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Who Pays for the Pollution Fees? Cost Transmission Along the Supply Chain

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Abstract

This paper studies the propagation of environmental regulation along the supply chain and quantifies its welfare implications. By incorporating input-output linkages into the workhorse tax incidence model, we derive statistically sufficient representations of the incidence under a general imperfect competition framework. In the context of China's SO2 emission regulation, we show that emission fees affect manufacturing producers through two channels. First, manufacturing producers bear the full brunt of emissions fees imposed directly on them. Second, emission fees imposed on their upstream suppliers translate into higher input costs faced by manufacturing producers, who bear 29% of the burden. Neglecting the role of the latter would result in an underestimation of 5%–13% of the cost burden for most industries.

Keywords: Input-Output Linkage, Emission Fees, Incidence, Pass-Through

JEL: H22, H23, Q52, D57, L60

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1 Introduction

The growing attention to pollution has led to the implementation of increasingly stringent environmental policies aimed at raising the cost of pollution emissions. This has led to concerns that increased emission costs will not only make polluting firms less competitive but can also indirectly hurt downstream firms or consumers due to higher input prices. Despite the above concerns, relatively little is known about how environmental regulation would propagate along the supply chain and who would ultimately bear the cost burden (i.e., incidence). In the literature on incidence estimation, while the incidence of output tax (Weyl and Fabinger, 2013) has been well explored, how the cost is transmitted along the supply chain across firms has been less studied. As modern production heavily relies on collaborations through complex and interlocking supply chains, input-output linkages serve as a crucial mechanism for the propagation and amplification of cost shocks, generating an additional source of welfare loss.

In this paper, we estimate the economic incidence of environmental regulation by considering input-output linkages under a general imperfect competition framework.[1] In the context of China's environmental regulation on SO2 (sulfur dioxide) emission, we show that emission fees affect firms through two channels. The emission fees directly charged to downstream producers are proportional to total output and act as output taxes, which we refer to as output emission fees. The emission fees charged upstream producers, which we refer to as input emission fees, lead to higher input costs for downstream producers and result in additional indirect costs to downstream firms. The latter is a less explored channel in the literature. To help bridge this gap, we derive statistically sufficient representations for the latter building on the tax incidence literature (e.g., Weyl and Fabinger, 2013; Ganapati et al., 2020) and calculate the between-firm economic incidences.

China provides a good setting to study the incidence of SO2 emission fees. Due to rapid industrialization and the coal-dominated energy mix, China's SO2 emissions peaked at 25.89 million tons in 2006 and became the world's largest SO2 emitter. In an effort to reduce pollution, the Chinese government has introduced emission fee policies to address the increasingly severe challenge of SO2 pollution. Given China's considerable share in global SO2 emissions, it is crucial to evaluate the effectiveness of its SO2 emission control policy.

We use various firm-level data, including the Annual Survey of Industrial Firms, China Customs data, and the Chinese Environmental Statistical Database, to construct output and input emission fees. The output emission fee, which measures a firm's direct cost exposure, is calculated as the firm's pollution intensity multiplied by the regional emission fee, where the firm-level pollution intensity is calculated as the SO2 emissions divided by output quantity. The input emission fee,

[1] The framework nests a broad range of imperfect competitions, such as Cournot and Bertrand competition, as we don't need to take an explicit stance on how firms compete.

which measures the indirect cost exposure, is constructed as the weighted average of the ad valorem equivalents (AVE) of output emission fees charged to the firm's suppliers. The weights are input shares from China's inter-province input-output table in 2012.

We first investigate the cost transmission of emission fees along the supply chain, specifically how marginal costs and output prices respond to changes in input and output emission fees. To do this, we estimate a translog production function for each industry (Ackerberg et al., 2015), obtain firm-level time-varying markups (De Loecker and Warzynski, 2012), and recover marginal costs as output prices divided by estimated markups. There are two main empirical findings (Figure 1). First, a 1% increase in output emission fees only leads to a 0.006% increase in output prices. Second, a 1% increase in input emission fees leads to a 0.04% increase in output prices. For the latter, the price transmission of input emission fees can be broken down into two parts. Specifically, a 1% increase in input emission fees is associated with 0.07% higher marginal costs, and 73% of the increase in marginal costs is passed on to downstream buyers. This decomposition suggests that the low price transmission of input emission fees is mainly due to the modest increase in marginal costs.

Next, we estimate the economic incidences of input and output emission fees. In a general oligopolistic market without input-output linkages, producers shoulder almost all the welfare loss, while buyers pay only 0.7%. In the presence of input-output linkages, cost shocks are further propagated and amplified through production networks. 29% of the additional welfare cost induced by input emission fees is borne by producers. In total, the input channel results in an additional 7% welfare loss.[2][3]

We then assess the effectiveness of emission fees in reducing SO2 emissions. To distinguish the short-term effects from the long-term effects, we adopt a dynamic difference-in-difference (DID) design. We find that emission fees have an immediate and significant effect on SO2 emission reduction. Furthermore, we explore the channels through which SO2 emissions are reduced by decomposing total emissions at the firm level into pollution intensity (SO2 emissions per unit) and production quantity. We find that it is the reduction in quantity that drives the immediate reduction in SO2 emissions. In contrast, the pollution intensity does not decrease significantly, suggesting that firms do not upgrade their green technologies and adjust their production mode in the short term.

[2] The additional welfare losses are greater than 10% for some industries, such as food, agriculture, paper and books, and textile fibers, where these industries take up 12% of the manufacturing employment and 15% of the manufacturing output.

[3] Without loss of generality, we include all manufacturing industries rather than focusing on a few industries whose products are more homogeneous. We acknowledge the potential bias and perform industry-specific analysis to check. Based on the estimated elasticity of substitution, we identify how well each industry fits the product homogeneity assumption in incidence estimation.

This paper builds on the literature on tax incidence estimation. Under general imperfect competition, Weyl and Fabinger (2013) provide sufficient statistics for the incidence of output tax, and Ganapati et al. (2020) provide sufficient statistics for the incidence of energy input cost. Our work complements the literature by incorporating input-output linkages into the incidence estimation. In the context of emission fee transmission between firms, we allow the output emission fees imposed on upstream suppliers to be translated into higher input costs for downstream producers and show that input-output linkages provide another important channel for the welfare loss of emission fees.

Another related strand of literature focuses on evaluating the effectiveness and efficiency of environmental regulations from the perspectives of pollution emission and air quality (Karplus et al., 2018; Shapiro and Walker, 2018; Almond and Zhang, 2021; Greenstone et al., 2021; Shapiro, 2022; Jacobsen et al., 2023; Karplus and Wu, 2023), energy intensity (Martin et al., 2014), output, profits, and productivity (Martin et al., 2016). This paper contributes to the literature by quantifying the economic incidence of emission fees and exploring the underlying forces behind its emission reduction effect.

This paper is also related to the literature on the role of input-output linkages in the propagation and amplification of shocks. Input-output linkages have been shown to be quantitatively non-trivial in transforming firm-specific or regional shocks. The existing literature focuses on the impacts on output (Gabaix, 2011; Boehm et al., 2019; Carvalho et al., 2021), sales, market value (Barrot and Sauvagnat, 2016), productivity, employment (Acemoglu et al., 2016; Caliendo et al., 2018), and volatility (Di Giovanni et al., 2014), while the impact on economic incidence is less explored. We extend the literature by studying the role of input-output linkages in affecting the impacts of cost shocks on output prices, markups, and welfare.

Lastly, this paper complements the extensive empirical literature on pass-through estimation, which includes the pass-through of energy tax and subsidy (Marion and Muehlegger, 2011; Fabra and Reguant, 2014; Kopczuk et al., 2016; Miller et al., 2017; Pless and van Benthem, 2019), exchange rate (Campa and Goldberg, 2005; Goldberg and Hellerstein, 2008; Gopinath et al., 2010; Amiti et al., 2014), tariff (Amiti et al., 2019; Fajgelbaum et al., 2020), minimum wage (Aaronson, 2001; Harasztosi and Lindner, 2019; Leung, 2021; Renkin et al., 2022), government medical payments (Duggan et al., 2016; Cabral et al., 2018; Carey, 2021), and commodity production cost (Nakamura and Zerom, 2010; Hong and Li, 2017). Specifically, Fabra and Reguant (2014), Miller et al. (2017), and Pless and van Benthem (2019) find almost complete or more than complete pass-through of energy tax and subsidy in Spanish electricity, Portland cement, and US solar markets. In this paper, we investigate the pass-through of pollution emission fees, namely how input and output emission fees are differentially transmitted to output prices, and provide a better understanding of the overall price effects of emission fees in the presence of supply chains.

The paper proceeds as follows. Section 2 presents a theoretical framework on the economic incidences of input and output emission fees. Section 3 describes the background, data, and variable construction. Section 4 presents the empirical settings, and Section 5 presents the corresponding results. Section 6 evaluates the effectiveness of emission fees in reducing SO2 emissions and explores the underlying forces. Finally, Section 7 concludes.

2 Theoretical Framework

The estimation of tax incidence has always played a central role in tax policy evaluation. The existing literature focuses on the within-firm effect and targets firms directly charged with taxes. Weyl and Fabinger (2013) investigate the economic incidence of output tax under general imperfect competition. Ganapati et al. (2020) extend the incidence analysis to the input cost in the context of energy price transmission. The more responsive output prices are to increases in energy prices, the more cost burdens are shifted from producers to their buyers. Compared to the literature, we extend the analysis by estimating between-firm tax incidence under imperfect competition. In the context of SO2 emission control, we explore the role of the input-output linkages in translating the emission fees imposed on upstream suppliers into higher input costs borne by downstream firms.

Following the literature (e.g., Weyl and Fabinger, 2013, Ganapati et al., 2020), we adopt similar assumptions to guide our incidence estimation. First, products outside the industry of interest are supplied in a perfectly competitive manner.[4] Second, the demand and supply functions are smooth, and the excess demand (the gap between the demand and supply of a particular product) decreases with prices, ensuring a unique equilibrium price at which demand balances supply. Third, the direct emission fees paid by firms can be perceived as an output tax only if we assume that the production technology remains unaffected in the short term after the increase in emission fees.[5]

2.1 Incidence of Output Emission Fees

We study the incidence of output emission fees under general imperfect competition following Weyl and Fabinger (2013). There are N identical single-product firms producing homogeneous products

[4]This simplifying assumption allows us to ignore product substitutions across industries. Furthermore, the perfectly competitive supply of inputs implies complete pass-through in the input market, which simplifies our setting and allows us to focus on studying the welfare distribution between producers and their downstream buyers.

[5]This assumption will be violated if firms adopt cleaner production technology in response to higher emission fees. In Section 6, we provide supportive empirical evidence to show that the increase in emission fees does not significantly lower firm-level pollution intensity, implying no green technology upgrading in the short term.

in the industry. The demand faced by each firm is fully symmetric, and the firm-level demand elasticity equals the market-level demand elasticity (Genesove and Mullin, 1998). Let Φ^O denote the pollution intensity, defined as the pollutant emissions per unit, and F^O denote the rate at which emission fees are charged, i.e., the price per unit of pollutants emitted. We assume constant returns to scale such that the average variable costs equal the marginal costs. Marginal costs can be divided into two components: fee-exclusive marginal costs and output emission fees. The former, denoted by MC, depends on input prices and quantities needed to produce one unit of product. The latter, denoted by EC^O, is the product of the emission fee rate F^O and the pollution intensity Φ^O. To distinguish the effects of output and input emission fees, we explicitly write EC^O rather than taking it as an implicit part of the marginal costs. Hereafter, marginal costs refer to fee-exclusive marginal costs unless otherwise stated. The profit of firm i selling Q_i units at market price P is

$$\Pi_i = \left(P - MC - EC^O\right) Q_i.$$

Let $\varepsilon_D \equiv -d\log Q/d\log P$ denote the market-level elasticity of demand, which measures the percentage change in total market-wise quantity Q in response to a percentage change in the market price P. Let $L \equiv \left(P - MC - EC^O\right)/P$ denote the Lerner (1934) Index, which is a measure of markup and is defined as the difference between the firm's output price and fee-inclusive marginal cost divided by its price. $\rho^O \equiv \partial P/\partial EC^O$ is the price transmission of output emission fees, defined as the marginal change in prices due to an infinitesimal increase in output emission fees. The change in producer surplus PS for an infinitesimal increase in output emission fees is

$$\frac{\partial PS}{\partial EC^O} = N\frac{\partial \Pi_i}{\partial EC^O} = NQ_i\left[\left(1-\varepsilon_D L\right)\rho^O - 1\right].$$

As shown by Weyl and Fabinger (2013), the change in consumer surplus CS is given by $\partial CS/\partial EC^O = -\rho^O Q$, where $Q = NQ_i$ is the aggregate quantity in equilibrium. The economic incidence of output emission fees under oligopoly, i.e., the ratio of welfare loss borne by consumers to that borne by producers, is given by

$$I^O \equiv \frac{\partial CS/\partial EC^O}{\partial PS/\partial EC^O} = \frac{\rho^O}{1-\left(1-\varepsilon_D L\right)\rho^O}. \tag{1}$$

where the consumer welfare loss $\partial CS/\partial EC^O$ is determined by the aggregate quantity Q and price transmission ρ^O, and the producer welfare loss $\partial PS/\partial EC^O$ is determined by the aggregate quantity Q and the marginal emission costs paid by producers $1-\left(1-\varepsilon_D L\right)\rho^O$. Set the elasticity-adjusted Lerner index $\varepsilon_D L$ as the conduct parameter θ that captures the degree of competition in the market. Note that perfect competition ($\theta = 0$ and $\rho^O = 1$) and monopoly ($\theta = 1$) are both special cases.[6] Under perfect competition, consumers bear all the welfare loss.

