent reviews). One reason results differ is that carbon pricing schemes vary greatly in their structure, coverage, and magnitude. In addition, the majority of studies examine aggregated data at the sector and/or country level, which makes it difficult to account for important heterogeneity in marginal pricing and abatement costs across firms.[1] The relatively few studies that analyze micro-data on individual firms or plants estimate average treatment effects around the introduction of a particular carbon pricing scheme. Since emission pricing differs significantly in magnitude across schemes and over time, however, it is perhaps not surprising that results vary greatly across studies.[2]

Using data from Sweden, we construct the longest firm-level panel to date on economic activity and CO_2 emissions for the population of manufacturing firms over 1990–2015. Our analysis aims to contribute to the existing literature in several ways.

First, we provide estimates of carbon pricing elasticities for the manufacturing sector by relating the marginal cost of emitting a unit of CO_2

[1] Examining sector-level emissions and using synthetic control methods, Rafaty, Dolphin, and Pretis (2021) conclude that the introduction of carbon pricing has only reduced aggregate emissions by 1%–2%, with most abatement occurring in the electricity and heat sector (rather than manufacturing). They also estimate a small and imprecisely estimated carbon pricing elasticity. Using a differences-in-differences approach, Pretis (2022) finds small effects on sector-level emissions from the introduction of carbon taxation in British Columbia, particularly outside of transportation. In contrast, using synthetic panel methods on individual sectors, Andersson (2019) finds that the Swedish carbon tax reduced transport emissions by 11%, and Leroutier (2022) estimates that UK power sector emissions declined by 20%–26% following the implementation of the UK Carbon Price Support scheme. Using aggregate data for 31 European countries, Metcalf and Stock (2023) estimate a 4%–6% reduction in emissions for a $40/ton carbon price covering 30% of emissions.

[2] These studies include Bartram, Hou, and Kim (2022), who find that the California cap-and-trade system failed to reduce CO_2 emissions and led to substantial carbon leakage to other U.S. states; Colmer et al. (2022), who estimate that French manufacturing firms reduced their CO_2 emissions by 14%–16% after the introduction of EU ETS; Dechezleprêtre, Nachtigall, and Venmans (2023), who use a broader set of EU ETS countries and find average emission reductions of around 10%; and Ahmadi, Yamazaki, and Kabore (2022), who estimate that the introduction of the British Columbia carbon tax reduced emissions by 4%.

to actual emissions for every firm and year. Such elasticities can be used to assess different carbon pricing schemes, for example, by calibrating macroeconomic models of optimal climate policy (such as Golosov et al. 2014; Acemoglu et al. 2016). Our data set is large in both the cross-sectional and time-series dimensions, which enables econometric identification due to numerous changes in tax rates and firm-level exemptions over time. It also allows estimation of the full dynamic response to carbon pricing, where we can account for the time it takes for firms to adapt their technologies and business models (Dessaint, Foucault, and Fresard 2022). We are thus able to provide precise estimates of carbon pricing elasticities, unlike the earlier literature, which either bases estimates on aggregated country- or sector-level time-series data, or estimates average treatment effects around the introduction of a given carbon pricing scheme.[3]

Second, our micro-data enable us to investigate the heterogeneity in carbon pricing elasticities across firms and subsectors. Both the incentive and the ability of firms to lower their emissions in response to carbon pricing will differ depending on, for example, production technology, abatement costs, financial constraints, mobility of production, and the competitive environment (e.g., Ederington, Levinson, and Minier 2005; Gillingham and Stock 2018; Xu and Kim 2022; Martin et al. 2014; Lyubich, Shapiro, and Walker 2018). Since the bulk of CO_2 emissions are concentrated to a few subsectors, and often to a few large firms within each subsector, such heterogeneity has large implications for the aggregate impact of carbon pricing.

Third, existing evidence on the effectiveness of carbon pricing have been mixed, and several studies have found limited impact of carbon pricing schemes on aggregate CO_2 emissions from manufacturing (see, e.g., Rafaty, Dolphin, and Pretis 2021, and the references therein). In contrast, the elasticities we uncover from micro-data imply economically significant effects of carbon pricing on manufacturing emissions. These elasticities can be applied to infer expected emission reductions across carbon pricing schemes with different price levels and industry structures, which increases the external validity compared to previous studies.

Our data set includes comprehensive information on financials and CO_2 emissions for the universe of Swedish manufacturing firms over the period 1990–2015. Sweden serves as an ideal testing ground for analyzing the incidence and impact of carbon pricing. It was one of the first countries to introduce a carbon tax in 1991, levied on the heating emissions from manufacturing firms, and the Swedish carbon tax rate is currently the highest

[3] Two exceptions are Germeshausen (2020), who estimates the price sensitivity of CO_2 emissions from German power plants in the EU ETS, and Dussaux (2020), who estimates the elasticity of energy use to fuel (rather than carbon) prices for a sample of French manufacturing firms, which are then used to simulate the economic effects of carbon pricing.

in the world.[4] In addition, several subsequent changes in tax rates, various tax exemptions, and the introduction of the EU Emissions Trading System (ETS) toward the end of our sample lead to substantial variation in effective marginal tax rates across firms and over time, facilitating econometric identification.

When the carbon tax scheme was introduced in 1991, it contained various tax exemptions for the highest emitters, motivated by the desire to mitigate "carbon leakage" (i.e., CO_2-emitting plants closing in Sweden and/or moving to other jurisdictions). As a result, the 10% of firms with the highest CO_2 emissions had significantly lower (sometimes even zero) marginal carbon tax rates, despite facing a high average tax rate (reducing average EBIT margins by more than 6 percentage points). Consistent with reduced marginal incentives, we find that the emission intensity of the highest-emitting firms decreased only modestly between 1990 and 2015, while the remaining 90% of firms facing higher marginal carbon tax rates experienced significantly higher reductions.

To measure short-term responses, we follow previous literature and perform difference-in-differences analysis around the introduction and subsequent changes of the carbon tax regime, utilizing the caps on total tax payments for the highest emitters. In the first test, we focus on the 10% most emitting sectors and sort firms into two groups: those qualifying for exemptions around the introduction of the carbon tax in 1991–1992 and those that did not. The results show that a rise (decline) in marginal cost is associated with decreasing (increasing) firm-level emission intensity. We also study the reintroduction of a carbon tax payment exemption in 1997 and obtain similar results.

We then examine the longer-term relationship between emission intensity and the marginal emission tax a firm faces, including both the explicit CO_2 tax and the implicit tax from the price of emission rights for firms with installations under the EU ETS. Using data from about 4,000 manufacturing firms, covering 85%–90% of Sweden's manufacturing CO_2 emissions over 1990–2015, we find a significantly negative relationship between firm-level CO_2 emission intensity and the marginal cost of emissions. In our main specification, which includes firm and year fixed effects, we estimate that a 1% increase in the marginal emissions cost share reduces carbon emissions per unit of (PPI-deflated) sales by roughly 2% over a 3-year period. This magnitude is stable over the introduction of the EU ETS in 2005 and robust to including tighter sets of fixed effects, more lags, and various firm-level controls.

We also document significant heterogeneity in the response to carbon pricing. We first sort firms into two groups based on the ex ante costs of reducing CO_2 emissions, using data on air pollution abatement costs and expenditure (PACE; see Becker 2005). Firms in low PACE sectors, that is, where it is relatively cheaper and easier to reduce emissions, display a carbon

[4] According to World Bank (2022), just under 70 carbon pricing schemes are in place in 2022, covering just under one quarter of global CO_2 emissions. Only six of these were introduced before 2000, and two-thirds of them were introduced after 2010.

pricing elasticity of around three, compared to an elasticity less than two in high PACE sectors. To get at carbon leakage risk, we further separate low and high PACE sectors based on the ex ante mobility of their assets (Ederington, Levinson, and Minier 2005). The smallest point estimate is for firms in high PACE and low-mobility sectors, with an elasticity of 1.7. This group, containing firms that face high abatement costs and are less able to avoid tax by moving production, comprises between 80% and 90% of aggregate manufacturing CO_2 emissions. We find similar results when we instead separate firms by whether their subsector is included on the EU "carbon leakage list" (European Commission 2009).

Since access to external financing might affect the ability of firms to invest in abatement, we explore whether financial constraints affect carbon pricing elasticities. Following the literature, we consider firms that are privately held (rather than listed), smaller, younger, and with lower dividend payout ratios as being more financially constrained (see, e.g., Saunders and Steffen 2011; Hadlock and Pierce 2010; Bartram, Hou, and Kim 2022). Less constrained firms display elasticities between two and three, whereas estimates for their more constrained counterparts are insignificant and consistently less than one. The difference in elasticities is only found among firms with high abatement costs, while financial constraints have no visible effect on firms with low abatement costs, consistent with financial constraints primarily hurting firms for which abatement requires significant investment.

To assess the economic importance of these findings, we relate the estimated elasticities to changes in aggregate manufacturing emissions of CO_2 in our sample period. Following Grossman and Krueger (1993) and Levinson (2009), we decompose the change in aggregate emissions into scale, composition, and technique effects. CO_2 (heating) emissions from the Swedish manufacturing sector decreased by 31% over 1990–2015. The decomposition attributes 3 percentage points of this decrease to lower aggregate output ("scale") and 10 percentage points to the changing composition of Swedish manufacturing toward lower-emitting subsectors. By definition, the remaining 18 percentage points (58% of the total reduction) is attributed to changes in technology ("technique"). We then use our estimated carbon elasticities to calculate the contribution from carbon pricing on these aggregate reductions. Our calculations suggest that carbon pricing, through its effect on reduced emission intensities, can account for between one-third up to almost all of the total decrease in CO_2 emissions from manufacturing over our sample period.

In terms of implications, we believe that our findings are relevant for discussions on optimal carbon taxation more generally (e.g., Nordhaus 1993; Bovenberg and De Mooij 1994; Bovenberg and Golder 1996; Pindyck 2013; Gillingham and Stock 2018; Stock 2020). While our reduced-form estimates ignore potentially important general equilibrium effects, they confirm that even in a unilateral carbon pricing scheme (as in Conte, Desmet, and Rossi-Hansberg 2022), firms do respond to the marginal cost of emitting CO_2 in a way consistent with economic theory. Our results also imply that Sweden could have achieved significantly larger reductions in CO_2 without the various tax exemptions that reduced marginal incentives to reduce emissions for the highest-emitting firms.

We also contribute to the literature examining the effects of environmental policy on firms (e.g., Fowlie 2010; Greenstone, List, and Syverson 2012; Fowlie, Reguant, and Ryan 2016; He, Wang, and Zhang 2020; Brown, Martinsson, and Thomann 2022; Bartram, Hou, and Kim 2022; Hartzmark and Shue 2023).[5] By estimating elasticities rather than average treatment effects, we uncover several sources of heterogeneity in firms' responses to carbon pricing and show that they are of economic importance.

Finally, our paper is part of a growing literature documenting the connections between finance and the environment (e.g., Bolton and Kacperczyk 2021; Giglio et al. 2021; Hong, Li, and Xu 2019; Ilhan, Sautner, and Vilkov 2021; Bartram, Hou, and Kim 2022; Giannetti et al. 2023).[6] Specifically, our study adds to the work examining the legal and financial determinants of environmental behavior (e.g., Akey and Appel 2021; Bartram, Hou, and Kim 2022; Brown, Martinsson, and Thomann 2022; Xu and Kim 2022) by showing that financial constraints play an important role in determining the response of firms' CO_2 emissions to carbon pricing.