2.2 Incidence of Input Emission Fees

We now incorporate the input-output linkages into the incidence analysis of input emission fees. There are three layers along the supply chain, namely upstream suppliers, producers, and downstream buyers. Producers buy inputs from upstream suppliers and sell output to downstream buyers.

The input emission fees, EC^I, are constructed as the weighted average of the output emission fees paid by the firm's upstream suppliers, where the weight is the input share. Let $\rho^I \equiv \partial P/\partial EC^I$ denote the price transmission of input emission fees, defined as the marginal change in prices caused by an infinitesimal increase in input emission fees. Let $\gamma^I \equiv \partial MC/\partial EC^I$ denote the cost shifter, defined as the marginal change in marginal costs in response to an infinitesimal increase in input emission fees. The incidence of input emission fees in an oligopolistic market can be written as

$$I^I \equiv \frac{\partial CS/\partial EC^I}{\partial PS/\partial EC^I} = \frac{\rho^I}{\gamma^I - (1-\varepsilon_D L)\,\rho^I}. \tag{2}$$

The intuition behind equation (2) is similar to the incidence of output emission fees in equation (1). The consumer welfare loss $\partial CS/\partial EC^I$ is determined by the aggregate quantity Q and price transmission ρ^I, and the producer welfare loss $\partial PS/\partial EC^I$ is determined by the aggregate quantity Q and the input emission fees paid by producers $\gamma^I - (1-\varepsilon_D L)\,\rho^I$. Let $\rho^I_{MC} \equiv \partial P/\partial MC$ denote the pass-through of marginal costs to output prices, so that we get the relationship $\rho^I = \partial P/\partial EC^I = (\partial P/\partial MC)\left(\partial MC/\partial EC^I\right) = \rho^I_{MC}\gamma^I$. Substituting the relationship into equation (2) gives

$$I^I = \frac{\rho^I_{MC}}{1-(1-\varepsilon_D L)\,\rho^I_{MC}}. \tag{3}$$

The equation (3) shows that estimating the incidence of input emission fees requires only three parameters: ρ^I_{MC}, L, and ε_D. In contrast, estimation with equation (2) requires four parameters. Furthermore, we learn that consumers bear all welfare loss of input emission fees under perfect competition.[7]

[6] As shown by Weyl and Fabinger (2013), the price transmission of output emission fees under perfect competition can be written as $\rho^O = 1/(1+\varepsilon_D/\varepsilon_S)$, where ε_S is the elasticity of supply. Constant returns to scale indicate perfectly elastic supply ($\varepsilon_S = \infty$) and thus complete price transmission ($\rho^O = 1$). The price transmission under monopoly is not a constant but depends on the curvature of the demand function.

[7] Under perfect competition, the price is equal to the fee-inclusive marginal cost, i.e., $P = MC + EC^O$, and then

3 Background, Data, and Variable Construction

In this section, we first describe China's SO2 emission fee policy. Then, we display the data and describe variable constructions.

3.1 Background

The Chinese government has formulated a series of environmental policies to control SO2 emissions, of which pollution fees are an important market-oriented tool for the government to internalize the negative externality of polluters. The SO2 emission fee system underwent two stages of development: full implementation and subsequent adjustments. The former began in 2003 and the latter in 2007. Appendix Table B1 summarizes China's regional SO2 emission fee policies. As different cities have adopted policies at different times, there are sufficient regional and timing variations to empirically identify the effect of emission fees.

During the 10th Five-Year Plan period (2001–2005), the Chinese government set emission limits for 12 major pollutants and required a 10% reduction in SO2 emissions. To achieve this goal, the Ministry of Ecology and Environment announced the implementation of emission fees and initiated a pollution control policy in 2003. From July 31 of the same year, in cities other than Beijing, Hangzhou, Zhengzhou, and Jilin, SO2 was taxed at 0.21 Chinese yuan per kilogram.[8] The SO2 emission fees increased to 0.42 Chinese yuan per kilogram from July 1, 2004, and increased to 0.63 Chinese yuan per kilogram from July 1, 2005. The 11th Five-Year Plan (2006–2010) set an additional 10% SO2 emission reduction target below the 2005 level. Correspondingly, in 2007, the State Council required local governments to double the SO2 emission fees from 0.63 Chinese yuan per kilogram to 1.26 Chinese yuan per kilogram. Between 2007 and 2013, 12 provinces doubled their SO2 emission fees.[9] For regions that made mid-year (e.g., April 1, July 1, July 10, and August 1) adjustments, we set the emission fees for the current year as the simple average of pre- and post-adjustment levels.[10]

we can get $\rho^I_{MC} = \partial P/\partial MC = 1$. Combined with $L = 0$, we can get that consumers bear all welfare loss of input emission fees.

[8]From 1999 to 2005, Beijing charged 1.20 Chinese yuan per kilogram of SO2 generated by high-sulfur coal and 0.50 Chinese yuan per kilogram of SO2 generated by low-sulfur coal. From July 1, 2005, the SO2 emission fees of low-sulfur coal in Beijing increased to 0.63 Chinese yuan per kilogram, equal to the emission fees in other cities. For Beijing, we use the SO2 emission fees of low-sulfur coal in our analysis.

[9]Shanxi and Heilongjiang only imposed emission fees on firms that did not complete the construction of flue gas desulfurization facilities or emitted excess SO2, which was inconsistent with the regulations in other provinces. Hence, the two provinces are excluded from our analysis.

[10]Tianjin made emission fee adjustments at the end of 2010, so we set its emission fees for 2010 at the pre-adjustment level and the following year at the post-adjustment level.

The Chinese government has also implemented some other environmental regulations to combat pollution (Zhang et al., 2017; Almond and Zhang, 2021; Karplus and Wu, 2023), which we will address as confounders in our empirical analysis. For example, in 2007, China launched an SO2 emission trading schemes pilot including 11 provinces and established its first environmental court in Guiyang.[11] In 2010, the National Development and Reform Commission initiated the first low-carbon pilot program, covering five provinces and eight cities. The following second and third batches of low-carbon cities in 2012 and 2017 included 28 and 45 other cities, respectively.

3.2 Data and Variable Construction

We use five datasets in the analysis: the Annual Survey of Industrial Firms (ASIF) collected by China's National Bureau of Statistics (NBS), the firm-level trade data collected by China Customs, the Chinese Environmental Statistical Database (CESD) collected by China's Ministry of Environmental Protection, city-level SO2 emission fees, and regional input-output tables for 2012 reported by the NBS. To link the three firm-level data, we use the unique firm IDs provided by the Easy Professional Superior data platform to track firms over time and across databases. To address the changes in Chinese Industry Classification (CIC) codes in 2003 and 2013, we use industry concordances provided by the NBS to ensure consistency throughout the sample period. To incorporate changes in the Harmonization System (HS) product codes in 2002, 2007, and 2012, we utilize conversion tables provided by the United Nations to convert the 6-digit HS codes after 1996 to their 1996 counterparts.

3.2.1 Annual Survey of Industrial Firms

Our firm-level production data (2000–2013) is from the ASIF database, which covers all state-owned and above-scale non-state firms in mining, manufacturing, and public utility sectors. The above-scale firms refer to those with annual sales exceeding 5 million Chinese yuan before 2011 and 20 million Chinese yuan thereafter. The ASIF database provides information on firm-level input and output, such as the gross output, intermediate inputs (materials), number of employees (labor), and fixed assets (capital). These variables are used to estimate industry-specific production functions in equation (6) in Section 4.

In the analysis, we focus on manufacturing firms and drop observations with fewer than eight employees following Brandt et al. (2012). Observations with missing or negative values for the above key variables in the production function are dropped. Data in 2010 is excluded due to a

[11]The setup of environmental courts accelerated with the guidance of the Supreme People's Court thereafter, and there were more than 100 environmental courts in over 60 cities at the end of 2014.

lack of key variables. We deflate nominal capital and materials using the corresponding input price deflators, the construction of which can be found in Appendix D1. Note that intermediate inputs are not reported for 2008–2013, and the corresponding estimation approach is also detailed in Appendix D1.[12]

3.2.2 Export Data

Firm-level export transaction records on both export values (in US dollars) and export quantities are from China's Customs Bureau (2000–2013). The data records detailed information by product, trade partner, and year. To estimate a quantity-based production function and recover the marginal costs, we need firm-level output price information. However, such information is usually unavailable in the firm production data. To deal with this data limitation, we make full use of the export transaction records to construct a proxy for firm-level output prices.[13]

The calculating procedure goes as follows. We first convert the export values to Chinese-yuan-denominated ones using the annual average U.S.-China exchange rate from the China Stock Market Accounting Research database. Then we calculate the firm-level annual output prices by taking the export-weighted geometric average of all its export prices recorded in a given year and deflate the output prices to the 2000 level using the corresponding industry price index. The industry-level output price index is also calculated based on the export data from China Customs. We remove outliers by trimming the top and bottom 5% of all recorded export prices annually for each industry and then construct the industry-level price as the export-weighted geometric average of all individual prices in the industry. All annual industry-level prices are adjusted to a common 2000 basis to obtain the required price index. Industries in this paper correspond to 22 broadly defined industries in Appendix C2 unless otherwise stated. Column (1) of Appendix Table E1, Panel A reports the industry average of firm-level output prices.

3.2.3 Chinese Environmental Statistical Database

The CESD is considered to be the most comprehensive panel dataset of firm-level pollution emissions provided by the Ministry of Environmental Protection, covering the majority of industries in China. Firms in the CESD are from three sectors, namely (1) mining, (2) manufacturing, and

[12]The ASIF database does not detail product-specific input expenditure allocations within firms for multi-product firms. Labor, capital, and intermediate inputs are only available at the firm level. We categorize each multi-product firm by the major 6-digit HS product that contributes the most to its total export value. And we assume that all of its input expenditures are attributed to producing its major product.

[13]The use of export prices to proxy output prices may not be entirely reliable since the two are not commonly equal. We demonstrate in Appendix D2 that even in the presence of firm-heterogeneous spreads between output and export prices, we can still obtain an incidence estimate that is not contaminated by output-price bias.

(3) electricity, heat, water production and supply. The data provides basic information (e.g., firm name, location, and CIC code), total output value, actual discharge of major pollutants (e.g., chemical oxygen demand (COD), ammonia nitrogen (NH3), nitrogen oxides, and SO2), and other environmental information. The firm-level emission data is the key to translating the regional SO2 emission fees into firm-heterogeneous emission costs.

We supplement the consolidated data from the ASIF database and China Customs with SO2 emissions from the CESD to calculate firm-level pollution intensity and emission fee exposure. Pollution intensity is calculated as total SO2 emissions divided by production quantity. A firm's direct emission cost is calculated as its pollution intensity multiplied by the regional SO2 emission fees. For firms not recorded in the CESD, we use their corresponding 4-digit (or 3-digit) CIC industry-province-level average pollution intensity to replace the missing values.[14] The industry-province-level pollution intensity is calculated as the revenue-weighted average of all firms in a given industry and province.[15]

3.2.4 SO2 Emission Fees

SO2 emission fees paid by each firm are jointly determined by the regional emission fees and firm-specific pollution intensity. The regional emission fees, taken from the official websites of the Ministry of Ecology and Environment and local governments, are matched to firm-level data (ASIF) based on firm location information. The firm-specific pollution intensity is calculated based on the emission data provided by the CESD. Based on the two variables, we get the emission costs per unit, i.e., output emission fees (Chinese yuan per unit). Columns (4) and (5) of Appendix Table E1, Panel A report the industry-level output emission fees and the share of revenue directly paid on SO2 emissions.

3.2.5 Input-Output Linkages

We utilize a inter-province input-output table containing 42 IO industries and 31 Chinese mainland provinces for 2012 to calculate the AVE of input emission fees.[16] Similar to input tariffs constructed

[14] As shown in Appendix C1, only 11% of firms appear in all three firm-level databases, and dropping observations without pollution information will cause serious sample selection bias.

[15] All manufacturing firms in the CESD are included when calculating industry-province-level average pollution intensity for statistical reliability. The CESD reports the total output value for each firm. Firm-level output prices are needed to translate output value to quantity when calculating pollution intensity. Output prices for those firms with no export records are replaced by the corresponding 4-digit (or 3-digit) CIC industry prices. A concordance between 6-digit HS and 4-digit CIC codes is constructed to calculate the CIC industry prices based on export records from China Customs.

[16] The use of the input-output table for 2012 may lead to endogeneity problems since firms could have adjusted their input distributions in response to emission fee policies. Input-output tables established before the implementa-

by Amiti and Konings (2007), input emission fees of IO industry s in city c, $EC^I_{s,c}$, are constructed as the weighted average of its upstream industries' output emission fees:

$$EC^I_{s,c} \equiv \sum_{(n,d)\in S_{s,c}} \frac{input^{n,d}_{s,c}}{total\ input_{s,c}} \times VEC^O_{n,d} \ , \tag{4}$$

where $S_{s,c}$ denotes the set of upstream industries of the IO industry s in city c, $input^{n,d}_{s,c}$ denotes the output of IO industry n in city d purchased by IO industry s in city c as inputs, and $VEC^O_{n,d}$ denotes the AVE output emission fees of IO industry n in city d. Total input can be divided into intermediate inputs and value-added, that is, $total\ input_{s,c} = \sum_{(n,d)\in S_{s,c}} input^{n,d}_{s,c} + value\text{-}added_{s,c}$. The input-output table provides interindustry trade flows among 31 provinces, and we set the same input shares for all cities within a province. Column (3) of Appendix Table E1, Panel A reports the industry-level input emission fees.[17]

4 Empirical Specification

The incidence estimation of input and output emission fees consists of four steps. First, we describe how to obtain output elasticities from industry-specific production function estimation and how to recover marginal costs (MC). Second, we quantify the effects of input and output emission fees on marginal costs, markups, and output prices, from which we can get the price transmission (ρ^O and ρ^I). Third, we study how increases in marginal costs induced by input emission fees are passed through to output prices (ρ^I_{MC}), enabling us to estimate the incidence of input emission fees with equation (3). Fourth, we estimate the industry-specific demand elasticity (ε_D).

4.1 Recovering Marginal Costs

We recover a firm's marginal cost with its output price P_{it} and markup u_{it} based on $MC_{it} = P_{it}/u_{it}$. The estimation of a firm's multiplicative markup follows the procedure proposed by De Loecker and Warzynski (2012), who estimate it under the assumption of cost minimization. Let Q_{it} represent the physical output of firm i in year t. The output Q_{it} is a function of variable inputs X^v_{it} (e.g., intermediate inputs and electricity) that are costlessly adjusted and dynamic inputs (e.g., capital

tion of emission fees would be a better option. However, the available interregional input-output table for 2002 loses crucial regional information as it only contains eight areas rather than 31 provinces. To ensure additivity across different industries, the input emission fees are the AVE. This is because the input-output table is value-based, not quantity-based.

[17]The input market is assumed to be perfectly competitive, indicating complete price transmission of upstream suppliers' output emission fees to their output prices.

and sticky labor) that are subject to adjustment costs. λ_{it} is the Lagrange multiplier in cost minimization associated with the output constraint. λ_{it} represents firm i's marginal costs since it measures how much the (minimized) production costs would increase if its output constraint were relaxed a little bit. Let P_{it}^{v} and P_{it} denote the input price of X_{it}^{v} and the price of firm i's output, respectively. The first-order condition of cost minimization implies that the firm's multiplicative markup u_{it} equals the ratio of a variable input's output elasticity and that input's expenditure share in total revenue:

$$u_{it} = \left[\frac{\partial Q_{it}}{\partial X_{it}^{v}} \frac{X_{it}^{v}}{Q_{it}}\right] \left[\frac{P_{it}^{v} X_{it}^{v}}{P_{it} Q_{it}}\right]^{-1}, \tag{5}$$

where $u_{it} \equiv P_{it}/\lambda_{it}$ is the multiplicative markup, $(P_{it}^{v} X_{it}^{v}) / (P_{it} Q_{it})$ is the expenditure share on input v in total revenue, which is directly available in the data, and $(\partial Q_{it}/\partial X_{it}^{v})(X_{it}^{v}/Q_{it})$ is the output elasticity of input v, which can be obtained by estimating the production function.[18]

To identify the output elasticity of a variable input, we adopt a translog production function. Translog specification accommodates sufficient variations in output elasticities across firms and years. We estimate the three-factor translog production function for each industry, which is given by

$$\begin{aligned} q_{it} = &\beta_l l_{it} + \beta_m m_{it} + \beta_k k_{it} + \beta_{ll} l_{it}^2 + \beta_{mm} m_{it}^2 + \beta_{kk} k_{it}^2 \\ &+ \beta_{lm} l_{it} m_{it} + \beta_{lk} l_{it} k_{it} + \beta_{mk} m_{it} k_{it} + \omega_{it} + \varepsilon_{it}, \end{aligned} \tag{6}$$

where q_{it} denotes the log output quantity of firm i in year t. There are three inputs, where l_{it}, m_{it}, and k_{it} denote log labor, material, and capital inputs, respectively. Based on equation (6), the material output elasticity θ_{it}^{m} can be expressed as $\theta_{it}^{m} = \beta_m + 2\beta_{mm} m_{it} + \beta_{lm} l_{it} + \beta_{mk} k_{it}$.[19] The output elasticities of labor and capital can be computed similarly. The term ω_{it} represents the unobserved productivity shocks that are potentially associated with firm i's input decisions. The presence of ω_{it} introduces an omitted variable bias into the OLS estimates of equation (6). To address this concern, we rely on the insight of Levinsohn and Petrin (2003) and use the approach developed by Ackerberg et al. (2015) to estimate the production function.[20]

The above approach, which recovers marginal costs through estimating production function, has three main advantages. First, the production function approach does not need to impose typical

[18] Unless otherwise stated, the revenue in this paper refers to the gross output value, which equals the firm's output quantity multiplied by its output price.

[19] Although translog coefficients (e.g., β_m, β_{mm}, β_{lm}, and β_{mk}) are constrained to be constant, we can still get time-varying, firm-level output elasticity due to cross-sectional and temporal variations in input decisions.

[20] Ackerberg et al. (2015) invert the general demand function for materials conditional on labor to control for unobserved productivity. Ackerberg et al. (2015) rely on conditional rather than the unconditional input demand function used in Levinsohn and Petrin (2003) to avoid the collinearity problem.

parametric assumptions on demand curves, market structure, and degrees of competitiveness. In particular, it allows us to estimate markups and marginal costs without taking an explicit stance on how firms compete. Second, the production function approach obtains valid estimates as long as material inputs are flexible, regardless of the assumptions made on other inputs. Third, although a particular functional form for production is needed, the translog specification we adopt is highly flexible and can be viewed as a second-order approximation to any arbitrary. These advantages enable us to obtain a general estimate of emission fee incidence in the following analysis.

4.2 Effects of Emission Fees on Marginal Costs, Markups, and Prices

The effects of emission fees on marginal costs, markups, and prices are informative to understand the transmission of emission fees. Our estimated marginal costs in Subsection 4.1 do not include output emission fees. Thus, emission fee policies only have an effect on marginal costs via the input channel generated from input-output linkages. The emission fees imposed on upstream suppliers raise the prices of intermediate inputs and the marginal costs of downstream firms. We quantify the effect of input emission fees on marginal costs with the following regression:

$$mc_{isct} = \gamma_{\varepsilon}^{I} ec_{sct}^{I} + \eta_i + \pi_t + v_{it}, \tag{7}$$

where mc_{isct} denotes the log marginal cost of firm i in city c and IO industry s at year t.[21] ec_{sct}^{I} represents the log input emission fees, i.e., $ec_{sct}^{I} \equiv \log EC_{sct}^{I}$. The regression also includes firm fixed effects η_i and year fixed effects π_t. Other specifications introduce 4-digit CIC industry-province fixed effects to control for cross-sectional heterogeneity across industries and regions (e.g., the uneven spatial distribution of manufacturing firms and typical features of different industries). Province-year or city-year fixed effects are also included to control for other confounding environmental regulations implemented during our sample period, such as emission trading schemes, low-carbon city pilot, and environmental courts. The main coefficient of interest, γ_{ε}^{I}, captures the elasticity of marginal costs with respect to input emission fees, while γ^{I} in incidence expression denotes marginal cost changes in levels and can be calculated as $\gamma^{I} = \partial MC/\partial EC^{I} = \gamma_{\varepsilon}^{I}\left(MC/EC^{I}\right)$.

We then turn to the effects on prices and markups. As emission fees affect prices and markups through two channels, we include both input and output emission fees in the regression:

$$y_{isct} = \beta^{I} ec_{sct}^{I} + \beta^{O} ec_{isct}^{O} + \eta_i + \pi_t + v_{it}, \tag{8}$$

where y_{isct} is the outcome (prices or markups) in logs and ec_{isct}^{O} represents log output emission

[21] IO industries in this paper refer to the 42 industries included in the inter-province input-output table for 2012. A concordance between IO and CIC industries is constructed to determine the IO industry each firm belongs to.

fees.[22] When the dependent variable is log output prices, $\beta^I = \partial \log P / \partial \log EC^I$ and $\beta^O = \partial \log P / \partial \log EC^O$ capture the elasticity of prices with respect to input and output emission fees, respectively. The price transmission in levels of input and output emission fees can be calculated as $\rho^I = \partial P / \partial EC^I = \beta^I \left(P/EC^I\right)$ and $\rho^O = \partial P / \partial EC^O = \beta^O \left(P/EC^O\right)$, respectively.

4.3 Marginal Cost Pass-Through

Estimating the incidence of input emission fees with equation (3) requires the marginal cost pass-through ρ^I_{MC}.[23] We quantify how marginal cost increases induced by input emission fees are passed through to output prices with the following regression:

$$p_{isct} = \rho^I_{MC,\varepsilon} \times mc_{isct} + \eta_i + \pi_t + v_{it}, \tag{9}$$

where p_{isct} and mc_{isct} denote firm-level log output prices and log marginal costs. The main coefficient of interest, $\rho^I_{MC,\varepsilon}$, measures the elasticity of output prices to marginal costs, whereas ρ^I_{MC} used in equation (3) is marginal cost pass-through in levels and can be written as $\rho^I_{MC} = \rho^I_{MC,\varepsilon}\,(P/MC)$.

It is important to point out that OLS estimates of equation (9) may suffer endogenous problems. For example, output prices and marginal costs may be jointly influenced by unobserved product quality. The production of high-quality products requires high-quality inputs (Verhoogen, 2008; Kugler and Verhoogen, 2012). Thus, firms producing high-quality products will have high output prices as well as high marginal costs. When estimating the marginal cost pass-through, we rely on exogenous emission fee policies to address the possible endogeneity. Marginal costs are instrumented with input emission fees. Equation (7) shows the first stage for equation (9).

[22]There are some zero values in output emission fees EC^O, and thus we add a tiny constant before log-transformation, that is, $ec^O_{isct} \equiv \log(EC^O_{isct} + 1\mathrm{E}-11)$. The minimum value of non-zero EC^O is at $1\mathrm{E}-10$ level, and we choose $1\mathrm{E}-11$ to maintain the original distribution of non-zero output emission fees. We also apply an alternative inverse hyperbolic sine (arcsinh) transformation for robustness in Appendix Table E4. The coefficient with arcsinh transformation, β^O, can be converted into elasticity by $\partial \log P / \partial \log EC^O = \left(\partial \log P / \partial \operatorname{arcsinh} EC^O\right)\left(EC^O/\sqrt{(EC^O)^2+1}\right) = \beta^O \left(EC^O/\sqrt{(EC^O)^2+1}\right)$.

[23]It is easier than the estimation with equation (2) which requires the price transmission of input emission fees ρ^I and the cost shifter γ^I. In addition, we cannot precisely measure firm-level input emission fees due to the lack of detailed information on each firm's input bundle. Input emission fees are used as the key independent variable when estimating ρ^I and γ^I, but as the instrumental variable when estimating ρ^I_{MC}. So equation (3) seems to be a better choice.

4.4 Demand Estimation

In order to estimate the incidence under imperfect competition, we also need industry-specific demand elasticity, which is estimated with the following specification:

$$\log Q_{ct} = -\varepsilon_D \log P_{ct} + \alpha_y t + \eta_c + v_{ct}, \tag{10}$$

where Q_{ct} represents the industry's total quantity in city c at year t and P_{ct} represents the industry's market price. The demand elasticity regression also includes a time trend and city fixed effects as control. t represents the time trend, η_c represents the city fixed effects, and v_{ct} represents the error term. The coefficient of interest, ε_D, is demand elasticity. Because OLS estimation of equation (10) suffers from the well-known simultaneity problem, we instrument the market prices with city-level emission fees and revenue-weighted average pollution intensity.

5 Main Results

5.1 Estimating Marginal Costs and Markups

Markups and marginal costs are derived from the estimations of translog functions. As shown in equation (5), we estimate the markup for each firm with the ratio of material output elasticity to material revenue share. Then, we recover firm-level marginal costs as output prices divided by markups. The industry averages of the material revenue share and output prices are shown in Panel A of Appendix Table E1. Considering that the average is sensitive to extreme values, we also provide industry medians of the above variables in Appendix Table E2. The output elasticities are from the translog production functions, and the corresponding coefficients are reported in the Appendix Table E3.

Panel B of Appendix Table E1 reports the industry-level statistics derived from production functions. Columns (1) to (3) of Panel B report the average output elasticities of labor, capital, and materials, respectively. There are two points worth noting. First, the estimated output elasticities differ considerably across input factors, and materials have the largest output elasticities among the three inputs, consistent with the results in Ganapati et al. (2020). Second, the output elasticities for a given input vary considerably across industries. For example, the electrical machinery industry has an average material output elasticity of 0.73, whereas for the rubber industry it is 1.35. Column (4) of Panel B reports the average returns to scale, which is the sum of the three output elasticities. The average returns to scale for all industries range from 0.92 to 1.39, and most industries do not exhibit noticeable increasing or decreasing returns to scale.

Columns (5) and (6) of Appendix Table E1, Panel B show the average estimated markups and marginal costs by industry. The average markups are larger than 1 for all industries, indicating that firms typically have some market power to ask for output prices above their marginal costs. The rubber industry has the highest markup of 1.94, rejecting the commonly used assumption of a perfectly competitive market.