1. Carbon Pricing in Sweden

Sweden introduced its carbon tax in 1991 alongside a handful of countries.[7] The tax was part of a comprehensive reform and included elements of so-called (”green tax shifting”) with the idea to increase costs on polluting and lower, for instance, labor taxes (see, e.g., Jonsson, Ydstedt, and Asen 2020).[8] Some reasons for Sweden being an early adopter of carbon pricing are the lack of significant fossil fuel resources and (perhaps as a result) the absence of significant anticlimate lobbying (e.g., Meckling, Sterner, and Wagner 2017; Sterner 2020). Internet Appendix A provides further background on the introduction and evolution of Swedish carbon taxation.

The Swedish carbon tax is levied on fossil fuels used either in combustion engines (“mobile emissions”) or for heating (“stationary emissions”). The tax

5 A related literature documents evidence of how changes in price and policy induce a shift from dirty fossil-fuel-based technical change to clean technologies (e.g., Newell, Jaffe, and Stavins 1999; Popp 2002; Hassler, Krusell, and Olovsson 2021).

6 See Giglio, Kelly, and Stroebel (2021) for a survey.

7 Finland (1990), the Netherlands (1990), Poland (1990), Norway (1991), and Denmark (1992) were the other countries introducing carbon taxation around this time. See World Bank (2022) and Shah and Larsen (1992) on international carbon pricing schemes, and Brännlund, Lundgren, and Marklund (2014) and Scharin and Wallström (2018) for reviews of the Swedish carbon tax.

8 This is in line with arguments that optimal carbon pricing should be revenue neutral (e.g., Conte, Desmet, and Rossi-Hansberg 2022; Timilsina 2022). We control for the possible confounding effects from concurrent changes in labor and corporate income taxation in the empirical analysis below (see Table 5).

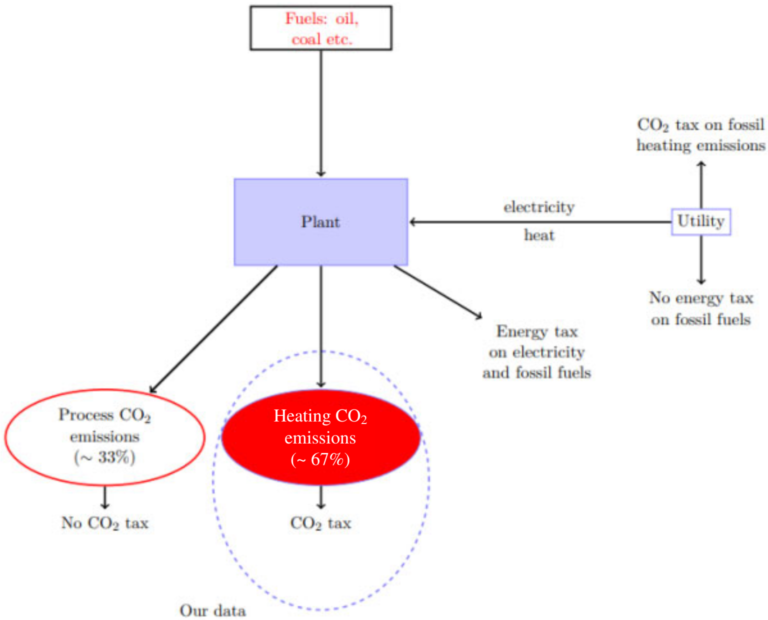

Figure 1
Carbon and energy taxation of an industrial plant
This figure illustrates the carbon and energy taxation for a manufacturing plant in Sweden in 2019. *Heating CO_2 emissions* refers to the emissions released from the combustion of fossil fuels. *Process CO_2 emissions* refers to the carbon dioxide emissions released in the actual manufacturing process (i.e., not combustion of fossil fuels). *Utility* is the power plant that produces heat and/or electricity, and *Plant* is the industrial manufacturing plant.

on mobile emissions primarily affects road transportation (and is included in the after-tax price of fuel "at the pump"), while the tax on stationary emissions is levied on power plants and manufacturing firms. This study focuses on the stationary emissions tax on manufacturing firms, summarized in Figure 1. Manufacturing production releases heating and process CO_2 emissions and the carbon tax on stationary emissions is levied on emissions from heating only, while process CO_2 emissions are exempt. A plant must declare the use of its fossil fuel separately for production and heating and the tax is levied on heating fuel inputs in proportion to the implied emissions of CO_2 during combustion.[9] Since the Swedish manufacturing sector uses about one-third of its fossil fuel for production and the remainder for heating, about two-thirds of the sector's stationary CO_2 emissions are subject to carbon taxation.

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[9] See Statistics Sweden. (2018) for details on how the Swedish emissions data are collected. Inferring CO_2 emissions from fuel consumption is the dominant measurement method among environmental agencies around the world, while direct measurement using Continuous Emissions Monitoring Systems (CEMS) is less common (see United States Environmental Protection Agency. 2016). The fuel consumption method has been found to be at least as accurate as the CEMS method (see Quick 2014; Bryant, Bundy, and Zong 2015).

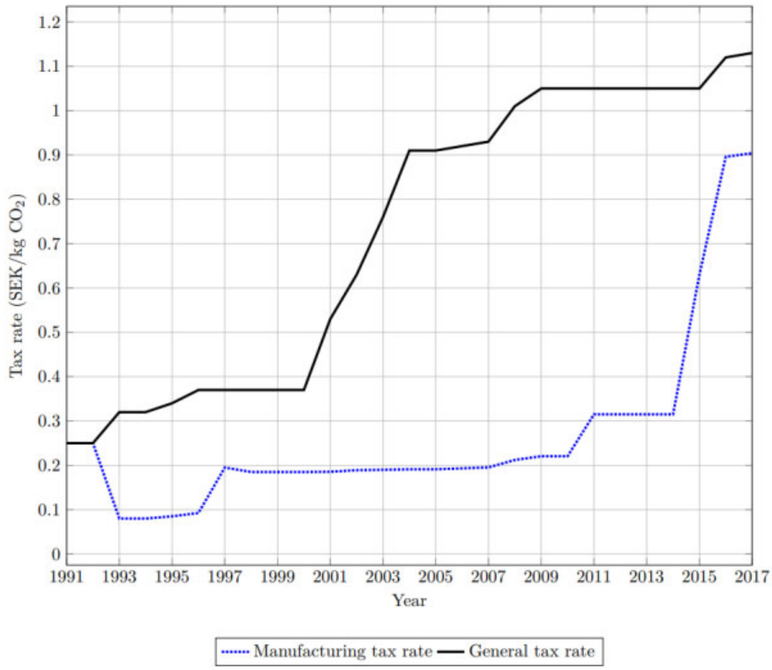

Figure 2
Carbon tax rate, in nominal values
This figure displays the nominal carbon tax rates (Swedish krona per kilogram of emitted carbon dioxide) for Sweden from 1991 to 2017. *Manufacturing tax rate* refers to the tax rate for the manufacturing sector (SNI 10-33 in the SNI2007 nomenclature), while *General tax rate* refers to the tax rate for nonindustrial firms and households.

Figure 2 plots the evolution of the Swedish carbon tax rate over time. When it was introduced in 1991, the tax was levied at a rate of 0.25 Swedish krona (SEK) per kilogram (kg) of emitted CO_2 across all sectors in the economy.[10] Already at this point, however, Swedish carbon taxation incorporated various caps and exemptions (summarized in Table 1) for the highest-emitting firms. We discuss these in greater detail in Section 2.2.

In 2005, the European Union introduced a cap-and-trade scheme for CO_2 emissions, the *European Union Emissions Trading System* (EU ETS), which had major implications for Swedish carbon taxation. Installations covered by the EU ETS were gradually phased out of the Swedish carbon tax regulation over 2008–2011 (Government Bill 2007/2008:1 2007). Emission allowances were allocated for free to the participating plants (or "installations") in the pilot phase (i.e., 2005–2007), and the bulk of emission rights were distributed for free in the second trading phase (2008–2012) as well. In the third phase,

10 In 1991, one USD was roughly equal to 6.50 SEK. Over our sample period, the exchange rate fluctuated between 6 and 9 SEK per USD.

Table 1
Summary of the rates in the Swedish carbon tax system

	Carbon tax rates (SEK/kg)				
Year	Standard rate	Manufacturing rate	General exemptions	Cement, glass lime	Firms in EU ETS
1990	No tax	No tax	No tax	No tax	Before EU ETS
1991	0.25	0.25	Manufacturing rates if CO_2 + Energy tax <= 1.7% of sale, untaxed further emissions	Manufacturing rates if CO_2 + Energy tax <= 1.7% of sale, untaxed further emissions	
1992	0.25	0.25	Manufacturing rates if CO_2 + Energy tax <= 1.2% of sale, untaxed further emissions	Manufacturing rates if CO_2 + Energy tax <= 1.2% of sale, untaxed further emissions	
1993	0.32	0.08	Manufacturing rate	Industry rate up to 1.2 % of sales, untaxed further emissions (“1.2% rule”)	
1994	0.32	0.08			
1995	0.34	0.09			
1996	0.37	0.09			
1997	0.37	0.19	Manufacturing tax rate up to 0.8% of sales, exceeding emissions: 25 % of general manufacturing CO_2 tax rate (“0.8 % rule”)	0.8% rule is applied first, emissions exceeding 1.2 % of sales are untaxed	
1998	0.37	0.19			
1999	0.37	0.19			
2000	0.37	0.19			
2001	0.53	0.19			
2002	0.63	0.19			
2003	0.76	0.19			
2004	0.91	0.19			
2005	0.91	0.19			Manufacturing rate + exemptions where applicable
2006	0.92	0.19			

(*Continued*)

Table 1
(Continued)

			Carbon tax rates (SEK/kg)		
Year	Standard rate	Manufacturing rate	General exemptions	Cement, glass lime	Firms in EU ETS
2007	0.93	0.20		Special exemption removed	
2008	1.01	0.21			
2009	1.05	0.22			EU ETS+15% of standard rate for plants under EU ETS
2010	1.05	0.22			
2011	1.05	0.315			
2012	1.05	0.32	Manufacturing rate up to 1.2%: Exceeding: 24% of manufacturing rate		
2013	1.05	0.32			No CO_2 tax for installations covered by EU ETS
2014	1.05	0.32			
2015	1.05	0.63	Special exemption removed		

This table summarizes the special provisions that enacted tax reliefs for certain industrial enterprises. *Standard rate* applies for households and nonindustrial firms, *Manufacturing rate* is the applicable rate for manufacturing enterprises (SNI10-33 under SNI2007 nomenclature), and the exemptions in *Manufacturing rate + exemptions where applicable* are the 0.8% and the 1.2% rules.

starting in 2013, auctions of emission rights were introduced, although for manufacturing plants most emission rights were continued to be distributed for free, motivated by carbon leakage concerns.[11]

2. Carbon Pricing across Firms, Sectors, and Over Time

2.1 Data and sample construction

Our sample is constructed by matching plant- and firm-level registry data (including accounting variables, number of workers, sector classifications) with CO_2 emissions for the time period 1990–2015. The Swedish Environmental Protection Agency (SEPA) provided data on CO_2 emissions at plant- and firm-level (including emissions under the EU ETS). We obtain registry data for listed and unlisted Swedish corporations from *Upplysningscentralen* (UC) for the period 1990–1997 and *Bisnode Serrano* for 1998–2015.

To compute emission intensities, our sample firms need to have data on both sales and CO_2 emissions. The number of firms with CO_2 emissions data changes during our sample period (see Table B.1 in the Internet Appendix), most notably in 1997–1999 and 2003–2006, when only emissions by larger plants were collected by SEPA. Since the largest emitters are always sampled, our data consistently covers between 80% and 95% of aggregate manufacturing CO_2 emissions in any given year (Figure A.1 in the Internet Appendix). Over the entire period 1990–2015, our sample covers 85% of aggregate CO_2 heating emissions and 87% of total (process plus heating) CO_2 emissions (Figure A.2 in the Internet Appendix) from the Swedish manufacturing sector.

Since historical firm-level records of actual carbon taxes paid could not be provided by the Swedish tax authority, we calculate both the effective marginal tax and the overall carbon tax payments from the actual CO_2 heating emissions for each plant and firm each year, using the carbon tax schedule (including possible exemptions) that was in place for the corresponding year.[12] For the EU ETS period, we infer the emissions subject to the Swedish carbon tax as the difference between emissions reported in SEPA and emissions according to the European Union Transaction Log (the official registry of EU ETS). For the regression analysis, we require sample firms to have at least four consecutive yearly observations to allow for lagged independent variables. A detailed description of the sample construction are provided in subsection B.1 and subsection B.2 of the Internet Appendix and in Sajtos (2020). Table 2 provides summary statistics for the key variables. We then sort our sample firms into different manufacturing subsectors based on CO_2 emissions intensity

[11] Dechezleprêtre, Nachtigall, and Venmans (2023) provides an overview of the EU ETS and its different trading phases.

[12] We use the plant-level emissions data collected by Statistics Sweden to construct official statistics. The same methodology is used by the Swedish tax authority to calculate carbon taxes. For a description of how the Swedish carbon tax is levied, see in Hammar and Åkerfeldt (2011), pp. 6-9.

Table 2
Summary statistics

	OBS	Mean	Median	SD	Min	Max
Emissions-to-sales	24,943	0.0072	0.0021	0.0184	0.0000	> 0.100
MC of emissions-to-sales	24,943	0.0010	0.0004	0.0017	0.0000	0.0104
MC of emissions-to-EBIT	24,904	0.0143	0.0034	0.0995	−0.4164	0.5900
Nr of workers	24,884	234	45	908	0	n/a
Capital intensity	24,682	0.6083	0.3255	0.9010	0.0022	5.6367
EU ETS	24,943	0.0673	0.0000	0.2505	0.0000	1.0000
Low pace	24,943	0.4658	1.0000	0.4988	0.0000	1.0000
High pace	24,943	0.4788	0.0000	0.4996	0.0000	1.0000
Low pace & Low mobility	24,943	0.2064	0.0000	0.4047	0.0000	1.0000
Low pace & High mobility	24,943	0.2547	0.0000	0.4357	0.0000	1.0000
High pace & Low mobility	24,943	0.2927	0.0000	0.4550	0.0000	1.0000
High pace & High mobility	24,943	0.1780	0.0000	0.3825	0.0000	1.0000
Not on leakage list	24,943	0.5043	1.0000	0.5000	0.0000	1.0000
On leakage list	24,943	0.4931	0.0000	0.5000	0.0000	1.0000
D1-D4	24,943	0.3969	0.0000	0.4893	0.0000	1.0000
D5-D8	24,943	0.4265	0.0000	0.4946	0.0000	1.0000
D9-D10	24,943	0.1725	0.0000	0.3778	0.0000	1.0000
Public firm	16,328	0.2257	0.0000	0.4181	0.0000	1.0000
Private firm	16,328	0.7743	1.0000	0.4181	0.0000	1.0000
Large firm	16,328	0.4789	0.0000	0.4996	0.0000	1.0000
Small firm	16,328	0.5211	1.0000	0.4996	0.0000	1.0000
High dividend firm	16,328	0.5137	1.0000	0.4998	0.0000	1.0000
Low dividend firm	16,328	0.4863	0.0000	0.4998	0.0000	1.0000
Mature firm	16,328	0.4995	0.0000	0.5000	0.0000	1.0000
Young firm	16,328	0.5005	1.0000	0.5000	0.0000	1.0000

This table reports summary statistics in the key variables included in this study. The firm-level data are from UC and Bisnode and consist of CO_2-emitting firms with at least four consecutive observations over 1990–2015 and a primary NACE industry classification between 10 and 33. Monetary values are adjusted and expressed in constant 2010 Swedish krona (SEK). CO_2 emissions are expressed in kilograms (kg). *MC of emissions-to-sales* is the emissions cost (marginal cost multiplied by emissions) share relative to sales for firm i in year t. *MC of emissions-to-EBIT* is relative to earnings before interest and taxes. *Capital intensity* is the ratio between fixed assets and workers. *EU ETS* is an indicator variable taking on the value one if the firm is regulated under EU ETS some time during the sample period, and zero otherwise. *Low (High) pace* (pollution abatement costs and expenditure) is an indicator variable taking on the value one if the firm is located in an industry below (above) the median in terms of air pollution abatement costs and expenditures relative to sales, and zero otherwise. *Low (High) mobility* is an indicator variable taking on the value one if the firm is located in an industry above (below) the median in terms of the real structures capital stock to sales, and zero otherwise. *Not on leakage list* and *On leakage list* are indicator variables taking on the value one if the sector the firm is operating in is either not on or on the EU's Carbon leakage list. *D1-D4* is an indicator variable taking on the value one if the firm is located in an industry in the first to fourth decile in terms of CO_2 emission to sales in 1990, and zero otherwise. *D5-D8* and *D9-D10* are based on firms from deciles 5–8 and 9–10, respectively. Decile 1 (10) means lowest (highest) emission intensity. The firm ownership and financing variables are available over 1996–2015. *Public (Private) firm* is an indicator variable taking on the value one (zero) if the firm is (not) listed on a Swedish stock exchange. A firm is considered publicly listed if at least one firm in the corporate group is publicly listed at least once during the sample period. *Large (Small) firm* is an indicator variable taking on the value one (zero) if the firm is above (below) the median in book value of total assets (averaged over the sample period and measured at the corporate group level) within its four-digit NACE industry. *High (Low) dividend firm* is an indicator variable taking on the value one (zero) if the firm is above (below) the median in dividend payout divided by book value of total assets (averaged over the sample period and measured at the corporate group level) within its four-digit NACE industry. *Mature (Young) firm* is an indicator variable taking on the value one (zero) if the firm's founding year (measured at the corporate group level) is below (above) the median within its four-digit NACE industry.

in 1990. Specifically, we sum up all (heating) CO_2 emissions as well as PPI-deflated sales across all firms in each four-digit industry each year. For deflating sales, we use 2010 as the base year and deflate using the Swedish Producer Price Index at the four-digit NACE code level. Removing the effect of sector-level price variation on sales is important to ensure that changes in emission intensities are not completely driven by changing output prices (e.g., resulting from producers passing on carbon tax to their customers). We then rank the industries depending on the ratio between aggregate emissions divided by aggregate sales in 1990 (the year before the introduction of the carbon tax) from highest to lowest and divide them into deciles. This results in 10 bins of about 20 four-digit industries each. We describe how Swedish manufacturing CO_2 emissions have evolved over our sample period in the Internet Appendix C.

Table B.2 in the Internet Appendix shows the distribution of emissions across two-digit NACE sectors. The most emission intensive manufacturing firms are found in nonmetallic mineral products, (such as cement, plaster, mortar, and glass production), coke and refined petroleum products, paper and paper products, textiles, basic metals (particularly iron and steel production), chemicals, and food (particularly sugar production). These seven sectors contain 82% of the four-digit subsectors in deciles 9 and 10 and jointly account for almost 88% of aggregate manufacturing CO_2 emissions in 1990.

2.2 The effect of changing carbon tax regimes

Our identification relies on cross-sectional variation in firms' marginal tax rates, allowing us to control for time, firm, and year times sector dummies to isolate the effect of carbon pricing on emissions. This variation is due to the various exemptions that high-emitting firms enjoyed at various times during our sample period, summarized in Table 1. Figure 3 illustrates the tax rates a hypothetical firm would face across different regimes.

The numerous changes in the tax schedule lead to substantial variation in carbon taxation in both the time-series and the cross-section. Figure 4 shows how the average effective tax rate, computed as total carbon taxes paid divided by total CO_2 (heating) emissions (*Average tax*), and the marginal tax rate for the next emitted unit of CO_2 (*Marginal tax*) evolves over time for two types of firms. The first type is a firm with emissions consistently below the thresholds for tax exemptions and that does not have any plants included in the EU ETS. For such firms, the average tax rate equals the marginal tax rate throughout the sample period. The second type is a firm whose emissions consistently lie above the carbon tax exemption thresholds and whose plants eventually transition into the EU ETS. Before EU ETS, the average tax rate exceeded the marginal tax rate for high-emitting firms, except for 1993–1996, when exemptions had been removed. After EU ETS was introduced in 2007, the implicit marginal tax rate, reflected in the price of emission rights, increased considerably, while the average tax rate stayed roughly constant due to free allocations of emission rights.[13]

[13] During the 2008–2011 transition period, the marginal cost of emissions equalled the weighted sum of emission allowance prices and marginal carbon tax rates for firms under the EU ETS (the latter could be equal to zero if

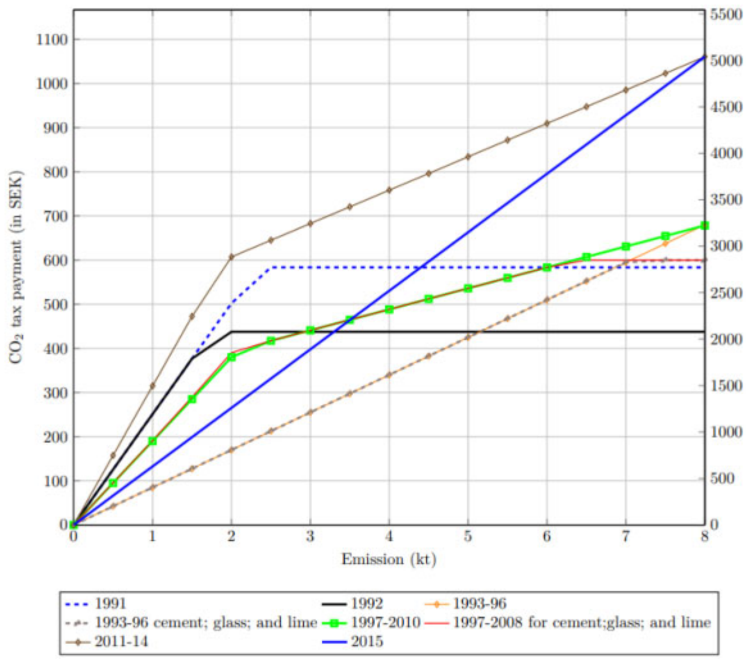

Figure 3
Changes to the carbon tax: Emissions and carbon tax payments by regime
This figure compares the carbon tax payments under the different regimes through a representative manufacturing firm. The hypothetical firm earns 50,000 SEK each year, and assumed to burn only coal in 1991 and 1992. All carbon tax payments with the exception of 2015 are shown on the vertical axis on the left side. Carbon tax payments in 2015 are shown on the vertical axis on the right side.

The significant differences in marginal and average tax rates across groups have important economic implications, as a firm's incentive to reduce CO_2 emissions depends on the former while its effective tax payments depend on the latter. Before the introduction of the EU ETS, high-emitting firms thus had relatively low marginal incentives to reduce emissions, despite paying a large fraction of their profits in carbon tax. After the introduction of EU ETS, marginal emission costs for high emitters increased substantially, while overall carbon tax payments decreased due to the free allowance of emission rights.

2.3 Decomposing Sweden's manufacturing CO_2 emissions

In Figure 5, we decompose the change in aggregate CO_2 emissions from Swedish manufacturing using the framework developed in

the combined costs of emissions exceed the designated exemption threshold). From 2011 plants covered by the EU ETS were completely exempt from the carbon tax.