5.2 Effects of Input and Output Emission Fees

Baseline Results

In this subsection, we study the impacts of input and output emission fees on prices, marginal costs, and markups. Table 1 shows the price effects, where we regress firm-level log output prices on log input and output emission fees following equation (8). Column (1) controls for firm fixed effects and year fixed effects. Column (2) includes 4-digit CIC industry-province fixed effects to absorb time-invariant industry and regional heterogeneity. Columns (3) and (4) further include province-year and city-year fixed effects to account for other confounding environmental regulations. The results are robust with different sets of fixed effects. All columns show positive and statistically significant coefficients of input and output emission fees, indicating that emission fees raise output prices through both input and output channels. The most rigorous specification in Column (4) shows that the price transmission of input emission fees is 0.043, implying that a 1% increase in input emission fees leads to a 0.043% increase in output prices. Output emission fees exhibit a significantly positive but low price transmission of 0.006, consistent with the small share of revenue directly paid on SO2 emissions in Column (5) of Appendix Table E1, Panel A.[24] One standard deviation increase in input (output) emission fees can explain 3.9% (2.2%) of one standard deviation increase in output prices.[25] Ignoring the cost transmission along input-output linkages will result in a substantial underestimation of the price effects of emission fees.

The low price transmission of input emission fees to output prices can be broken down into the transmission of input emission fees to marginal costs and that of marginal costs to output prices. The former reveals the extent to which input emission fees increase the total costs of producing a

[24] Appendix Table E4 presents a robustness check with the alternative arcsinh transformation applied to output emission fees. Column (4) of Panel A shows a significant positive coefficient of 0.046 and 0.68 for input and output emission fees, respectively. Given the average conversion ratio, $EC^O/\sqrt{(EC^O)^2+1}$, is 0.014, the arcsinh coefficient of output emission fees can be translated into an elasticity coefficient of 0.010 ($= 0.68 \times 0.014$). The sign and magnitude of price transmission are both consistent with our baseline results, indicating that our results are robust to the quantitative difference between ad-hoc transformations.

[25] The standard deviations of log output prices, input emission fees, and output emission fees are 2.36, 2.12, and 8.50, respectively. The explanatory power of input emission fees is 0.039 ($= 0.043 \times 2.12/2.36$), and that of output emission fees is 0.022 ($= 0.006 \times 8.50/2.36$).

Table 1: Effects of Emission Fees on Output Prices

Output prices	(1)	(2)	(3)	(4)
ec^I	0.015***	0.018***	0.047***	0.043***
	(0.006)	(0.007)	(0.008)	(0.008)
ec^O	0.006***	0.006***	0.007***	0.006***
	(0.001)	(0.001)	(0.001)	(0.001)
N	445,097	445,097	445,097	445,097
Adjusted R2	0.79	0.79	0.79	0.79
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes		
CIC industry-province fixed effects		Yes	Yes	Yes
Province-year fixed effects			Yes	
City-year fixed effects				Yes

Notes: This table reports the results of regressing log output prices on log input and output emission fees with equation (8). Standard errors in parentheses are clustered at the firm level.
Significance: * 0.10, ** 0.05, and *** 0.01.

product, while the latter determines how the increased costs are distributed between producers and downstream buyers. Panels A and B of Table 2 explore the two transmission steps, respectively.

Panel A of Table 2 shows how input emission fees increase marginal costs following equation (7). In all four specifications, the regressions give the expected positive signs of coefficients. The most parsimonious specification in Column (1) indicates that a 1% increase in input emission fees is associated with a 0.025% increase in marginal costs. The regression with CIC industry-province and city-year fixed effects in Column (4) yields a higher positive effect of 0.073, suggesting that the input-output linkages translate the emission fees imposed on upstream suppliers into higher marginal costs of downstream firms.

The modest increase in marginal costs may arise from input substitution and potential upstream imperfect competition. We assume a perfectly competitive input market for simplicity when estimating the incidence, in which prices of intermediate inputs move equi-proportionally with the AVE emission fees of upstream suppliers. However, the potential imperfect competition in the input market may lead to an incomplete increase in intermediate input prices. Meanwhile, when inputs are taxed with emission fees, firms can not only transmit increased costs to their buyers but also substitute away from taxed inputs to avoid paying the tax (Ganapati et al., 2020), which provides more options for firms to offset the cost shock of input emission fees than that of output emission fees.

Panel B of Table 2 presents how firms adjust their markups differentially in response to changes in input and output emission fees. Column (4) shows that a 1% increase in input emission fees leads to a 0.019% decrease in markups. Lower markups can partially offset the additional costs arising from input emission fees and lead to an incomplete pass-through of marginal costs to output prices. For output emission fees, Column (4) also shows a negative and statistically significant coefficient. The above findings are consistent with the incomplete pass-through estimation in the literature (e.g., Atkeson and Burstein, 2008; Amiti et al., 2014). Firms lower their markups following a cost shock to offset increased costs and maintain their prices under the threat of trade diversion.

Table 2: Effects of Emission Fees on Marginal Costs and Markups

Marginal costs	(1)	(2)	(3)	(4)
Panel A. Effect of input emission fees on marginal costs.				
ec^I	0.025***	0.050***	0.078***	0.073***
	(0.006)	(0.007)	(0.009)	(0.009)
N	445,097	445,097	445,097	445,097
Adjusted R2	0.80	0.80	0.80	0.80
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes		
CIC industry-province fixed effects		Yes	Yes	Yes
Province-year fixed effects			Yes	
City-year fixed effects				Yes
Markups	(1)	(2)	(3)	(4)
Panel B. Joint effects of input and output emission fees on markups.				
ec^I	-0.001	-0.021***	-0.021***	-0.019***
	(0.002)	(0.002)	(0.002)	(0.002)
ec^O	-0.0004***	-0.0001	-0.0002	-0.0003**
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	445,097	445,097	445,097	445,097
Adjusted R2	0.70	0.73	0.73	0.74
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes		
CIC industry-province fixed effects		Yes	Yes	Yes
Province-year fixed effects			Yes	
City-year fixed effects				Yes

Notes: This table reports the effects of emission fees on marginal costs and markups. Panel A reports the results of regressing log marginal costs on log input emission fees with equation (7). Panel B reports the results of regressing log markups on log input and output emission fees with equation (8). Standard errors in parentheses are clustered at the firm level.
Significance: * 0.10, ** 0.05, and *** 0.01.

Industry Heterogeneity

To explore cross-industry heterogeneity, we consider two empirical practices to identify industry-specific price transmission. The first approach is to introduce interactions between key independent variables and industry dummies to the baseline regressions (Table 3). The second approach is to perform the baseline regressions separately for each industry (Appendix Table E5). Panel A of Table 3 reports industry-specific price transmission of input and output emission fees. A few points are worth noting. First, except for the food industry, all other industries exhibit a significantly positive or insignificant relationship between prices and output emission fees. Second, most industries show significantly positive price transmission of input emission fees. Third, the price transmission varies considerably across industries. Taking input emission fees as an example, the coefficient of textile fibres is 0.098, while the clothing industry has a smaller and less significant coefficient of 0.026. Panel B of Table 3 reports the estimated effect of input emission fees on marginal costs for each of the 22 industries. With the exception of vehicles, the coefficients of all other industries are significantly positive or statistically insignificant. Appendix Table E5 reports similar results from industry-by-industry regressions, in which output emission fees exhibit expected positive and statistically significant price transmission for most industries, while the coefficients of input emission fees are less significant. This is not surprising considering the sufficient variation in firm-specific output emission fees and the vulnerability of IO industry-province-specific input emission fees to variate power reduction caused by sample splitting.

5.3 Marginal Cost Pass-Through

Baseline Results

We now estimate the marginal cost pass-through with equation (9), which quantifies how output prices respond to increases in marginal costs. Exogenous emission fee policies allow us to deal with the endogenous problem by embedding the effects of input emission fees on marginal costs into the pass-through regressions. Panel A of Table 4 reports the results of regressing log output prices on log marginal costs, where marginal costs are instrumented by input emission fees. Column (1) shows an almost complete pass-through of 0.93. The coefficient decreases to 0.73 in Column (4) after introducing 4-digit CIC industry-province and city-year fixed effects, indicating that a 1% increase in marginal costs leads to a 0.73% increase in output prices.

For a better understanding of the direct and indirect channels, Figure 1 displays the transmission path of emission fees based on the results in Subsections 5.2 and 5.3. Output emission fees impose direct costs on the firm, of which only 0.6% are passed to its downstream buyers. The supply chain can translate the output emission fees imposed on the firm's upstream suppliers into input emission fees. A 100% increase in input emission fees results in a 7.3% increase in marginal costs, of which 73% is further passed on to the firm's downstream buyers. As we can see, the modest increase in marginal costs plays an important role in the incomplete price transmission of input emission fees. For input emission fees, the change in the total surplus of the firm and its downstream

Table 3: Industry-Specific Effects of Emission Fees on Prices and Marginal Costs

Output prices	ec^O (1)	SE (2)	ec^I (3)	SE (4)
Panel A. Industry-specific effects of input and output emission fees on output prices.				
Agriculture	-0.002	0.002	0.084***	0.010
Food	-0.005*	0.002	0.089***	0.011
Chemicals	0.004*	0.002	0.043***	0.010
Chemical products	0.010***	0.002	0.028**	0.010
Plastic	0.005***	0.002	0.045***	0.010
Rubber	0.045***	0.005	-0.048***	0.013
Skins and leather	0.004*	0.002	0.041***	0.010
Wood and furniture	-0.0003	0.002	0.031***	0.010
Paper and books	-0.001	0.002	0.078***	0.012
Textile fibres	-0.002	0.001	0.098***	0.010
Textile fabrics	0.022***	0.002	-0.014	0.010
Clothing	0.016***	0.001	0.026**	0.009
Shoes and hats	0.002	0.002	0.062***	0.010
Stone and glass	0.007***	0.002	0.066***	0.010
Iron and steel	0.013***	0.002	0.054***	0.010
Basic metal	0.011***	0.002	0.012	0.010
Machinery	0.010***	0.002	-0.041**	0.010
Electrical machinery	0.001	0.001	0.046***	0.010
Vehicles	0.018***	0.003	-0.048***	0.010
Instruments	0.0001	0.003	0.027*	0.011
Toys	-0.0006	0.002	0.084***	0.010
Miscellaneous	-0.007	0.004	0.136***	0.012

Marginal costs	ec^I (1)	SE (2)
Panel B. Industry-specific effects of input emission fees on marginal costs.		
Agriculture	0.090***	0.010
Food	0.093***	0.011
Chemicals	0.069***	0.010
Chemical products	0.056***	0.010
Plastic	0.076***	0.009
Rubber	0.019	0.013
Skins and leather	0.068***	0.010
Wood and furniture	0.052***	0.009
Paper and books	0.093***	0.012
Textile fibres	0.119***	0.009
Textile fabrics	0.015	0.010
Clothing	0.061***	0.008
Shoes and hats	0.085***	0.010
Stone and glass	0.076***	0.010
Iron and steel	0.077***	0.010
Basic metal	0.046***	0.010
Machinery	0.007	0.010
Electrical machinery	0.046***	0.010
Vehicles	-0.030**	0.011
Instruments	0.028*	0.012
Toys	0.100***	0.011
Miscellaneous	0.129***	0.012

Notes: Panel A reports the results of regressing log output prices on log output and input emission fees with industry interaction terms when controlling for the firm, 4-digit CIC industry-province, and city-year fixed effects. Panel B reports the results of regressing log marginal costs on log input emission fees. SE represents the standard errors clustered at the firm level.
Significance: * 0.10, ** 0.05, and *** 0.01.

buyers depends on how the input emission fees affect the firm's marginal costs, while the welfare loss distribution between the firm and its downstream buyers depends on the extent to which the increased marginal costs are passed on to its downstream buyers.

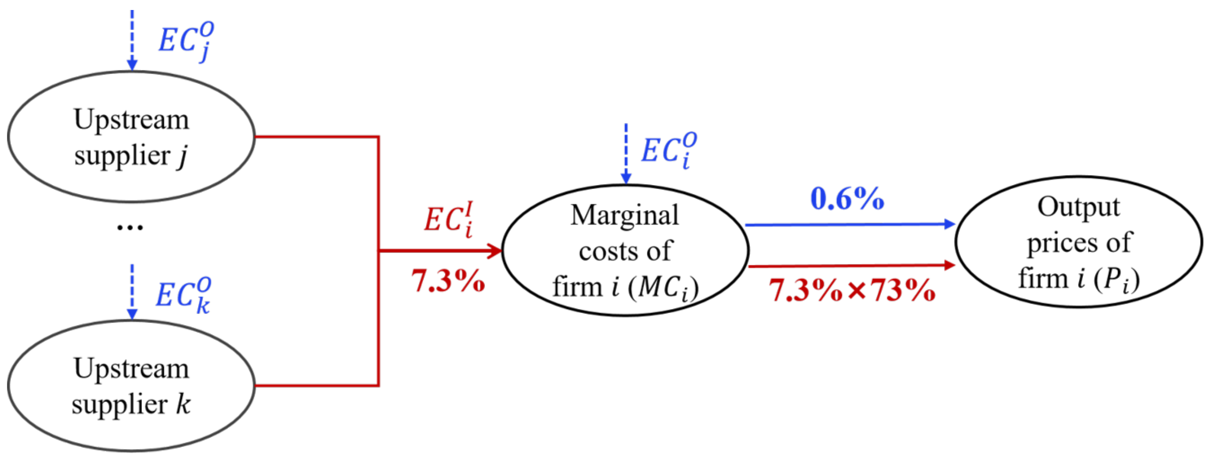


Figure 1: Transmission of Emission Fees along the Supply Chain

Industry Heterogenerity

We also estimate industry-specific marginal cost pass-through to investigate cross-industry heterogeneity. The results are reported in Panel B of Table 4. All industries exhibit a statistically significant marginal cost pass-through between 0.5 and 0.9, indicating that the majority of indirect costs induced by input emission fees are passed to downstream buyers.