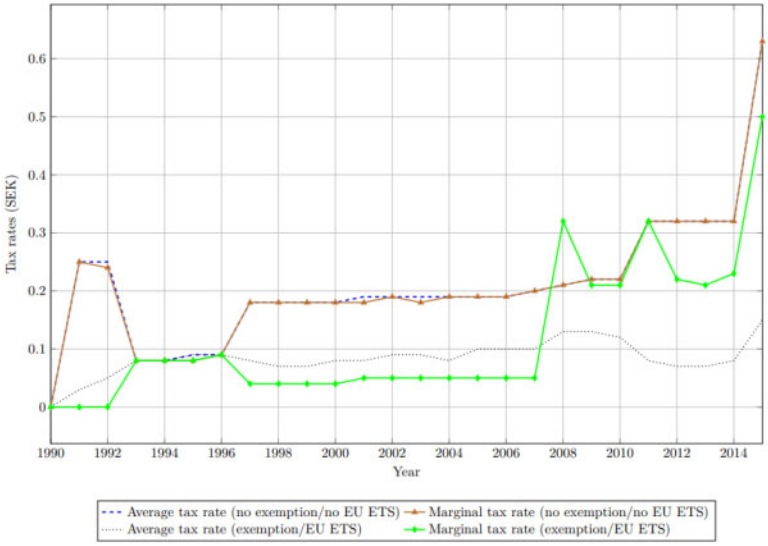

Figure 4
Average and marginal tax rates (1990–2015)
This figure displays the average and marginal tax rates depending on whether the firm is eligible for carbon tax exemptions and covered by the EU ETS. *no exemption/no EU ETS* denotes firms that are not regulated by the EU ETS and are not entitled to carbon tax exemption, *exemption/EU ETS* refers to the firms with available exemptions until they enter the emission trading scheme. Marginal tax rates for EU ETS are the price for emission rights.

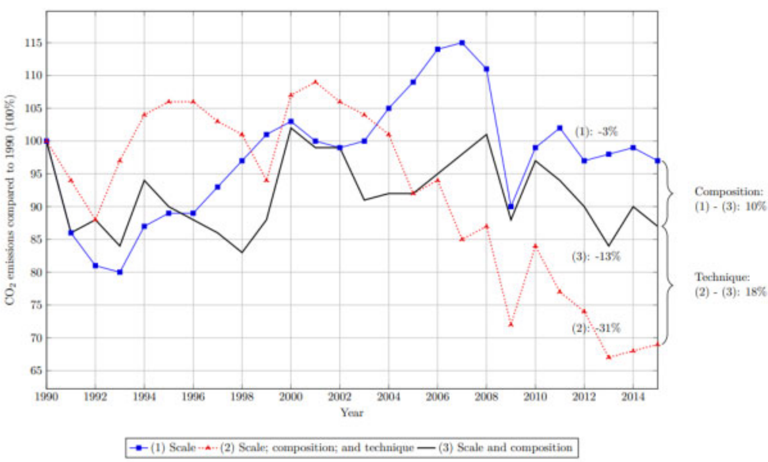

Figure 5
Carbon dioxide emissions from Swedish manufacturing (1990–2015)
This figure displays the decomposition of the Swedish carbon dioxide emission reduction. *Scale* captures how emissions would have evolved without tangible technological progress and structural changes in the manufacturing sector. *Composition* refers to the change in industry composition, and *Technique* captures the technological progress in the industrial sector.

Grossman and Krueger (1991) and Grossman and Krueger (1993).[14] The actual level of CO_2 emissions in 2015 was 31% lower than in 1990, representing the combined scale, composition and technique effects. Holding sector composition and emission intensities constant from 1990 and onward, CO_2 emissions would only have decreased by 3% in 2015, reflecting a 3% decrease in manufacturing output. Keeping emission intensities constant, but also allowing sector composition to change as in the data, CO_2 emissions would have been 13% lower. The 10% difference is the composition effect, indicating that a move toward less carbon-intensive manufacturing subsectors accounts for almost a third of the aggregate decrease in emissions. The residual technique effect is 18%, or almost two-thirds of the reduction in CO_2 emissions 1990–2015.

The technique effect incorporates the impact of carbon pricing on emission intensities that is the focus of our study. A few caveats are in order, however. First, at least part of the decrease attributed to scale and composition was also likely affected by carbon pricing. Since it is difficult to estimate carbon pricing elasticities of output reliably using our reduced-form approach, we choose to focus on emission intensities in this study.[15] To the extent carbon pricing also decreased the consumption of goods produced by higher-emitting firms, we will be underestimating the total effect of carbon pricing on aggregate emissions. Second, our emission intensity measure normalizes emissions with sales (e.g., revenues of a steel company) rather than actual output (e.g., tons of steel produced). While we deflate sales with PPI at the four-digit NACE level, our estimates can still be affected by relative price changes across firms within each four-digit subsector (see Foster, Haltiwanger, and Syverson 2008). As a result, the carbon pricing elasticities we estimate may also capture other strategic responses beyond changes in production technology, such as within-sector differences in pricing power (as in De Loecker and Warzynski 2012), and/or product mix across firms, and therefore should be interpreted in a broader sense.[16]

3. Short-Term Effects of Carbon Pricing

Before estimating carbon pricing elasticities, we first examine the short-run responses of firm-level emission intensities to the introduction and subsequent changes in the Swedish carbon taxation scheme. Similar to Colmer et al.

14 This approach is formalized in Copeland and Taylor (1994) and further discussed in Copeland and Taylor (2004). We follow the approach described in section I of Levinson (2009), who applies this decomposition to U.S. sulphur dioxide emissions. See Internet Appendix D for a detailed description of how Figure 5 was constructed.

15 One reason is that total output changes are more likely to be due to "carbon leakage," that is, goods produced in Sweden simply being replaced by foreign-produced goods. We discuss the potential impact of "carbon leakage" on our emission elasticity estimates in subsection 4.3.

16 This is a problem we share with much of the productivity literature (see, e.g., Foster, Haltiwanger, and Syverson 2008).

(2022), we use a difference-in-differences approach that compares the changes in emission intensities between otherwise similar firms whose marginal cost of emissions is affected differently by a change in taxation.

As is typical in event studies, the interpretation of the results implicitly depends on assumptions regarding the expectations and rationality of relevant decision makers. To the extent the subsequent changes in tax rates are anticipated by firms, this would affect their response to a current tax change. While it is plausible that the initial introduction of the carbon tax in 1991 was at least partly anticipated (which biases against finding a short-term response), the bipartisan political commitment to environmental taxation in Sweden in the wake of the major tax reform of 1991 (Government Bill 1989/90:111 1989) and the strong reliance of the government on environmental tax revenues (Tax Shift Commission 1997) make it less likely that firms anticipated subsequent changes in carbon taxation, at least until the introduction of the EU ETS.[17]

The introduction of carbon taxation in 1991 and its first revision in 1993 provide relatively clean events to analyze. In 1991 and 1992, caps were in place so that a firm's carbon tax never exceeded a certain percentage of sales. In 1993, these caps were removed in conjunction with an overall reduction in the statutory carbon tax rate. Accordingly, we divide firms into those who qualified for an exemption in 1991-1992 and those that did not. Table 3 reports average marginal costs (panel A) and emissions-to-sales (panel B) for the periods 1990, 1991–1992, and 1993–1996. We focus on firms from decile 10 as most emissions are concentrated there and the vast majority of firms are present in the sample for all years. We exclude firms in the cement, lime and glass sectors from this test as the tax changes did not apply to them.[18]

In 1990, before the tax was introduced, both groups of firms face a zero marginal cost of emitting carbon. After the introduction in 1991–1992, firms not qualifying for exemptions experienced a marginal tax increase of 0.203 Swedish krona (SEK) per kg of emitted CO_2, while firms with exemptions, despite paying substantial amounts of carbon taxes, still faced a zero marginal tax rate. In the 1993–1996 period, following the first tax change, both groups were taxed at 0.084 SEK/kg with no exemptions. This led to a marginal tax increase of 0.084 for firms with exemptions in the 1993–1996 period and a marginal tax decrease for the nonexemption group of −0.119. The difference-in-differences changes in marginal tax across groups are highly

[17] We provide additional detail on climate policy expectations in a Swedish setting in the Internet Appendix A. However, expectations aside, the direct effect of carbon taxes on firms' cash flows can also lead to an immediate response in and of itself (see Zwick and Mahon 2017). Furthermore, changes in carbon taxation can also coincide with other changes in taxation and the overall economic environment. We address the potential role of industry specific shocks unrelated to carbon taxation and other tax changes (e.g., green tax shifting) in the econometric tests below.

[18] Cement, lime and glass firms consistently enjoyed tax exemptions and effectively faced a zero marginal tax rate until the introduction of EU ETS.

Table 3
Firms with and without exemptions around the 1991, 1993, and 1997 tax changes

	Exemption (1)	No exemption (2)	Diff in groups (3)	w Ind. F.E. (4)
A. 1991 and 1993 events: Marginal cost of CO_2 (SEK/Kg)				
Period 1: 1990	0.0000	0.0000	0.0000	
			(1.0000)	
Period 2: 1991–1992	0.0000	0.2034	−0.2034	
			(0.0168)	
Period 3: 1993–1996	0.0842	0.0844	−0.0001	
			(0.0006)	
Difference periods: 2-1	0.0000	0.2034	−0.2034	−0.2036
	(1.0000)	(0.0096)	(0.0242)	(0.0239)
Difference periods: 3-2	0.0842	−0.1191	0.2033	0.2029
	(0.0009)	(0.0047)	(0.0118)	(0.0118)
B. 1991 and 1993 events: Emissions-to-sales				
Period 1: 1990	0.0865	0.0106	0.0759	
			(0.0053)	
Period 2: 1991–1992	0.1027	0.0110	0.0917	
			(0.0032)	
Period 3: 1993–1996	0.1005	0.0162	0.0843	
			(0.0032)	
Difference periods: 2-1	0.0162	0.0004	0.0158	0.0165
	(0.0115)	(0.0015)	(0.0060)	(0.0057)
Difference periods: 3-2	−0.0022	0.0052	−0.0074	−0.0071
	(0.0084)	(0.0015)	(0.0050)	(0.0047)
C. 1997 event: Marginal cost of CO_2 (SEK/Kg)				
Period 1: 1993–1996	0.0844	0.0845	−0.0001	
			(0.0008)	
Period 2: 1997–2000	0.0756	0.1721	−0.0964	
			(0.0068)	
Difference in periods	−0.0087	0.0876	−0.0964	−0.0968
	(0.0074)	(0.0031)	(0.0068)	(0.0065)
D. 1997 event: Emissions-to-sales				
Period 1: 1993–1996	0.0706	0.0170	0.0536	
			(0.0036)	
Period 2: 1997–2000	0.0784	0.0151	0.0633	
			(0.0038)	
Difference in periods	0.0078	−0.0019	0.0098	0.0100
	(0.0077)	(0.0014)	(0.0052)	(0.0047)

This table reports the change in marginal cost and emission intensity for firms with (column 1) and without exemptions (column 2) around the 1991 introduction of the carbon tax and subsequent change in 1993 (panels A and B) and the 1997 event (panels C and D). Column 4 reports the difference in difference controlling for four-digit industry fixed effects. The sample includes firms from decile 10 sectors in panels A and D and is restricted to firms with observations each year over 1993–2000 in panels C and D. Panels A and C present the marginal cost of emitting CO_2 for the manufacturing firms and panels B and D the emission intensities. Standard errors are displayed in parentheses.

significant around both the introduction (−0.203) and the subsequent change 1993–1996 (0.203).