5.4 Incidence

In this subsection, we empirically estimate the incidences of output and input emission fees with equations (1) and (3). Whether consumer surplus is negatively affected by emission fees depends on whether emission fee increases lead to higher product prices. Whether producers benefit or suffer from emission fees depends on whether the revenue increase from cost shifting is sufficient to offset the cost increase.

Besides the estimated marginal costs in Subsection 5.1, price transmission in Subsection 5.2, and marginal cost pass-through in Subsection 5.3, demand elasticity is also needed for computing incidence. Appendix Table E6 reports the industry-specific demand elasticity ($-\varepsilon_D$) estimated with equation (10). The dependent variable is the city-level log aggregate quantity. The independent variable is the log market price, which is the revenue-weighted geometric average of all firm-level output prices in the given city. The market price is instrumented by local emission fees interacted with revenue-weighted average pollution intensity. With the exception of the iron and

Table 4: Marginal Cost Pass-Through Estimates

Output prices	(1)	(2)	(3)	(4)
Panel A. Marginal cost pass-through				
Marginal costs	0.934***	0.572***	0.735***	0.731***
	(0.063)	(0.059)	(0.034)	(0.037)
N	445,097	445,097	445,097	445,097
Adjusted R2	0.94	0.80	0.90	0.90
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes		
CIC industry-province fixed effects		Yes	Yes	Yes
Province-year fixed effects			Yes	
City-year fixed effects				Yes

Output prices	Marginal costs (1)	SE (2)
Panel B. Industry-specific marginal cost pass-through		
Agriculture	0.675***	0.048
Food	0.667***	0.048
Chemicals	0.775***	0.041
Chemical products	0.775***	0.038
Plastic	0.773***	0.041
Rubber	0.843***	0.034
Skins and leather	0.761***	0.041
Wood and furniture	0.768***	0.038
Paper and books	0.722***	0.045
Textile fibres	0.664***	0.053
Textile fabrics	0.773***	0.034
Clothing	0.752***	0.039
Shoes and hats	0.732***	0.046
Stone and glass	0.672***	0.042
Iron and steel	0.708***	0.041
Basic metal	0.786***	0.037
Machinery	0.845***	0.032
Electrical machinery	0.710***	0.036
Vehicles	0.776***	0.029
Instruments	0.734***	0.034
Toys	0.701***	0.048
Miscellaneous	0.534***	0.057
Firm fixed effects	Yes	
CIC industry-province fixed effects	Yes	
City-year fixed effects	Yes	

Notes: Panel A reports the estimated marginal cost pass-through using the whole sample. The dependent variable is the firm-level log output prices, and the independent variable is the firm-level log marginal costs instrumented by input emission fees. Panel B reports the industry-specific marginal cost pass-through estimated with industry interaction terms when controlling for the firm, 4-digit CIC industry-province, and city-year fixed effects. Standard errors in parentheses in Panel A and represented by SE in Panel B are clustered at the firm level.

Significance: * 0.10, ** 0.05, and *** 0.01.

steel industry, all other industries exhibit a negative coefficient, indicating that an increase in market price leads to a decrease in aggregate demand.

To simplify exposition, we report the change in consumer surplus as a percentage of the total change in producer and consumer surplus, that is, $I/(I+1) = (\partial CS/\partial EC)/(\partial CS/\partial EC + \partial PS/\partial EC)$.[26] When calculating the incidence, we replace the price transmission in levels with the corresponding estimated elasticity because the latter is less susceptible to outliers. The first row in Table 5 reports the incidence estimated using the whole sample. Column (2) reports the incidence of output emission fees estimated with equation (1), and 0.65% of welfare loss is borne by downstream buyers under oligopoly. As shown in Column (6), the incidence of input emission fees estimated with equation (3) is 71% under oligopoly.

As mentioned in Section 2, our incidence estimation relies on the assumption of homogeneous products. For a wider-scope analysis, we include all manufacturing industries, and their differentiated products may be a potential source of estimation bias. We then perform industry-specific analysis and identify the extent of product differentiation in each industry through the elasticity of substitution to give an explicit insight into the reliability of our estimation. Specifically, a higher elasticity of substitution between varieties indicates a greater extent of product homogeneity (Feenstra, 1994; Broda and Weinstein, 2006). Ossa (2015) estimates the elasticity of substitution at the 3-digit SITC-Rev3 level (Standard International Trade Classification Revision 3). We map the elasticities provided by Ossa (2015) to our 6-digit HS codes by utilizing the correspondence table from the United Nations. The median value for each industry proxies its degree of product differentiation.

To clarify how much our results are influenced by unobservable product quality, we repeat our baseline regressions in equations (7) to (9) within 11 more homogeneous industries whose elasticity of substitution fall into the top 50%. The signs and statistical significances of regression coefficients reported in Appendix Table E7 are consistent with our baseline results. Meanwhile, we find equal price transmission of output emission fees in Appendix Table E7 and Table 1. The marginal cost pass-through in Appendix Table E7 is slightly lower than that in Table 3. Thus, we learn that the influence of product differentiation on our results is limited.

We report the industry-specific incidence from the most homogeneous to the most differentiated industries in Table 5. Column (1) reports the elasticity of substitution for each industry, ranked from highest (homogeneous) to lowest (differentiated). The top-ranked industries fit better with the product homogeneity assumption and have more reliable incidence estimations. Columns (2) and (3) report the incidence of output emission fees under oligopoly and monopoly, respectively.

[26] The consumers are mainly referred to as buyers of intermediate inputs rather than consumers of final goods. For more details, please refer to Appendix E2.

As discussed in Section 2, perfect competition and monopoly are both special cases of oligopoly. Buyers bear all welfare loss under perfect competition, and the corresponding incidence equals 100%, which is very different from our results under oligopoly. For the three most homogeneous industries, the incidence of output emission fees under oligopoly falls below 2%, indicating that producers bear the vast majority of the welfare loss from output emission fees. Columns (4) and (5) report the directions of consumer and producer surplus changes for each infinitesimal increase in output emission fees under oligopoly. For most industries, output emission fees cause a welfare loss to be shared between producers and their buyers.

Columns (6) to (9) of Table 5 report the industry-specific incidence estimation of input emission fees. There are a few points worth noting. First, except for instruments, all other industries have an incidence ranging from 50% to 100% under oligopoly. The incidences of the three most homogeneous industries are 66%, 70%, and 75%. These results, consistent with the incidence estimated using the whole sample, indicate that producers only pay a small share of the welfare loss from input emission fees while their downstream buyers bear the majority. Second, the traditional assumption of a monopolistic or perfectly competitive market would result in misleading incidence estimates. Taking the shoes and hats industry as an example, its incidence of input emission fees is 66% under oligopoly, while the number would be underestimated (overestimated) as 42% (100%) under monopoly (perfect competition).

To quantify the salience of input-output linkages, we report the welfare loss share of input emission fees in Column (10) of Table 5, where we exclude government tax revenue from welfare W ($W = CS + PS$) for simplicity. The welfare loss share estimated with the whole sample is 7%. For some industries (e.g., food, agriculture, paper and books, and textile fibres), the shares are larger than 10%. These industries take up 12% of the manufacturing employment and 15% of the manufacturing output. Columns (11) and (12) show the directions of welfare changes due to input and output emission fees. For most industries, welfare loss of emission fees comes from both the output and input channels. Thus, ignoring the input channel may lead to an underestimation of the total welfare loss of emission fees.

6 SO2 Emission Reduction and Decomposition

In this section, we first assess the effectiveness of emission fees in reducing SO2 emissions. To distinguish the short- and long-term effects of this policy, we adopt a dynamic DID specification. The findings suggest that the emission fee policy leads to an immediate and substantial reduction in SO2 emissions. We then decompose the total SO2 emission into total output and pollution intensity and explore the channels through which the SO2 emission is reduced. This analysis on

Table 5: Incidences of Input and Output Emission Fees

		Incidence (%): EC^O				Incidence (%): EC^I				Wefare loss share (%): EC^I		
	Elasticity of substitution	Oligopoly	Monopoly	$\frac{\partial CS}{\partial EC^O}$	$\frac{\partial PS}{\partial EC^O}$	Oligopoly	Monopoly	$\frac{\partial CS}{\partial EC^I}$	$\frac{\partial PS}{\partial EC^I}$	Share	$\frac{\partial W}{\partial EC^I}$	$\frac{\partial W}{\partial EC^O}$
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Overall		0.65	0.64	-	-	71.44	42.24	-	-	6.97	-	-
Shoes and hats	4.45	0.23	0.23	-	-	66.30	42.27	-	-	8.55	-	-
Clothing	4.11	1.55	1.53	-	-	70.25	42.91	-	-	6.07	-	-
Skins and leather	3.93	0.40	0.40	-	-	75.09	43.21	-	-	6.46	-	-
Toys	3.88	-0.06	-0.06	+	-	69.90	41.21	-	-	9.15	-	-
Food	3.61	-0.48	-0.48	+	-	48.73	40.00	-	-	11.36	-	-
Instruments	3.25	0.01	0.01	-	-	132.96	42.34	-	+	1.51	-	-
Machinery	3.19	1.05	1.04	-	-	85.15	45.81	-	-	0.67	-	-
Agriculture	3.13	-0.19	-0.19	+	-	54.15	40.30	-	-	10.08	-	-
Plastic	2.99	0.54	0.54	-	-	54.89	43.58	-	-	9.66	-	-
Textile fibres	2.74	-0.23	-0.23	+	-	56.48	39.91	-	-	12.28	-	-
Miscellaneous	2.71	-0.65	-0.65	+	-	50.01	34.80	-	-	12.08	-	-
Electrical machinery	2.63	0.09	0.09	-	-	84.07	41.52	-	-	3.75	-	-
Paper and books	2.45	-0.10	-0.11	+	-	51.84	41.91	-	-	11.50	-	-
Wood and furniture	2.35	-0.03	-0.03	+	-	76.44	43.43	-	-	4.95	-	-
Chemicals	2.34	0.35	0.35	-	-	63.44	43.65	-	-	7.75	-	-
Iron and steel	2.22	1.34	1.32	-	-	73.72	41.47	-	-	6.87	-	-
Rubber	2.12	4.42	4.31	-	-	61.90	45.74	-	-	2.48	-	-
Basic metal	2.08	1.08	1.08	-	-	59.93	44.01	-	-	5.66	-	-
Vehicles	2.03	1.82	1.78	-	-	82.23	43.70	+	+	-2.88	+	-
Chemical products	2.01	1.00	1.00	-	-	58.95	43.65	-	-	6.80	-	-
Stone and glass	1.91	0.73	0.72	-	-	60.79	40.19	-	-	7.75	-	-
Textile fabrics	1.73	2.23	2.19	-	-	65.27	43.61	-	-	1.74	-	-

Notes: This table reports the estimated incidences of input and output emission fees, where incidence is defined as the change in consumer surplus as a share of the total change in consumer and producer surplus. Column (1) reports the elasticity of substitution for each industry, ranked from highest to lowest. Columns (2) and (3) report the incidence of output emission fees estimated with equation (1) under oligopoly and monopoly. Columns (4) and (5) report the directions of consumer and producer surplus changes for each infinitesimal increase in output emission fees. $\frac{\partial CS}{\partial EC^O}$ in Column (4) takes the opposite sign with the price transmission of output emission fees ρ^O. $\frac{\partial PS}{\partial EC^O}$ in Column (5) is inferred by the direction in Column (4) and the incidence under oligopoly in Column (2). Columns (6) to (9) report similar results for the incidence of input emission fees, estimated with equation (3). $\frac{\partial CS}{\partial EC^I}$ in Column (8) takes the opposite sign of the product of cost shifter γ^I and marginal cost pass-through ρ^I_{MC}. $\frac{\partial PS}{\partial EC^I}$ in Column (9) is inferred by the direction in Column (8) and the incidence under oligopoly in Column (6). In the first row, the incidence is calculated using the price transmission and marginal cost pass-through estimated with the whole sample from Table 1 and Panel A of Table 4. The industry-level incidence is estimated using the industry-specific price transmission and marginal cost pass-through from Table 3 and Panel B of Table 4. Column (10) reports the welfare loss share of input emission fees, and its expression can be found in Appendix A. Columns (11) and (12) report the directions of welfare changes for input and output emission fees, respectively.

pollution intensity is also used to verify the assumption of no upgrade of green technology in the short term. In the main analysis, we treat emission fees directly paid by firms as an output tax. This implicitly indicates that firms' production technology remains unaffected by pollution fees in the short term. We verify this assumption in the following analysis.

The dynamic effects of emission fees are quantified through the full specification as follows:

$$Y_{it} = \alpha_i + \lambda_t + \sum_{l=-8}^{-2} u_l D_{it}^l + \sum_{l=0}^{6} u_l D_{it}^l + v_{it}, \quad (11)$$

where Y_{it} is the outcome of interest for firm i at year t, E_i is the treatment time, and $D_{it}^l \equiv \mathbb{I}\{t - E_i = l\}$ is an indicator for firm i being l years away from initial treatment at year t. The first summation in equation (11) captures the "lead" effects, and the second summation captures the "lag" effects. The sample period ranges from 2004 to 2013.[27] In the presence of treatment effect heterogeneity and variation in treatment timing, the estimates of equation (11) through conventional two-way fixed effects regressions might be biased (De Chaisemartin and d'Haultfoeuille, 2020; Goodman-Bacon, 2021; Sun and Abraham, 2021).The common practice of testing pre-trends with coefficients on the leads may also be unreliable. Thus, we adopt the efficient DID estimator proposed by Sun and Abraham (2021) for its robustness to the heterogeneity of treatment effects.

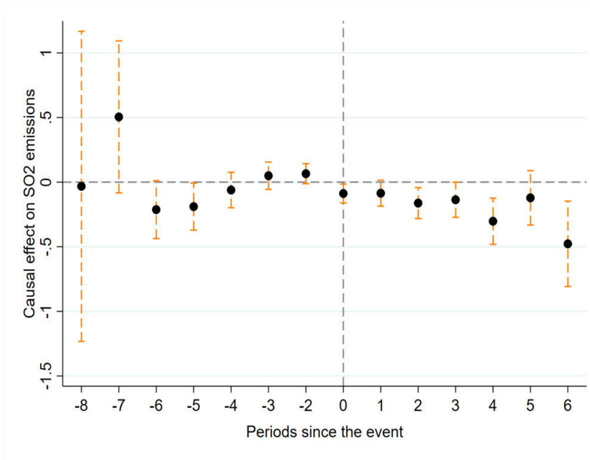
We first confirm the effectiveness of emission fees in pollution control by studying the changes in firm-level log SO2 emissions. Panel (a) of Figure 2 supports the parallel trends assumption with insignificant lead coefficients and exhibits negative effects after the policy. The negative effects are statistically significant for relative years $l = 0$, 2, 3, 4, and 6, indicating that higher emission fees lead to an immediate and long-lasting reduction in SO2 emissions.

To uncover the underlying forces behind the emission reduction in Panel (a), we follow Shapiro and Walker (2018) to decompose the total SO2 emissions into output quantity and pollution intensity (SO2 emissions per unit).[28] Panels (b) and (c) of Figure 2 show the dynamic treatment effects on log pollution intensity and log output quantity, respectively. As shown in Panel (b), there is no statistically significant reduction in pollution intensity after the policy except for $l = 4$. Panel (c) shows that higher emission fees lead to an immediate and long-lasting reduction in output

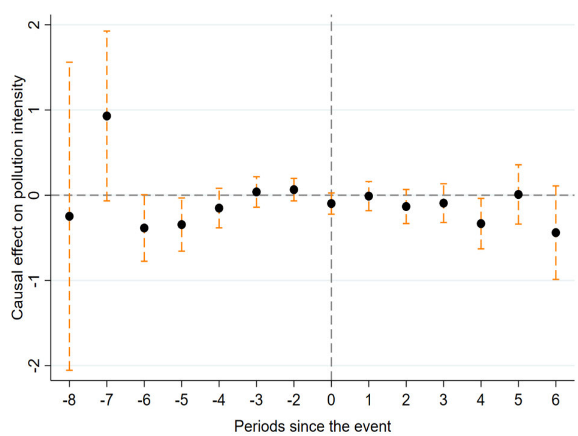
[27] Years before 2004 are dropped to isolate the influence of the full implementation of emission fees in 2003. In this section, we focus on the staggered doubling of emission fees across different provinces that began in 2007. The details are summarized in Appendix Table B1.

[28] Shapiro and Walker (2018) decompose changes in US pollution emissions into changes in three components, namely total output, product composition, and product-specific pollution intensity. The lack of pollution information at the product level prevents us from distinguishing the latter two channels. We rely on China Customs data to construct the export product composition and provide suggestive evidence that the emission fee policy lowers the export share of pollution-intensive products, as shown in Appendix Figures E2 and E3, where the construction of export share can be found in Appendix D1.

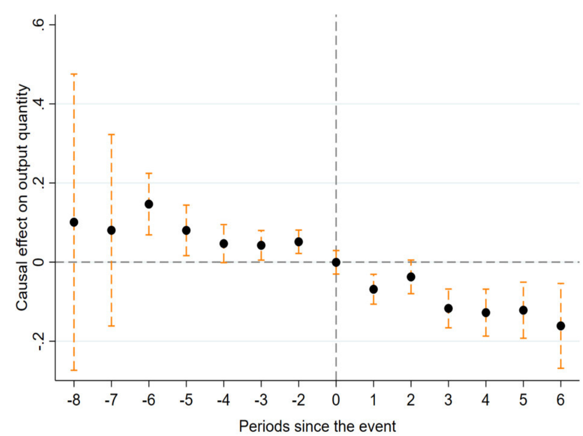
quantity, while we acknowledge that some lead coefficients (e.g., l = -6, -5, and -2) are significantly positive and do not perfectly satisfy the parallel trends assumption. The dynamic evolution of treatment effects indicates that the reduction in total SO2 emissions is primarily driven by lower output quantity, especially in the short term. The insignificant impacts on pollution intensity favorably support our implicit assumption that the short-term development of cleaner production technology is negligible. We also apply the "imputation" DID estimator proposed by Borusyak et al. (2021) as an alternative method in Appendix Figure E1 and have consistent results with our above findings. The sample used in this section is detailed in Appendix C1.



(a) Log SO2 emissions



(b) Log pollution intensity



(c) Log quantity

Figure 2: Decomposition of Pollution Emission Reduction

Note: This figure presents the dynamic effects of doubling emission fees on firm-level SO2 emissions (Panel (a)), pollution intensity (Panel (b)), and manufacturing output (Panel (c)), estimated through the approach proposed by Sun and Abraham (2021). The year right before treatment ($l = -1$) is excluded. Firm fixed effects, year fixed effects, and 4-digit CIC industry-year fixed effects are included. 95% confidence bands are shown, using standard errors clustered by firm.

7 Conclusion

Pollution control is an essential topic for both policymakers and academics. To help tackle this issue, there have been extensive discussions on the role of emission fees in internalizing the negative externalities associated with pollution. One implication emerged from these discussions is that the effectiveness of emission fees in internalizing the negative externalities depends on whether producers are able to shift emission cost burdens to consumers. It is crucial to precisely estimate how the welfare costs are distributed between producers and downstream buyers. Despite the literature on the incidences of output tax and input cost, the cost transmission along the supply chain has been less studied. It is important to consider this effect so that we will account for the indirect costs arising from input-output linkages apart from direct tax payments and have a better understanding of the policy's impacts on markups, prices, and welfare.

In this paper, we analyze the incidence of SO2 emission fees by considering input-output linkages under a general imperfect competition framework. We show that emission fees affect manufacturing producers through two channels. First, the emission fees directly imposed on producers act as an output tax. Second, emission fees imposed on upstream suppliers can raise the marginal costs of downstream producers, which acts as an input tax. We start by deriving statistically sufficient representations for emission fee incidences that account for input-output linkages, general imperfect competition, and incomplete pass-through. Empirically, we focus on the specific application of China's SO2 emission fees over 2000–2013 and study its price effect and economic incidence. For output emission fees, manufacturing producers pay almost all direct emission costs, and welfare loss also largely falls on them. For input emission fees, a 1% increase will translate into 0.07% higher marginal costs, and 73% of the indirect costs are further passed on to downstream buyers. Our incidence estimates suggest that producers pay 29% of the welfare loss from input emission fees, and their downstream buyers bear the rest.

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A Appendix: Theory

In this section, we derive the welfare loss share of input emission fees. We exclude government tax revenue from welfare W for simplicity and W equals the sum of producer and consumer surplus. As demonstrated in Section 2, the change in producer surplus PS with respect to output emission fees is $\partial PS/\partial EC^O = Q\left[(1-\varepsilon_D L)\,\rho^O - 1\right]$. The change in consumer surplus CS is $\partial PS/\partial EC^O = -\rho^O Q$. Thus, the welfare change arising from output emission fees can be written as

$$\frac{\partial W}{\partial EC^O} = \frac{\partial PS}{\partial EC^O} + \frac{\partial CS}{\partial EC^O} = -Q\left[1 + \varepsilon_D L \rho^O\right]. \tag{A1}$$

Similarly, the welfare change due to an infinitesimal increase in input emission fees is given by

$$\frac{\partial W}{\partial EC^I} = \frac{\partial PS}{\partial EC^I} + \frac{\partial CS}{\partial EC^I} = -Q\left[\gamma^I + \varepsilon_D L \rho^I\right]. \tag{A2}$$

Combining equations (A1) and (A2), we can determine how much of the total welfare loss is attributed to input emission fees with the following ratio:

$$\frac{\partial W/\partial EC^I}{\partial W/\partial EC^I + \partial W/\partial EC^O} = \frac{\gamma^I + \varepsilon_D L \rho^I}{\gamma^I + \varepsilon_D L \rho^I + 1 + \varepsilon_D L \rho^O}. \tag{A3}$$

B Appendix: Background

Appendix Table B1 displays the evolution of SO2 emission fees imposed by Chinese local governments. It shows the timings and amounts of emission fee adjustments made by different cities or provinces since 2003.

C Appendix: Data

In this section, we first provide further details of the data used in Sections 5 and 6. Then, we describe our industry classification.

C1 Sample

We first introduce our sample in the baseline analysis about price transmission and incidence in Section 5. To address the well-known bias between revenue and physical total factor productivity

Table B1: Implementation and Adjustment of SO2 Emission Fees.

	City/province	Date	Previous SO2 emission fees (Chinese yuan per kg)	New SO2 emission fees (Chinese yuan per kg)
Full implementation of SO2 emission fees	Hangzhou	2003.7.1	-	0.63
	Jilin	2003.7.1	-	0.63
	Beijing	2005.7.1	0.50	0.63
	Zhengzhou	2003.7.1	-	0.53
		2005.7.1	0.53	0.63
	Other cities	2003.7.1	-	0.21
		2004.7.1	0.21	0.42
		2005.7.1	0.42	0.63
Adjustments of SO2 emission fees	Jiangsu	2007.7.1	0.63	1.26
	Shandong	2008.7.1	0.63	1.26
	Shanghai	2009.1.1	0.63	1.26
	Guangdong	2010.4.1	0.63	1.26
	Liaoning	2010.8.1	0.63	1.26
	Tianjin	2010.12.20	0.63	1.26
	Xinjiang	2012.8.1	0.63	1.26
	Anhui	2008.1.1	0.63	0.84
		2009.1.1	0.84	1.05
		2010.1.1	1.05	1.26
	Hebei	2008.7.1	0.63	0.10
		2009.7.1	0.96	1.26
	Inner Mongolia	2008.7.10	0.63	0.95
		2009.7.1	0.95	1.26
	Guangxi	2009.1.1	0.63	0.95
		2010.1.1	0.95	1.26
	Yunnan	2009.1.1	0.63	0.95
		2010.1.1	0.95	1.26

Notes: This table summarizes the emission fee policies imposed by Chinese local governments. "Other cities" refer to cities other than Beijing, Hangzhou, Jilin, and Zhengzhou. Information on the adjustments of SO2 emission fees is from the official websites of the Ministry of Ecology and Environment and local governments.

(Foster et al., 2008), we estimate a quantity-based production function for "true" marginal costs. To obtain firm-level output prices that translate gross output value to output quantity, we turn to the export data from China Customs. The reported export values and quantities enable us to construct a measure for firm-level output prices, and we thus restrict our analysis to manufacturing firms with export records, as shown in Figure C1. Pollution information from the CESD is also essential in our analysis. Pollution intensity translates regional emission fees into firm-heterogeneous emission costs. For firms included in the CESD, we can divide their pollution emissions by production quantity to get their firm-specific pollution intensity. For firms not included in the CESD, we use their corresponding 4-digit (or 3-digit) CIC industry-province-level average pollution intensity.

Our above process avoids serious sample selection bias. There are 344,875 industrial firms in the ASIF database, amongst which a minor fraction of 37,927 firms appear in all three firm-level databases. Analysis based on a small group of firms may lead to serious sample selection bias and unreliable conclusions. We address this problem by expanding our feasible sample with industry-province-level average pollution intensity.