By construction, firms in the exemption group have higher emissions-to-sales than the nonexemption group (0.087 vs. 0.011 in 1990). After the introduction of the tax in 1991–1992, firms in the nonexempt group display similar emissions-to-sales ratios as they did in 1990. In contrast, firms in the exempt group, who still faced a zero marginal tax rate, increase their emissions-to-sales by about 18% (from 0.087 to 0.103). The diff-in-diff estimate of 0.016 is significant at the 1% level, consistent with higher marginal carbon taxes leading to lower emission intensities. In the 1993–1996 period, following the tax change, nonexempt firms (whose marginal tax was cut), experience a statistically significant increase in their emissions-to-sales of about 45%. Firms in the exempt group (whose marginal tax rate increased) instead saw a slight 3% decrease emissions-to-sales ratios. The diff-in-diff estimate between groups between 1991–1992 and 1993–1996 is a negative -0.007. While the diff-in-diff is not statistically significant at conventional levels, the change is again consistent with firms responding to carbon taxes by reducing emissions. Both diff-in-diff estimates are robust to including four-digit industry dummies (column 4).

In panels C and D of Table 3, we consider the subsequent tax change in 1997. The preceding years (1993-1996) was the only time during our sample period when all manufacturing firms (except for cement, lime and glass) faced the same marginal carbon tax rate. The tax change in 1997 more than doubled the marginal tax rate (from around 0.09 to 0.19 SEK/kg) but reintroduced an exemption for firms with tax payments above 0.8% of sales, for whom the marginal tax was reduced to one quarter of the statutory rate. We again focus on decile 10 subsectors, and divide firms into those qualifying for the exemption and those that did not. We require firms to be present during the entire period 1993–2000, to avoid capturing effects due to changes in the sample composition.

Panel C reports changes in marginal taxes. The two groups of firms face the same marginal cost of emitting CO_2 in the pre-period 1993–1996. The 1997 changes led exempt firms to experience a small marginal tax reduction of 0.009, while nonexempt firms faced a large increase in marginal tax of 0.087. Panel D shows the corresponding changes in emission intensities around this event. Again, by construction, exemption firms have higher emissions-to-sales ratios in the pre-period. While the differences within each group are not statistically significant, they both evolve as predicted: average emissions intensities increased by about 11% for exemption firms (whose marginal tax decreased) whereas it fell by about 11% for nonexempt firms (whose marginal tax increased). The diff-in-diff estimate of 0.0098 is positive and statistically significant, again indicating a negative short-run relationship between marginal carbon pricing and emission intensities.

The results from these event studies suggest that carbon pricing can have a visible impact on emissions even in the short run. But since significant adjustments of technology and/or strategy probably take several years for firms to fully implement, it is more relevant to evaluate the longer-term effects of such policies.

4. Estimation of Carbon Pricing Elasticities

4.1 Main specification

We now turn to the longer-term impact of carbon pricing on CO_2 emissions. As firms' incentives should depend on the marginal (rather than the average) cost (e.g., Cropper and Oates 1988), we let emission intensity be a function of the marginal carbon tax rate.

There are a few specification issues that need to be dealt with. First, some of the responses to carbon pricing involve significant investments and possibly other strategic changes that take time to implement. In addition, expectations about future tax changes may affect the speed of the response to current taxes. Since it is not theoretically clear at what time lag carbon pricing should affect firms' CO_2 emissions, we allow for the lag length to differ across specifications.[19] Second, the elasticity of emissions to carbon pricing is likely to be heterogeneous across firms and/or industries, since it depends on factors, such as the ability of firms to pass the tax on to their customers through higher prices,[20] the ability to move production to other jurisdictions, costs of emissions abatement, and the ability to finance such abatement. In addition to including fixed effects, we will address such heterogeneity by estimating elasticities for relevant subsamples.

Following Shapiro and Walker (2018) we estimate the base-line regression

$$\Delta ln\left(\frac{E_{\mathrm{i,t}}}{Y_{\mathrm{i,t}}}\right)=\alpha+\sum_{s=1}^{q}\beta_{\mathrm{s}}\cdot\Delta ln(1-C_{\mathrm{i,t\text{-}s}})+\mu_{\mathrm{i}}+\mu_{\mathrm{t}}+\epsilon_{\mathrm{i,t}}, \qquad (1)$$

where E is kilograms of CO_2 heating emissions divided by PPI-adjusted sales (Y, in 2010 SEK) for firm i in year t. $C_{i,t\text{-}s}$ is the emissions cost share relative to sales for firm i in year t-s.[21] For firms with plants covered under EU ETS we compute the marginal tax rate (per kg of CO_2 emissions) as the average marginal tax rate in a given firm-year under the Swedish carbon tax system (for the installations not under EU ETS) and the average market price of the emission trading permits in the corresponding year (for the installations covered by EU ETS). $ln(1-C_{i,t\text{-}s})$ captures the share of sales left after paying

[19] Similar issues around lag length also comes up when modeling of the response of the capital-output ratio to changes in corporate taxation (e.g. Bond and Xing 2015). Using text from regulatory findings, Dessaint, Foucault, and Fresard (2022) estimate an average investment horizon of 4.45 years for U.S.-listed firms, ranging between 3.12 years (Defense) and 7.15 years (Utilities) across FF49 industries (Fama and French 1997). In particular, Steel, Chemicals, and Refining—three of the sectors with the highest emission intensities—can be found among the 10 industries (of the 49) with the longest investment horizon in their sample.

[20] It should be noted that most Swedish manufacturing firms are limited in their ability to pass on the tax cost to customers, since the bulk of their production is exported in competitive world markets. Exports make up about 70% of manufacturing value added in Sweden, and over 80% in high-emitting sectors, such as basic metals, chemicals, and paper and paper products (Flam 2021).

[21] In Shapiro and Walker (2018), the specification in log differences is partly motivated by the need to account for firm-specific heterogeneity. While we are able to add firm fixed effects thanks to our long panel, we choose to keep the log differences specification to alleviate problems of unit roots in our variables.

Table 4
Carbon pricing and firm-level carbon emission intensity

	(1) All	(2) All	(3) All	(4) All	(5) All	(6) D1-D4	(7) D5-D8	(8) D9-D10
$\Delta\ln(1-C)_{(i,t\text{-}1)}$	0.751***	0.968***	1.170***	1.115***	1.171***	2.828***	1.246***	0.838***
	(0.146)	(0.157)	(0.229)	(0.248)	(0.276)	(0.884)	(0.441)	(0.284)
$\Delta\ln(1-C)_{(i,t\text{-}2)}$			0.402**	0.585***	0.732***	1.711***	0.741*	0.484*
			(0.179)	(0.210)	(0.231)	(0.656)	(0.440)	(0.258)
$\Delta\ln(1-C)_{(i,t\text{-}3)}$				0.377**	0.289*	2.184***	0.747**	−0.025
				(0.159)	(0.153)	(0.482)	(0.349)	(0.168)
$\sum \Delta\ln(1\text{-}C)$	0.751***	0.968***	1.572***	2.077***	2.193***	6.722***	2.733**	1.297***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.002)	(0.013)	(0.007)
Firm fixed effects	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Industry-year fixed effects	No	No	No	No	Yes	No	No	No
Observations	24,943	24,757	19,485	15,001	13,948	5,529	6,284	3,130
Within R^2	.007	.014	.019	.017	.020	.076	.016	.015

This table reports OLS estimates of Equation (1). $\Delta ln(E/Y)_{i,t}$ is the dependent variable. E is firm-level CO_2 emissions in kilograms (kg) and Y is firm-level, PPI-adjusted sales in Swedish krona (SEK). The sample comprises manufacturing firms in Sweden with both CO_2 emissions and sales data and with at least four consecutive observations over 1990–2015. D1-D4 include firms from the four-digit industries with emissions to sales in 1990 in the lowest 40%, D5–D8 from four-digit industries from the 5th to the 8th decile in terms of emissions intensity, and D9–D10 include firms from the highest 20% (i.e., the two highest deciles). Regressions in columns 2–8 include firm fixed effects. Regressions in columns 1–4 and 6–8 include year fixed effects and column 5 includes industry (four-digit NACE) by year fixed effects. C is the emissions cost share relative to sales for firm i in year t. The standard errors are clustered at the firm level. $\sum \Delta\ln(1\text{ - }C)$ present an F-test of joint significance. *p <.1; **p <.05; ***p <.01.

for one more unit of CO_2 emissions and makes it possible to take logs when $C_{i,t\text{-}s}=0$. The lagged terms of C allow for a delayed response to tax changes. We expect $\sum_{s=1}^{q}\beta_s>0$ if firms reduce emission intensities in response to marginal carbon pricing. μ_i captures firm-specific time-invariant factors that could affect the relation between CO_2 emissions and sales. μ_t absorbs changes in CO_2 emissions to sales that are common to all firms in a given year.

4.2 Baseline results

Table 4 presents baseline results from estimating Equation (1) with q=*1* up to q=*3*. In columns 1 and 2, we display results with the marginal cost share of sales at the beginning of the year without and with firm fixed effects. The change in the marginal cost of CO_2 emissions is strongly related to changes in firm-level carbon emissions intensity. The result implies that a change in the marginal cost of emissions to sales is associated with a change in carbon intensity by about a factor of one. (We will further discuss the economic magnitude of these estimates in Section 5.) Adding $\Delta ln(1-C_{\text{i,t-2}})$ (column 3) yields a larger estimate of the $t-1$ coefficient and a joint impact of around 1.6. In column 4 we also include a third lag $\Delta ln(1-C_{\text{i,t-3}})$, which increases the estimated joint impact to a total elasticity of 2.1 (with all three lag coefficients being statistically significant). In unreported regressions, we show that additional lags have small and a statistically insignificant coefficients and leave the joint estimated magnitude largely unchanged. We therefore choose the specification with $q=3$ as our baseline model.[22] In column 5 we include a full set of four-digit industry by year fixed effects to control for differences in industry trends and shocks over time, which results in a slightly higher estimated total elasticity of 2.2.

Since the top deciles of emitters account for a disproportionately large fraction of total CO_2 emissions, it is particularly relevant to investigate possible heterogeneity in this dimension. The remaining three columns in Table 4 show results for three subsamples split according to 1990 subsector emission deciles as in Tables B.3 and B.4 in the Internet Appendix.

Column 6 shows estimates for firms with low emission intensities in 1990 (the bottom 40% of four-digit sectors in terms of CO_2 emissions to sales in 1990). The joint effect is three times larger for this subsample. Recall from Table B.3 in the Internet Appendix that firms from these sectors comprise under 6% of CO_2 emissions. In column 7 we consider the group of firms from deciles 5 to 8. The estimated joint carbon pricing effect is 2.7 and highly statistically significant. In column 8, we consider firms from deciles 9 and 10, which have significantly higher emissions-to-sales ratios compared to firms in other manufacturing subsectors and jointly account over 80% of CO_2 emissions in 1990. The joint carbon pricing effect in this subsample is considerably lower than in the other deciles (reported in columns 6 and 7) and also lower than the one estimated for the full sample in column 4. The results in the final three columns in Table 4 suggest that firms in subsectors with production technologies associated with higher CO_2 emissions also have the highest cost of abatement. We carry out additional tests to shed more light on this possible mechanism below.

Table 5 reports the results from a set of additional robustness tests. To account for the possibility that EU's cap-and-trade system leads to different carbon pricing elasticities, we interact our marginal cost variable with an indicator variable taking on the value one if the firm-year is regulated under EU ETS and zero otherwise. We report results both for the full sample and for the subsample of firms in deciles 9 and 10, where almost all EU ETS regulated firms belong. We also control for the impact of broader changes to corporate taxation (by including the cost share of income taxes to sales) and for green tax shifting (by including labor taxes to sales), respectively, on firm CO_2 emissions.[23] Finally, following Brännlund, Lundgren, and Marklund (2014),

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[22] To make sure our results are not sensitive to the reduction in sample size from using three lags in column 4, we reestimate the specifications in columns 1–3 and find very similar results (see Table B.5 in the Internet Appendix).