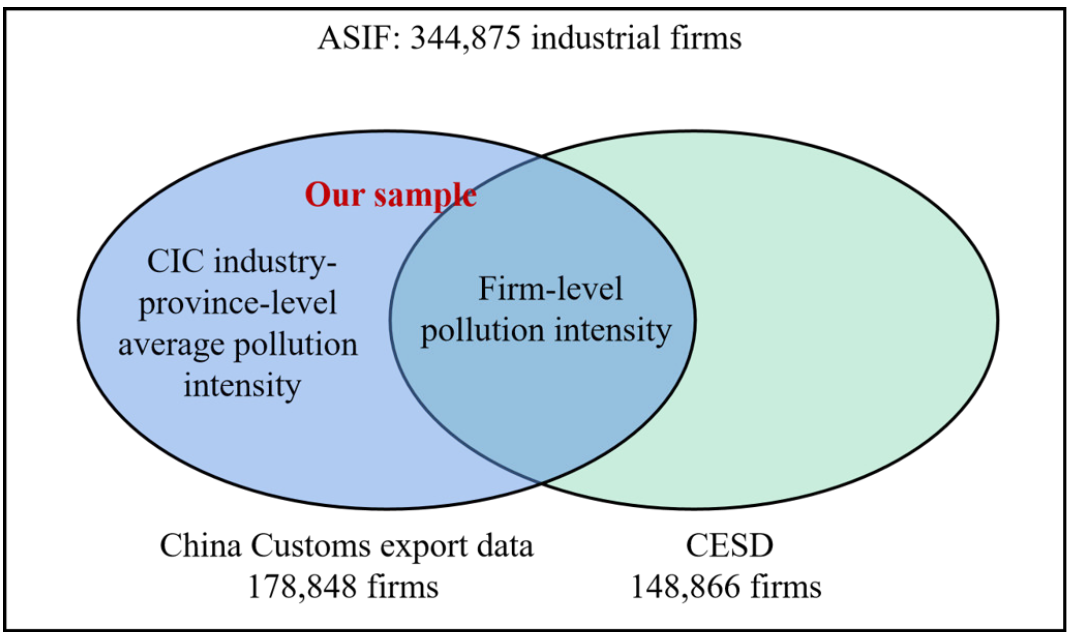


Figure C1: Regression Sample and Firm-Level Database Matching

We then describe the sample used in Section 6. The data in Panels (a), (b), and (c) of Figure 2 is from the CESD and China Customs. To obtain precise SO2 emissions at the firm level, we focus on firms in the CESD. Decomposing the SO2 emissions reported by the CESD into production quantity and pollution intensity needs output prices constructed from China Customs data. For firms not recorded by China Customs, we use their corresponding 4-digit (or 3-digit) CIC industry prices. We exclude firms with different addresses within the sample period to avoid treatment status changes due to migration rather than the imposition of a new emission fee policy. We then restrict our analysis to those firms that appear throughout 2004–2013 so that we maintain a balanced panel with a plausible sample size. We drop any years before 2004 to isolate the effects of the full implementation of SO2 emission fees in 2003.

We apply log transformation to SO2 emissions, pollution intensity, and production quantity. There are zero values in SO2 emissions and pollution intensity. The minimum value of non-zero SO2 emissions (pollution intensity) is at the unit (1E-10) level, and thus we add a constant of 0.1 (1E-11) before log-transformation. The practice allows for retaining zero-valued observations without disturbing the original distribution of non-zero ones.

C2 Industry Classification

This subsection introduces our 22 broadly defined industries. The industry definition in this paper is based on the 98 2-digit HS product classifications. First, special 2-digit HS products subject to strict government control or lacking fair market values are dropped, including tobacco (2-digit HS: 24), minerals (2-digit HS: 25–27), pharmaceutical products (2-digit HS: 30), pearls, jewelry, and precious metals (2-digit HS: 71), arms (2-digit HS: 93), and artworks (2-digit HS: 97). Manufacturing of large-scale transportation, namely railway (2-digit HS: 86), aircraft (2-digit HS: 88), and ships (2-digit HS: 89), is dropped to avoid outliers due to their extremely high unit prices. Second, to ensure sufficient sub-sample sizes for reliable estimates of industry-specific production functions, we integrate some 2-digit HS codes and obtain 22 industries. These industries are as follows: agriculture (2-digit HS: 01–16), food (2-digit HS: 17–23), chemicals (2-digit HS: 28–29), chemical products (2-digit HS: 31–38), plastic (2-digit HS: 39), rubber (2-digit HS: 40), skins and leather (2-digit HS: 41–43), wood and furniture (2-digit HS: 44–46 and 94), paper and books (2-digit HS: 47–49), textile fibers (2-digit HS: 50–55), textile fabrics (2-digit HS: 56–60), clothing (2-digit HS: 61–63), shoes and hats (2-digit HS: 64–67), stone and glasses (2-digit HS: 68–70), iron and steel (2-digit HS: 72–73), basic metals (2-digit HS: 74–83), machinery (2-digit HS: 84), electrical machinery (2-digit HS: 85), vehicles (2-digit HS: 90), instruments (2-digit HS: 90–92), toys (2-digit HS: 95), and miscellaneous (2-digit HS: 96).

D Appendix: Variable

D1 Variable Construction

Input price deflators

This subsection details the construction of deflators for capital and material inputs. The province-specific capital price deflators come from the China Regional Economic Database collected by China's NBS. Material price deflators are constructed using the ASIF data at the most detailed level possible. Firms' output prices are defined as their export prices, assuming domestic sales prices are proportional to export prices. Output prices of non-exporters are first approximated by 4-digit CIC industry average prices and then by 3-digit CIC industry average prices. After getting firm-level output prices, quantity is calculated as the firm's output value divided by its output price, and unit material cost is calculated as the firm's material input divided by its quantity. Assuming that the quantity of inputs used to produce one unit product remains constant between two consecutive years, the variation in the unit material cost measures the firm-specific material price changes. For each 4-digit CIC industry, we trim the 5% tails of the unit material cost changes and calculate the revenue-weighted geometric average of material price changes as the material price deflators.

Intermediate inputs for 2008–2013

Because the information on intermediate inputs is not reported for 2008–2013, we estimate it with the following equation:

$$M_{it} = \frac{C^s_{it}}{R^s_{it}} R_{it} - D_{it} - E_{it},$$

where M_{it} represents the intermediate inputs we need to estimate for firm i in year t. C^s_{it}/R^s_{it} is the cost-to-revenue ratio of sales, where sales cost is represented by C^s_{it} and sales revenue is represented by R^s_{it}. R_{it}, D_{it}, and E_{it} represent the total output value, asset depreciation, and employee compensation, respectively. The intuition of the first term on the right-hand side is to estimate total production costs under the assumption that the cost-to-revenue ratio of total output is equal to that of sales. Subtracting the capital and labor costs from the total production costs gives estimated intermediate inputs. To demonstrate the validity of this estimation approach, we apply it for 2000–2007 and compare the estimated and actual intermediate inputs. The paired t-test yields a p-value of 0.30, showing no significant differences between the estimated and actual intermediate inputs. The summary statistics in Figures D2 and D3 also confirm the validity of our approach.

Before estimating intermediate inputs for 2008–2013, we need to deal with the lack of data on employee compensation and asset depreciation for 2008 and 2009. We estimate these two indicators using data from the closest available year to 2008 or 2009 for each firm. The estimation relies on the assumption of stable ratios of asset depreciation to fixed assets and employee wages to total output, which allows us to estimate the firm's employee compensation (asset depreciation) for 2008 or 2009 with the current total output (fixed assets) and its corresponding ratio from the closest year. Note that employee benefits should be included in employee compensation. We ignore them when estimating intermediate inputs because employee benefits for 2008–2013 are not reported in the ASIF database and are negligible compared to employee wages.

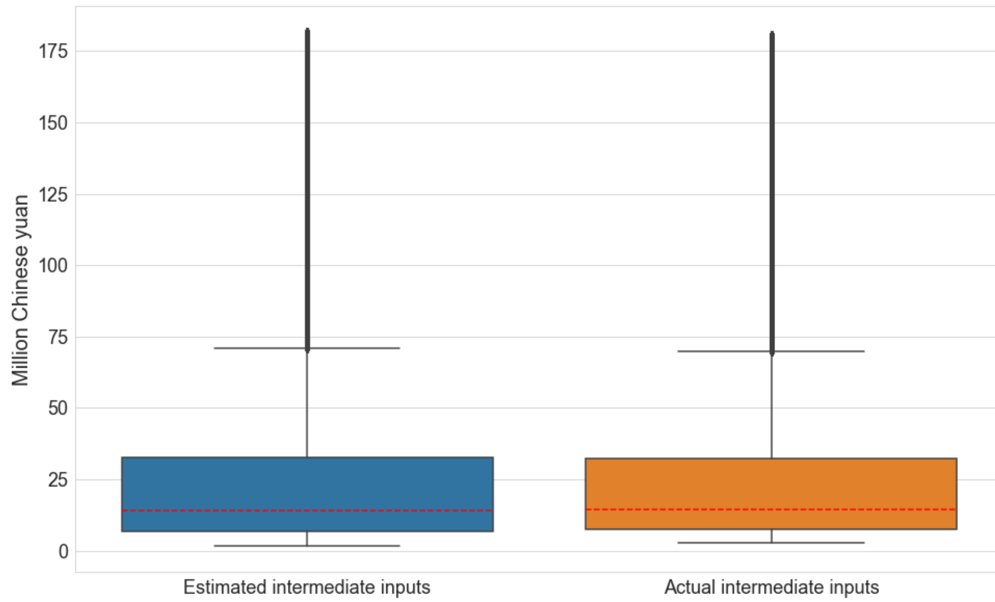


Figure D2: Distribution of Estimated and Actual Firm-Level Intermediate Inputs

Export Share of Pollution-Intensive Products

This subsection reports the calculation procedure of the export share of pollution-intensive products in Figures E2 and E3. First, we calculate the pollution intensity (SO2 emissions divided by output value) for each firm using firm-level pollution data from the CESD. We then compute the revenue-weighted average pollution intensity for each 4-digit CIC industry. Note that we choose the value-based pollution intensity rather than the quantity-based pollution intensity to ensure cross-industry comparability. Second, we use the constructed concordance between CIC and HS codes to map the average pollution intensity to 6-digit HS codes. We then rank all 6-digit HS products in the order of pollution intensity from highest to lowest. A product is defined as pollution-intensive if its pollution intensity falls into the top 50%. Finally, we calculate each firm's export share of pollution-intensive products in its total exports.

D2 Addressing Measurement Errors in Output Prices

As no Chinese database reports firm-level output prices, we rely on export prices recorded by China Customs. A possible concern is that the spreads between output and export prices may

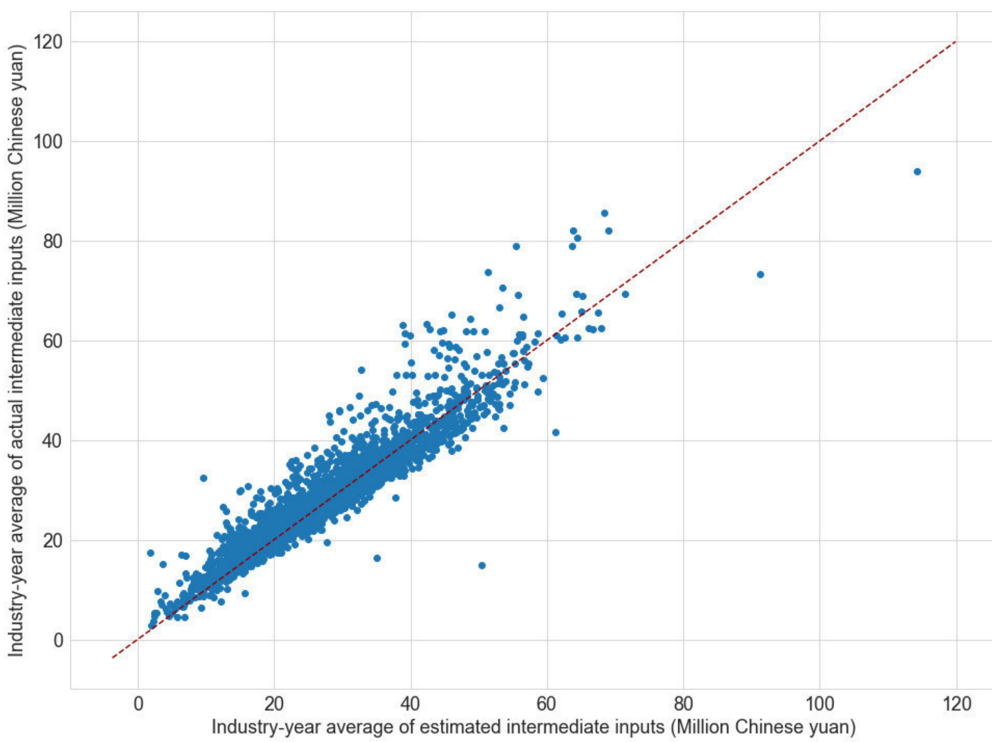


Figure D3: 4-digit CIC Industry-Year Average of Estimated and Actual Intermediate Inputs introduce bias into incidence estimation. However, we show that the spreads are not a problem when price transmission elasticity and demand elasticity are accurately estimated. The spreads in the numerator and denominator of key parameters cancel each other out completely, and we can still get a reliable incidence estimate. The detailed explanation is as follows.

We assume that there is a firm-level spread τ_{it} between the output and export prices, that is, $P_{it}^* = P_{it}(1+\tau_{it})$, where P_{it} is the actual output price and P_{it}^* is the export price recorded by China Customs. Hereafter, parameters with asterisks represent the estimated value, and those without asterisks represent the corresponding actual value.