[23] As discussed in Section 1, the carbon tax was initially a part of a larger tax reform which included elements of so-called "tax shifting." However, the correlations between the firm-level emissions cost share ($C_{i,t\text{-}s}$) and the corporate income tax ($CIT_{i,t\text{-}s}$) and the labor tax ($Labor_{i,t\text{-}s}$) shares, respectively, are only modest (−0.023 and −0.083). Our results are robust to including these firm controls in all tests.

Table 5
Carbon pricing and carbon emission intensity: EU ETS, firm size, and capital intensity

	(1) All	(2) D9-D10	(3) CIT	(4) Labor	(5) All	(6) All	(7) All
$\Delta\ln(1 - C)_{(i,t-1)}$	1.414***	1.025***	1.115***	1.134***	1.008***	1.012***	1.011***
	(0.327)	(0.392)	(0.247)	(0.265)	(0.253)	(0.252)	(0.253)
$\Delta\ln(1 - C)_{(i,t-2)}$	0.684***	0.508	0.586***	0.610***	0.512**	0.514**	0.515**
	(0.246)	(0.329)	(0.210)	(0.224)	(0.205)	(0.205)	(0.205)
$\Delta\ln(1 - C)_{(i,t-3)}$	0.351*	−0.208	0.374**	0.387**	0.245*	0.243*	0.245*
	(0.188)	(0.218)	(0.160)	(0.169)	(0.137)	(0.137)	(0.138)
EU ETS	0.000	0.000					
	(0.001)	(0.001)					
x $\Delta\ln(1 - C)_{(i,t-1)}$	−0.953**	−0.470					
	(0.390)	(0.407)					
x $\Delta\ln(1 - C)_{(i,t-2)}$	−0.317	0.008					
	(0.308)	(0.392)					
x $\Delta\ln(1 - C)_{(i,t-3)}$	0.180	0.630*					
	(0.303)	(0.378)					
$\Delta\ln(1 - T)_{(i,t-1)}$			0.004	0.006			
			(0.010)	(0.004)			
$\Delta\ln(1 - T)_{(i,t-2)}$			−0.011	0.006			
			(0.009)	(0.006)			
$\Delta\ln(1 - T)_{(i,t-3)}$			−0.004	0.005			
			(0.006)	(0.004)			
$\ln(EMP)_{(i,t)}$					−0.002***		−0.002***
					(0.001)		(0.001)
$\ln(CAP/EMP)_{(i,t)}$						0.001***	0.001***
						(0.000)	(0.000)
$\sum \Delta\ln(1 - C)$	1.359**	1.493**	2.075***	2.131***	1.765***	1.769***	1.770***
	(0.017)	(0.030)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	15,001	3,130	15,001	13,952	14,828	14,789	14,789
Within R^2	.021	.019	.018	.018	.027	.023	.030

Table 5 reports OLS estimates of Equation (1). $\Delta ln(E/Y)_{i,t}$ is the dependent variable. E is firm-level CO_2 emissions in kilograms (kg) and Y is firm-level, PPI-adjusted sales in Swedish krona (SEK). The sample comprises manufacturing firms in Sweden with both CO_2 emissions and sales data and with at least four consecutive observations over 1990–2015. In column 2 (D9 and 10), we only include firms from the four-digit industries with emissions to sales in 1990 in the highest 20% (i.e., the two highest deciles). All regressions include firm and year fixed effects. C is the emissions cost share relative to sales for firm i in year t. T is the share of corporate income taxes (CIT) relative to sales for firm i in year t in column 3 and the share of labor taxes (Labor) to sales for firm i in year t in column 4. Labor tax data ends in 2013 so the sample in column 4 is 1990–2013. *EU ETS* is an indicator variable taking on the value one when a firm-year has at least one plant regulated under EU ETS. The standard errors are clustered at the firm level. $\sum \Delta\ln(1 - C)$ present an F-test of joint significance. $^*p < .1$; $^{**}p < .05$; $^{***}p < .01$.

we include firm size and capital intensity as control variables. The estimated elasticities are essentially unchanged across these alternative specifications.

4.3 Heterogeneity and carbon leakage

4.3.1 Abatement costs and mobility. We now consider two additional sources of heterogeneity that have been shown in previous literature to affect firms' responses to environmental taxation: abatement cost and mobility.

First, while the marginal benefit of reducing a unit of emissions depends on the marginal tax rate, this has to be weighed against the marginal cost, which should be different depending on production technologies and other firm- or industry-specific characteristics. While we do not have access to marginal abatement costs (MAC) for different manufacturing subsectors (see Gillingham and Stock 2018), we utilize estimates of pollution abatement costs expenditures (PACE) (e.g., Becker 2005) as a proxy. Under the assumption that abatement cost curves are increasing and convex, industries with higher PACE would also have higher MAC. We use Swedish data on environmental protection expenditure to mitigate air pollution to construct an industry-level measure of PACE. Specifically, we first calculate the ratio of the sum of PACE and aggregated industry sales for each four-digit industry and take the average over the sample years.[24] We split the sample into low (below median-industry PACE) and high (above median-industry PACE) abatement costs and expenditures in columns 1 and 2 of Table 6. We estimate an elasticity of around 3 for firms in low-PACE sectors, compared to an estimate below 2 for firms in high-PACE sectors. This suggests that firms with lower abatement costs respond more to changes in the marginal CO_2 emission cost, consistent with the hypothesized cost-benefit trade-off.

Second, we consider how the geographic mobility of assets affects firms operating across low- and high-PACE sectors. Firms in high-mobility industries should be more likely to move their production facilities to other countries in order to avoid paying Swedish carbon tax compared to those in low-mobility industries. If firms move their most emission-intensive plants in response to an increase in carbon pricing, this might result in a higher estimated emission elasticity, since lower-emitting plants have higher elasticities.[25] Following Ederington, Levinson, and Minier (2005), we use Swedish investment survey data to calculate the ratio of the sum of the real structures capital stock to aggregate sales for each four-digit industry and average over the sample years.[26] Firms in sectors with a fixed-cost ratio above (below) the median are defined as having low (high) mobility.

[24] The environmental expenditure data are based on a survey from Statistics Sweden and spans 2002–2015. There is a potential issue of endogeneity, since total abatement costs over this period may have been a function of carbon pricing (although it should be noted that these costs primarily refer to pollution abatement in general, rather than reduction of greenhouse gases). This is mitigated by the fact that we are only using this measure to rank industries above versus below median, and these rankings are very stable over time. Moreover, our inferences on PACE are similar if we instead use US PACE data from U.S. Bureau of the Census (1990) normalized by value of shipments for each four-digit sector in 1990 to rank industries (using data from Becker, Gray, and Marvakov 2013).

[25] Another potential source of carbon leakage could be that firms reduce emissions through importing rather than manufacturing certain high-emission inputs. Analyzing Swedish data similar to ours, Forslid, Akerman, and Prane (2021) find that while increasing imports are associated with lower emission intensity, this effect is not due to the offshoring of dirty activities.

[26] Specifically, to measure the real structures capital stock, we (i) take for each firm-year from the investment survey the expenditure in real structures over total capital expenditure (structures plus equipment) and (ii) multiply this fraction with the value of tangible assets (Plant, Property, and Equipment) from the firm's balance sheet. In the case with missing values for four-digit industries, we use the mobility measure of the two-digit industry. Our results with mobility are robust to using US data from the NBER-CES Manufacturing Industry Database as in Ederington, Levinson, and Minier (2005).

Table 6
Carbon pricing and carbon emission intensity: PACE and mobility

	(1)	(2)	(3)	(4)	(5)	(6)
	PACE		Low PACE		High PACE	
	Low	High	Low mobility	High mobility	Low mobility	High mobility
$\Delta\ln(1 - C)_{(i,t-1)}$	1.320***	1.088***	1.375**	1.288***	0.942***	1.685***
	(0.394)	(0.297)	(0.586)	(0.491)	(0.335)	(0.651)
$\Delta\ln(1 - C)_{(i,t-2)}$	0.849***	0.527**	1.100***	0.614	0.552*	0.368
	(0.298)	(0.261)	(0.346)	(0.425)	(0.296)	(0.533)
$\Delta\ln(1 - C)_{(i,t-3)}$	0.832***	0.281	0.304	1.027***	0.228	0.399
	(0.213)	(0.202)	(0.279)	(0.267)	(0.199)	(0.598)
$\sum \Delta\ln(1 - C)$	3.000***	1.895***	2.779***	2.928***	1.721***	2.452*
	(0.000)	(0.001)	(0.006)	(0.003)	(0.006)	(0.059)
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	6,671	7,568	3,023	3,591	4,773	2,673
Within R^2	.024	.016	.034	.023	.013	.035

This table reports OLS estimates of Equation (1). $\Delta ln(E/Y)_{i,t}$ is the dependent variable. E is firm-level CO_2 emissions in kilograms (kg) and Y is firm-level, PPI-adjusted sales in Swedish krona (SEK). The sample comprises manufacturing firms in Sweden with both CO_2 emissions and sales data and with at least four consecutive observations over 1990–2015. All regressions include firm and year fixed effects. C is the emissions cost share relative to sales for firm i in year t. The standard errors are clustered at the firm level. $\sum \Delta\ln(1 - C)$ present an F-test of joint significance. *p <.1; **p <.05; ***p <.01.

Results are shown in columns 3–6 of Table 6. Firms in sectors defined as low PACE have a similar carbon pricing elasticity regardless of how mobile their assets are. This is intuitive, since firms with low costs of abating should be less likely to relocate in the face of higher carbon pricing. The mobility results for the high PACE subsample stand out for two reasons. First, almost two-thirds of the high PACE firms are located in sectors defined as being low mobility (similar to the finding in Ederington, Levinson, and Minier 2005). Second, the joint effect of $\Delta ln(1 - C)_{(i,t-s)}$ in the subsample of high PACE and high-mobility firms results in a higher estimated elasticity. This is noteworthy as the group of firms facing the highest costs of abating and at the same time have moveable assets are the most likely to consider relocation when faced with higher cost of emitting. The result should be interpreted with caution, however, as the subsample is small and the estimate is only marginally significant.

4.3.2 EU leakage list. In its effort to mitigate the risk that carbon pricing in the ETS would lead production to move outside of the European Union, EU classifies all industrial (four-digit) sectors with respect to their risk of such "carbon leakage." Plants in industries on the leakage list in turn receive a higher share of free allowances under the EU ETS.[27] Sectors can be deemed at risk

[27] For details, see https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/free-allocation/carbon-leakage_en. European Commission (2009) lists initial carbon leakages. Free allowances will be phased out in the EU ETS starting in 2026.

Table 7
Carbon pricing and carbon emission intensity: Carbon leakage

	(1)	(2)	(3)	(4)
	Leakage list		Leakage list Yes	
	No	Yes	Trade only	Emission
$\Delta \ln(1 - C)_{(i,t-1)}$	1.257***	1.062***	1.605**	0.956***
	(0.457)	(0.301)	(0.645)	(0.329)
$\Delta \ln(1 - C)_{(i,t-2)}$	0.565	0.609**	0.793	0.644**
	(0.419)	(0.247)	(0.504)	(0.303)
$\Delta \ln(1 - C)_{(i,t-3)}$	0.764**	0.214	0.950***	−0.057
	(0.332)	(0.170)	(0.308)	(0.193)
$\sum \Delta \ln(1 - C)$	2.585***	1.885***	3.348***	1.543***
	(0.009)	(0.000)	(0.008)	(0.007)
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	7,228	7,737	5,805	1,932
Within R^2	.015	.021	.039	.021

This table reports OLS estimates of Equation (1). $\Delta ln(E/Y)_{i,t}$ is the dependent variable. E is firm-level CO_2 emissions in kilograms (kg) and Y is firm-level, PPI-adjusted sales in Swedish krona (SEK). The sample comprises manufacturing firms in Sweden with both CO_2 emissions and sales data and with at least four consecutive observations over 1990–2015. All regressions include firm and year fixed effects. C is the emissions cost share relative to sales for firm i in year t. The standard errors are clustered at the firm level. $\sum \Delta \ln(1 - C)$ present an F-test of joint significance. $^{*}p < .1$; $^{**}p < .05$; $^{***}p < .01$.

because of (a) high costs of carbon pricing (i.e., sectors with high emission intensity), (b) high level of international competition (i.e., high levels of trade outside of the EU), or (c) being exposed to both of these factors. In addition to capturing differences related to PACE and mobility, this classification also accounts for the ability of an industry to pass on the carbon emission cost to their customers.

Table 7 reports the estimation results. We first differentiate between sectors that are on versus outside the leakage list. While sample sizes are similar across groups, it is worth noting that over 90% of aggregate manufacturing emissions originate from firms on the carbon leakage list. We estimate a carbon pricing elasticity of around 2.6 for firms not on the carbon leakage list, compared to an elasticity below 2 for those on the list. The lower elasticity for firms deemed as being at risk of carbon leakage is consistent with those firms facing a larger difficulty in reducing their emission-to-sales ratios.

We further split firms into different categories considered by the EU for assessing the risk of carbon leakage. In column 3 we separately consider sectors on the list due to trade concerns (based on criterion “C”). Firms in these sectors face high international competition, but operate with technologies having relatively low emission ratios. We retrieve a considerably higher carbon pricing elasticity of 3.3 for this group. This implies that these firms, while having a limited ability to pass on tax costs to customers due to competition, are able to reduce emissions through technological or strategic means at a relatively low cost. In the final column, we report the carbon pricing elasticity of carbon leakage sectors with high emission intensities.[28] For this group we find a considerably lower elasticity of around 1.5, similar in size to the results for firms in deciles 9 and 10 in Table 4 and for those in high PACE and low-mobility sectors in Table 6. The similarity is not surprising given the substantial overlap in sector classifications across these subsamples.

4.4 Financial frictions and carbon pricing

The effect of carbon pricing may also depend on the severity of other externalities and market frictions. In particular, capital market imperfections widen the gap between the external and internal costs of capital (e.g., Hubbard 1998), which impedes the ability of firms dependent on external financing to fund abatement investments. Oehmke and Opp (2022) present a theory of socially responsible investment and show that carbon taxes alone may not achieve first-best outcomes in the presence of financing constraints. Empirically, Xu and Kim (2022) provide evidence from U.S.-listed firms that financial constraints lead to increased toxic releases; Ng, Wang, and Yu (2023), using listed-firm data for 51 countries, document that financially constrained firms emit more CO_2; and Bartram, Hou, and Kim (2022) find that financially constrained firms under California's CO_2 cap-and-trade program moved capacity to unregulated states and increased emissions.[29] In contrast, Shive and Forster (2020) find that U.S. independent private firms emit less greenhouse gases than comparable listed firms or PE-backed firms, even though listed and PE-sponsored firms would be expected to have easier access to external financing (Saunders and Steffen 2011).[30] We add to this literature by noting that the impact of financial constraints on emissions should also depend on the firm's marginal benefit of abatement (captured in the marginal tax rate) relative to the marginal cost (captured by the carbon pricing elasticity). In particular, we test whether carbon elasticities are different across groups of firms based on their ex ante likelihood of being financially constrained. Since we only have ownership data from 1996, the tests in this section are conducted on the 1996–2015 subsample.[31]

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[28] These are all sectors outside those categorized as "C" in the EU classification, and is mutually exclusive to the sample in column 3. This subsample includes firms categorized in group "A" (high emissions and some trade concerns) or group "B" (very high emissions but no trade concerns).

[29] Related work include De Haas and Popov (2023), who find that CO_2-intensive industries reduce emissions faster in countries with more developed stock markets; and Lanteri and Rampini (2023) analyze how financial constraints affect clean technology adoption. In addition, the corporate finance literature on firm environmental responses has shown that stronger liability protection is associated with higher toxic emissions (Akey and Appel 2021), and that pollution taxes make high-emitting firms increase R&D, which in turn facilitates their adoption of existing abatement technologies (Brown, Martinsson, and Thomann 2022). A number of recent papers also document a climate risk premium (for a review, see Giglio, Kelly, and Stroebel 2021), and listed CO_2-emitters face higher costs of capital (Bolton and Kacperczyk 2021, Bolton and Kacperczyk 2023).

[30] Shive and Forster (2020) argue that their result is more consistent with listed companies being less stakeholder oriented due to short-term profit maximization (as in Farre-Mensa and Ljungqvist 2016).

[31] Our other reported regression results are very similar when reestimated on this shorter sample.

We focus on four proxies used in the literature that are available for most firm-years in our data set: listing status (Pagano, Panetta, and Zingales 1998; Saunders and Steffen 2011), size (Gertler and Gilchrist 1994; Hadlock and Pierce 2010), dividend payouts (Fazzari, Hubbard, and Petersen 1988; Bartram, Hou, and Kim 2022), and age (Gertler 1988; Hadlock and Pierce 2010). To conserve space, we report the sum of the three lags of the marginal cost share and their statistical significance in Table 8. For each firm sort we also display the elasticity across sectors with comparatively lower abatement costs (deciles 1-4 and low PACE sectors) and for those facing higher costs (deciles 9–10 and high PACE sectors). The complete regression results for each firm sort are compiled in Tables B.6, B.7, B.8, and B.9 in the Internet Appendix.[32]

We first sort firms according to their public listing status, where public firms are expected to be less capital constrained on average compared to private firms. We classify a firm as listed if at least one firm in the corporate group to which they belong is listed at least once during the sample period; the firm is otherwise classified as private.[33] Panel A shows the results from reestimating Equation (1) for these two subsamples. For listed firms, the estimated elasticity is larger than for the sample as a whole and highly statistically significant. In contrast, for unlisted firms, the elasticity is around one and insignificant.

Access to finance should also matter the most for firms in high-emitting sectors, since we would expect the investment needed for reducing emissions to be higher. Thus, if the difference in estimates between columns 1 and 2 of panel A is due to financing constraints, we would expect this difference to be more pronounced for high-emitting sectors. Columns 3 and 4 of panel A show a sizable elasticity for both public and private firms in low-emitting sectors (7.5 vs. 3.9). In high-emitting sectors, we estimate a statistically significant elasticity of 2.3 for listed firms (column 5), while it is only 0.4 and insignificant for privately held high-emitting firms (column 6). We find very similar results if we instead divide firms based on PACE (as in Table 6): firms in low PACE sectors have a similar elasticity regardless of listing status (columns 7 and 8), while in high-PACE sectors, only publicly listed firms display a significant elasticity (columns 9 and 10). These results suggest that financial constraints stifle CO_2 abatement for firms with large marginal benefits of abatement.[34]

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32 In robustness test we also sort according to the financial constraints indexes from Hadlock and Pierce (2010) (Size-Age) and Whited and Wu (2006) with very similar results (Table B.10 in the Internet Appendix).

33 We define a firm as listed in two other ways as robustness. In Table B.11 in the Internet Appendix, a firm is defined as listed if at least one entity in the corporate group to which they belong is listed during the entire sample period, where we drop all firms with switching ownership status in the corporate group. In Table B.12 we consider a firm as being publicly owned in a given year if at least one firm in the corporate group that year is listed at least once during the sample period.

34 The listing results are also opposite to what Shive and Forster (2020) found for the United States, where firms were not subject to carbon pricing.

Table 8
Carbon pricing and carbon emission intensity: Financing constraints

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
	All sectors		D1-D4 sectors		D9-D10 sectors		Low PACE		High PACE	
	A. Publicly listed									
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
$\sum$ Δln(1 - C)	2.220***	0.959	7.478***	3.902***	2.323***	0.401	3.173	2.659**	2.525***	0.739
	(0.001)	(0.206)	(0.002)	(0.000)	(0.004)	(0.628)	(0.277)	(0.019)	(0.001)	(0.408)
Observations	2,107	6,535	595	2,531	736	1,307	464	2,083	1,567	4,207
	B. Large firm									
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
$\sum$ Δln(1 - C)	2.115***	0.585	4.100***	4.607***	1.948*	0.680	1.920*	3.811**	2.066**	0.494
	(0.009)	(0.296)	(0.000)	(0.000)	(0.076)	(0.266)	(0.097)	(0.031)	(0.027)	(0.446)
Observations	4,138	4,504	1,581	1,545	886	1,157	1,254	1,293	2,801	2,973
	C. High-dividend payer									
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
$\sum$ Δln(1 - C)	2.699***	0.743	4.053**	4.243***	3.641***	-0.024	2.872	2.441**	2.671***	0.659
	(0.000)	(0.301)	(0.015)	(0.000)	(0.000)	(0.971)	(0.113)	(0.042)	(0.002)	(0.450)
Observations	4,209	4,433	1,558	1,568	930	1,113	1,273	1,274	2,822	2,952
	D. Mature firm									
	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
$\sum$ Δln(1 - C)	2.934***	0.562	4.457***	3.907***	3.072***	0.184	4.654***	1.615	2.838***	0.435
	(0.000)	(0.450)	(0.000)	(0.000)	(0.000)	(0.793)	(0.004)	(0.144)	(0.002)	(0.632)
Observations	3,814	4,779	1,489	1,613	799	1,232	1,167	1,365	2,549	3,194

This table reports $\sum$ Δln(1 - C) and the corresponding F-test based on OLS estimates of Equation (1) where $\Delta ln(E/Y)_{i,t}$ is the dependent variable. See Tables B.6, B.7, B.8, and B.9 in the Internet Appendix for detailed regression results for each panel. The sample period is 1996–2015. All regressions include firm and year fixed effects. *Public (Private) firm* is an indicator variable taking on the value one (zero) if the firm is (not) listed on a Swedish stock exchange. A firm is considered publicly listed if at least one firm in the corporate group is listed at least once during the sample period. *Large (Small) firm* is an indicator variable taking on the value one (zero) if the firm is above (below) the median in book value of total assets (averaged over the sample period and measured at the corporate group level) within its four-digit NACE industry. *High (Low) dividend firm* is an indicator variable taking on the value one (zero) if the firm is above (below) the median in dividend payout divided by book value of total assets (averaged over the sample period and measured at the corporate group level) within its four-digit NACE industry. *Mature (Young) firm* is an indicator variable taking on the value one (zero) if the firm's founding year (measured at the corporate group level) is below (above) the median within its four-digit NACE industry. $*p<.1$; $**p<.05$; $***p<.01$.

In panels B–D we consider firm size, dividend payout status, and age as alternative measures of ex ante financial constraints. These sorts are all defined within each four-digit NACE sector.[35] Firms that are smaller, younger, and that pay lower dividends are expected to be more financially constrained. Across all three sorts, we first take the average for each firm over the sample period and then we find the median firm by four-digit sector. We consider a firm as large (small), high (low) dividend payer or mature (young) if it is above the median in book value of assets, dividend-to-assets and number of years since incorporation, respectively (measured at the corporate group

35 Size and payout ratio are used in Bartram, Hou, and Kim (2022) to classify financially constrained firms. Age is also a widely financial constraint proxy (e.g., Hadlock and Pierce 2010).

level). We create the subsamples within sectors since the ability to reduce CO_2 depends on the sector-specific production technology. Within-sector sorting also controls for differential investment opportunities across sectors and ensures that subsamples are of similar size.

Results using different financial constraint indicators are similar. Across all sectors in columns 1 and 2, firms less likely to be financially constrained (larger, higher dividend payers, and older) display statistically significant elasticities between 2.1 and 2.9 compared to firms more likely to be constrained (smaller, lower dividends and younger) with statistically insignificant elasticities between 0.5 and 0.7. In low-emitting sectors (deciles 1–4) constrained and unconstrained firms exhibit similar elasticities of around 4, and we find no systematic differences within low-PACE sectors either. Instead, the effect of financial constraints is driven by firms in sectors with higher abatement costs (deciles 9 and 10 and high PACE sectors): larger, higher dividend, and older firms in high abatement sectors display elasticities between 2.1 and 3.6 compared to between 0.4 and 0.7 for smaller, lower dividend, and younger firms.[36]

We also consider how financial crises affect emissions abatement and report the results in Table B.13 in the Internet Appendix. We follow the classification in Laeven and Valencia (2018), according to which 2008 and 2009 are considered banking crisis years during our sample period 1996–2015. The emission-to-pricing elasticity is significantly lower (between 1 and 1.5) during crisis years across all firm sorts. During noncrisis years, firms classified as less financially constrained display highly significant elasticities between 2.5 and 3.2, while firms classified as financially constrained have elasticities of around one. During crisis years, the elasticity drops to around one for less constrained firms and around zero for more constrained firms. Overall, these results suggest that financial sector instability can further impede the ability of manufacturing firms to lower their carbon footprint.

5. Aggregate Effects: Quantifying the Economic Importance of Emission Elasticities

The results reported in Section 4 imply that emission intensities would have been higher in the absence of carbon pricing. To assess the economic significance of these estimates, we perform a reduced form calibration, which takes total output and the firms present in the market as exogenously given, and abstract from scale and composition effects from carbon pricing. Since those effects are also likely to be important, our calibration is not a proper equilibrium

36 This is consistent with Hartzmark and Shue (2023), who find that financing costs have a negligible effect on greenhouse gas emissions for low emitters but a large effect on high emitters. They argue that responsible investment policies that increase the cost of capital for brown firms might therefore be counterproductive.

counterfactual (Lucas 1976), but rather a back-of-the envelope way to gauge the quantitative importance of our elasticity estimates.[37]

Since we only perform this calibration with respect to emission intensities, while overall output, industry composition, and carbon tax rates vary across years, the estimated aggregate effect depends on the base year chosen for the counterfactual. We choose to focus on 2015, which marks the end of our sample and is also the year of the most recent change of the Swedish carbon pricing scheme (see Table 1).

From elasticity estimates in Section 4 we derive the implied change in firm-level emission intensities due to carbon pricing and then retrieve what the emissions intensity would have been in the absence of such pricing. Specifically, we calculate counterfactual emissions in the absence of carbon pricing for the year $t = 2015$ as follows:

$$\widehat{\left(\frac{E_{\mathrm{t}}}{Y_{\mathrm{t}}}\right)}^{\text{No tax}} = \left(\frac{E_{\mathrm{t}}}{Y_{\mathrm{t}}}\right) - \left(\sum_{s=1}^{3} \hat{\beta}_{\mathrm{s}} \cdot \left[ln(1 - C_{\mathrm{t\text{-}s}})) \right]\right). \tag{2}$$

The top row in Table 9 evaluates the baseline elasticity which is retrieved from using variation across all firm-years (column 4 in Table 4) in Equation (2). The observed, average carbon intensity across all firms in 2015 is 0.0049. Combining the estimated elasticities and the actual carbon pricing each firm faced in 2015, we estimate that the observed carbon intensity in the absence of carbon pricing would have been 0.0071 (column 4), or 47% higher than what was actually observed (column 5) in 2015.

This first calibration does not account for the significant heterogeneity across subgroups documented in Table 6, however. Panel A reports additional calibration results which accounts for heterogeneity with respect to PACE and mobility. Here, we compute Equation (2) separately for the four subgroups in columns 3–6 in Table 6. We estimate that firms in low PACE sectors operating with low- and high-mobility assets, respectively, would have had 74% and 68% higher emissions intensity in 2015 without carbon pricing. Among high PACE firms the corresponding numbers are 27% and 38% higher for low- and high-mobility sectors, respectively. We then weigh each subgroups' implied emissions intensity with its share of CO_2 emissions. Based on these estimates, the emissions intensity in Swedish manufacturing would have been around 30% higher in the absence of carbon pricing, which is a smaller implied difference compared to the one obtained in the previous calibration. This can be explained by firms in high PACE and low-mobility sectors (with lower elasticities) accounting for 90% of manufacturing CO_2 emissions in 2015. Keeping the size and composition of manufacturing sales constant over time, our 30% effect on carbon intensity would translate in to an aggregate CO_2 emissions reduction of the same magnitude. Given that

37 See Shapiro and Walker (2018) for a structural, general equilibrium approach to this question.

Table 9
Economic magnitude based on the 2015 carbon pricing change and emissions intensities

	(1) Share CO_2	(2) Elasticity	(3) CO_2 intensity	(4) Without tax	(5) Relative
A. PACE, mobility, and aggregate emissions					
All	1.0000	2.0769	0.0049	0.0071	47%
Low pace & Low mobility	0.0415	2.7789	0.0033	0.0057	74%
Low pace & High mobility	0.0125	2.9284	0.0025	0.0042	68%
High pace & Low mobility	0.9021	1.7213	0.0077	0.0098	27%
High pace & High mobility	0.0438	2.4516	0.0049	0.0068	38%
Aggregate emissions					30%
B. PACE, Leakage list, and deciles					
Low pace sectors	0.0541	3.0003	0.0029	0.0054	83%
High pace sectors	0.9459	1.8948	0.0067	0.0087	31%
Not on leakage list	0.0758	2.5853	0.0039	0.0060	52%
On leakage list	0.9242	1.8850	0.0058	0.0078	33%
Deciles 1-4	0.0310	6.7230	0.0025	0.0069	175%
Deciles 5-8	0.0591	2.7340	0.0039	0.0069	78%
Deciles 9-10	0.9099	1.2970	0.0142	0.0174	23%
C. Ownership, size, dividend payout, and age					
Public firm	0.4684	2.2195	0.0074	0.0103	39%
Private firm	0.5316	0.9591	0.0044	0.0050	14%
Large firm	0.7077	2.1150	0.0047	0.0065	38%
Small firm	0.2923	0.5854	0.0049	0.0056	12%
High dividend firm	0.4110	2.6990	0.0047	0.0071	51%
Low dividend firm	0.5890	0.7429	0.0050	0.0050	0%
Mature firm	0.6616	2.9335	0.0045	0.0076	69%
Young firm	0.3384	0.5620	0.0051	0.0057	13%

This table reports the share of aggregate CO_2 emissions across subsamples in 2015 (in column 1), the estimated elasticity (in column 2), the actual CO_2-to-sales in 2015 for each subsample (in column 3), the value from subtracting the product of the elasticity and actual carbon pricing change in 2015 to the actual CO_2-to-sales (in column 4), and the ratio of column 4 and column 3 (in column 5).

aggregate manufacturing CO_2 emissions declined by 31% over the sample period (see Section 2.3), this suggests that the effect of carbon pricing on emission intensities was an important driver of these reductions.

For completeness, panel B displays the implied carbon intensities for the other subsamples considered in Section 4. Calibrating based on these dimensions yields similar magnitudes, because of the substantial overlap across the different classifications.

Panel C also shows the aggregate economic significance of financial constraints on emission intensities using the estimates from Table 8. Had all Swedish manufacturing firms had the same carbon-pricing elasticities as less financially constrained firms, the aggregate effect of carbon pricing would have been between 38% and 69% (rather than of 30%). In contrast, if all firms had had elasticities similar to financially constrained firms, the aggregate carbon pricing effect would have ranged from 0% to 14%. This implies that financial constraints can have an economically significant impact on carbon reductions.

Table B.14 of the Internet Appendix displays results from calibrating Equation (2) using alternative base-years, chosen to coincide with major changes in Swedish carbon taxation (1991, 1997, 2008, and 2011). The calibration results for 2008 or 2011 are similar to Table 9. If we instead base our calibration on 1991 or 1997, however, the implied emissions intensity in the absence of carbon pricing would only be 12%–14% higher, that is, one-third of the effect for the other base-years.[38] This reflects the fact that the highest emitters faced much lower marginal carbon tax in those years, due to the exemptions they enjoyed. After these firms transitioned into the EU ETS, this was no longer the case.

To summarize: when we base our calibration on the post 2005 period in Sweden (with marginal costs consistently equal or higher than average costs) we predict that emission intensity would have been around 30% higher without taxation, which implies that the entire decline in manufacturing emissions 1990–2015 could potentially be attributed to carbon pricing. Under the carbon tax schedule in place prior to the EU ETS, the reduction in emissions would have been substantially lower.

6. Conclusions

In 1991, Sweden introduced a tax on CO_2 emissions that currently remains the highest in the world. We assemble a comprehensive data set of around 4,000 Swedish manufacturing firms and track firm-level CO_2 emissions over 1990–2015. Our results imply a statistically robust and economically meaningful inverse relationship between CO_2 emissions and the marginal cost of emitting CO_2. While the average emissions-to-carbon pricing elasticity is around two for manufacturing as a whole, there is considerable heterogeneity across firms and subsectors, with the highest emitters having substantially lower elasticities. Financial constraints significantly reduce the carbon pricing elasticity for firms in sectors with high abatement costs, but have no visible impact in low abatement cost sectors. Aggregate emissions of CO_2 from Swedish manufacturing decreased by about 31% between 1990 and 2015, while total manufacturing output only decreased by 3% over the same period. Simple calibrations imply that carbon pricing, through its effect on emission intensities, can account for a major part of the emission reductions.

An advantage of our approach is that we estimate carbon pricing elasticities that account for heterogeneity across firms and sectors, which can be used for evaluating other carbon pricing schemes where the price level and industry composition differ. That said, the fact that we consider one particular country

[38] We report the share of CO_2 emissions for each event year across subsamples in Table B.15 in the Internet Appendix.

may obviously limit the external validity of our results. The fact that Sweden is well-endowed with fossil-free energy resources is likely to have contributed to the substantial reduction of CO_2 emissions. Also, a relatively low level of political uncertainty, particularly with respect to climate policy, may have increased the willingness of firms to make the necessary investments in emissions abatement (Baker, Bloom, and Davis 2016). Moreover, Sweden is a small open economy with a highly export-dependent manufacturing sector. As a result, the ability of Swedish manufacturing firms to pass on carbon pricing to their customers is likely to be more limited compared to countries with larger home markets, such as the United States.

We believe our findings raise several avenues for future research. In particular, it would be important to investigate the mechanisms through which firms achieved their emission reductions. Were reductions achieved by switching to lower-emitting production processes for existing products (technological improvements), increasing the prices of existing products (pass-through) or changing their product mix toward products with lower emissions and/or higher prices (compositional changes)? What role did investments in capital and R&D, plant openings or closings, and changing imports and exports play in reducing emissions? Finally, by using a structural general equilibrium approach (e.g., Shapiro and Walker 2018) one could estimate the effects of carbon pricing not just on emission intensities, but also on aggregate output and industry composition.

Code Availability: The replication code and data are available in the Harvard Dataverse at https://doi.org/10.7910/DVN/9NWRW8.

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