We first discuss the marginal cost bias introduced by price spreads. Let q_{it}^* denote the log estimated quantity, which is calculated as the gross output value divided by the export price P_{it}^*. The relationship between q_{it}^* and the actual log quantity q_{it} can be expressed as $q_{it}^* = q_{it} - \log(1+\tau_{it})$. Taking the firm-level price spreads into consideration, we can rewrite the translog function in equation (6) as

$$\begin{aligned} q_{it}^* =& \beta_l l_{it} + \beta_m m_{it} + \beta_k k_{it} + \beta_{ll} l_{it}^2 + \beta_{mm} m_{it}^2 + \beta_{kk} k_{it}^2 \\ &+ \beta_{lm} l_{it} m_{it} + \beta_{lk} l_{it} k_{it} + \beta_{mk} m_{it} k_{it} - \log(1+\tau_{it}) + \omega_{it} + \varepsilon_{it}. \end{aligned} \tag{D1}$$

Price spreads in the form of $\log(1+\tau_{it})$ are introduced into the error term of the production function, leading to an endogeneity problem. As shown by De Loecker et al. (2016) and Brandt et al. (2017), if the state variables determining the firm's input decisions can also represent the unobserved firm-heterogeneous spreads, then consistent estimates are still available. In this case, the possible endogeneity of price spreads is already controlled for by the non-parametric control function for unobservable productivity shocks. Both material expenditure and revenue are directly reported by our data, ensuring that the material revenue share is undisturbed by the price spreads. Thus, the consistent estimate of material output elasticity offers a desirable markup estimate u_{it} (material output elasticity divided by material revenue share). Our estimated marginal cost MC_{it}^* equals the actual marginal cost MC_{it} multiplied by the price spread: $MC_{it}^* = P_{it}^*/u_{it} = P_{it}(1+\tau_{it})/u_{it} = MC_{it}(1+\tau_{it})$.

In the above setting, we demonstrate that the firm-level Lerner Index is not contaminated by price spreads. Calculating the Lerner Index needs prices, marginal costs, and output emission fees. Output emission fees EC_{it}^{O*} are calculated as the regional emission fees F_{it}^O multiplied by firm-level pollution intensity Φ_{it}^{O*} (pollutant emissions divided by quantity). The estimated quantity introduces bias into pollution intensity. Specifically, the estimated pollution intensity Φ_{it}^{O*} can be expressed as the actual pollution intensity Φ_{it}^O multiplied by $(1+\tau_{it})$. Thus, we can rewrite our estimated Lerner Index as

$$L_{it}^{*} = \frac{P_{it}^{*} - MC_{it}^{*} - \Phi_{it}^{O*} \times F_{it}^{O}}{P_{it}^{*}} = \frac{P_{it}(1+\tau_{it}) - MC_{it}(1+\tau_{it}) - \Phi_{it}^{O}(1+\tau_{it})F_{it}^{O}}{P_{it}(1+\tau_{it})} = L_{it}.$$

As we can see, the spreads in the numerator and denominator cancel each other out completely, leaving us with an estimated L_{it}^{*} equal to the actual Lerner Index L_{it}.

We then prove that if price transmission elasticity and demand elasticity are accurately estimated, we can still get reliable incidence estimates even in the presence of output-price bias. Take the incidence of output emission fees in equation (1) as an example. Let β^{O} denote accurately estimated price transmission elasticity of output emission fees and ρ_{it}^{O} denote the actual price transmission in levels. We can get the relationship: $\rho_{it}^{O} = \beta^{O}\left(P_{it}/EC_{it}^{O}\right)$. Our estimated price transmission in levels ρ_{it}^{O*} is calculated from β^{O} combined with P_{it}^{*} and EC_{it}^{O*}. There are biases in P_{it}^{*} and EC_{it}^{O*}, but they also cancel each other out:

$$\rho_{it}^{O*} = \beta^{O} \times \frac{P_{it}^{*}}{\Phi_{it}^{O*}F_{it}^{O}} = \beta^{O} \times \frac{P_{it}(1+\tau_{it})}{\Phi_{it}^{O}(1+\tau_{it})F_{it}^{O}} = \rho_{it}^{O}.$$

Let I_{it}^{O*} denote the estimated incidence of output emission fees for firm i at year t, which can be expressed as

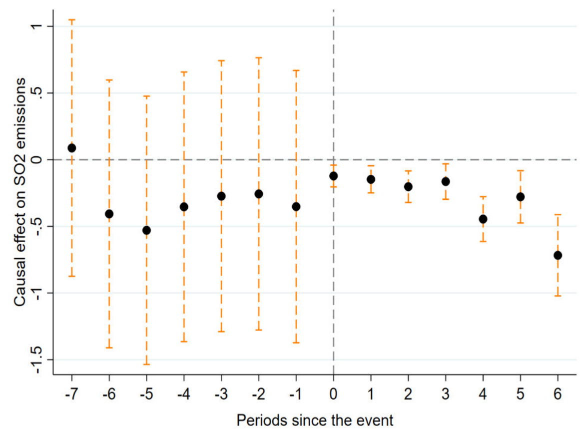
$$I_{it}^{O*} = \frac{\rho_{it}^{O*}}{1-(1-\varepsilon_D L_{it}^{*})\rho_{it}^{O*}} = \frac{\rho_{it}^{O}}{1-(1-\varepsilon_D L_{it})\rho_{it}^{O}} = I_{it}^{O}. \tag{D2}$$

Equation (D2) shows that incidence is uncontaminated by measurement errors in output prices. To obtain reliable industry-level incidence estimates, each step of the procedure needs to be carefully arranged. As we can see, Lerner Index L_{it} and price transmission ρ_{it}^{O} are not influenced by price spreads. However, prices, marginal costs, and output emission fees, which are used to construct the Lerner Index and price transmission, are biased. Thus, we first calculate the Lerner Index and price transmission for each firm-year observation, then average all firm-year values to obtain the industry-level parameters, and finally compute incidence. Our processing sequence differs from that of Ganapati et al. (2020), who first calculate industry-level averages of prices and marginal costs and then compute the incidence. For their industry-level Lerner Index and price transmission, aggregations of firm-level price spreads are not guaranteed to cancel each other out completely unless all firms in the data are strictly symmetric.

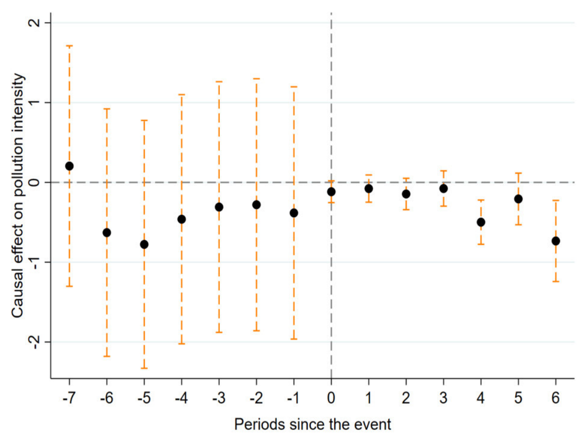
One possible concern is that the price spreads may lead to an endogeneity problem in price transmission estimation. However, there are two points that limit the severity of the problem. Take the price transmission estimates of output emission fees in equation (8) as an example. First, firm-specific deviations from output prices and output emission fees appear with opposite signs in the estimating equation and cancel out. Second, we include firm fixed effects in all regressions, which can control for all time-invariant endogeneity. Other stricter specifications introduce additional fixed effects and further limit the endogeneity issue.

E Appendix: Empirics

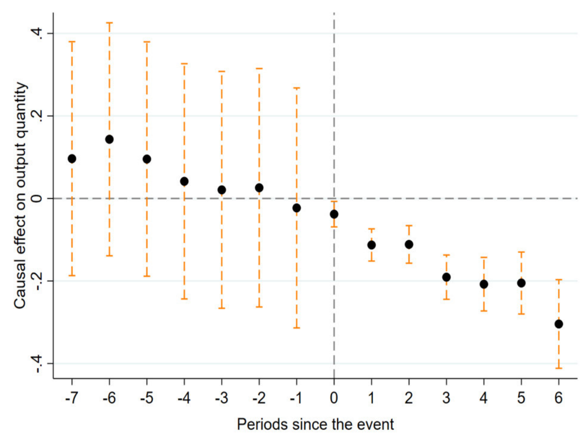
E1 Supplementary Results



(a) Log SO2 emissions



(b) Log pollution intensity



(c) Log quantity

Figure E1: Decomposition of Pollution Emission Reduction

Note: This figure presents the dynamic effects of doubling emission fees on firm-level SO2 emissions (Panel (a)), pollution intensity (Panel (b)), and manufacturing output (Panel (c)), estimated through the "imputation" method proposed by Borusyak et al. (2021). This method separates the testing of parallel trends assumption from the causal effect estimation and does not need to exclude $l = -1$. Firm and year fixed effects are included. 95% confidence bands are shown, using standard errors clustered by firm.

Table E1: Summary Statistics of Key Variables: Mean

	Output prices	Material revenue share	Input emission fees	Output emission fees	Emission cost share of revenue	Observations
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A. Statistics from data.						
Agriculture	39	0.79	0.05	210.72	0.62	17,506
Food	23	0.76	0.05	49.48	0.97	11,427
Chemicals	451	0.78	0.19	65.57	2.14	16,652
Chemical products	227	0.76	0.16	12.55	1.16	13,294
Plastic	70	0.76	0.13	11.91	1.00	23,567
Rubber	444	0.74	0.16	49.57	0.57	4,739
Skins and leather	191	0.75	0.07	379.22	1.42	10,140
Wood and furniture	320	0.82	0.15	155.57	18.85	29,730
Paper and books	35	0.75	0.14	3.44	0.42	8,436
Textile fibres	39	0.81	0.15	10.09	0.38	16,426
Textile fabrics	131	0.80	0.15	14.42	0.27	8,163
Clothing	92	0.75	0.09	11.49	0.78	57,370
Shoes and hats	101	0.75	0.07	32.43	0.72	13,786
Stone and glass	53	0.74	0.25	41.68	3.46	14,567
Iron and steel	58	0.82	0.10	284.26	71.48	23,231
Basic metal	153	0.78	0.08	46.09	4.00	16,512
Machinery	43,827	0.86	0.05	2,861.02	45.47	55,501
Electrical machinery	2,631	0.80	0.03	171.36	125.00	62,199
Vehicles	11,017	0.82	0.03	2,468.10	243.18	14,761
Instruments	4,438	0.77	0.05	80.59	60.10	12,728
Toys	53	0.74	0.14	5.75	1.32	9,483
Miscellaneous	26	0.77	0.09	2.90	4.94	4,879
Overall	6,416	0.79	0.09	518.68	38.66	445,097
	Output elasticity			Returns	Markup	Marginal
	Labor	Capital	Materials	to scale		cost
	(1)	(2)	(3)	(4)	(5)	(6)
Panel B. Statistics derived from production function estimates.						
Agriculture	0.17	0.05	1.02	1.24	1.38	29
Food	0.25	0.08	1.06	1.39	1.58	17
Chemicals	0.28	-0.10	1.16	1.34	1.65	289
Chemical products	0.31	-0.13	1.10	1.28	1.60	146
Plastic	0.19	-0.09	1.16	1.26	1.66	45
Rubber	0.09	-0.31	1.35	1.13	1.94	256
Skins and leather	0.41	-0.11	0.97	1.28	1.44	189
Wood and furniture	0.19	-0.10	0.98	1.07	1.46	288
Paper and books	0.27	-0.01	1.10	1.36	1.61	23
Textile fibres	0.30	-0.09	1.16	1.37	1.54	30
Textile fabrics	0.08	0.01	1.11	1.20	1.58	86
Clothing	0.04	-0.01	1.14	1.18	1.64	61
Shoes and hats	0.20	-0.05	1.00	1.15	1.41	79
Stone and glass	0.25	-0.09	1.07	1.24	1.66	39
Iron and steel	0.21	0.06	1.07	1.34	1.52	54
Basic metal	0.38	-0.14	1.09	1.32	1.60	124
Machinery	0.44	-0.17	1.01	1.28	1.78	51,804
Electrical machinery	0.66	-0.07	0.73	1.32	1.21	4,998
Vehicles	0.18	-0.05	0.79	0.92	1.22	20,529
Instruments	0.84	-0.27	0.79	1.36	1.56	7,597
Toys	0.39	-0.15	0.98	1.22	1.51	48
Miscellaneous	0.55	-0.12	0.89	1.32	1.27	22
Overall	0.32	-0.08	1.01	1.25	1.53	8,125

Notes: This table reports the averages of key variables by industry. Panel A reports statistics directly observed from our data. Panel B reports statistics derived from production function estimates. The material revenue share is calculated as material expenditure divided by total revenue. Input emission fees are the weighted average of AVE output emission fees, where the weights are input shares from the inter-province input-output table. Output emission fees are the emission costs per unit. The emission cost share of revenue is calculated as emission costs divided by total revenue. This table reports input emission fees, output emission fees, and emission cost share of revenue multiplied by 1000. Output elasticities come from a gross-output translog production function with labor, capital, and materials as inputs. Returns to scale are the sum of the three output elasticities. Markups are estimated as material output elasticities divided by material revenue shares. Marginal costs are recovered as output prices divided by estimated markups. Prices are adjusted to a common 2000 basic using the industry-specific price index.

Table E2: Summary Statistics of Key Variables: Median

	Output prices (1)	Material revenue share (2)	Input emission fees (3)	Output emission fees (4)	Emission cost share of revenue (5)	Observations (6)
Panel A. Statistics from data.						
Agriculture	15	0.77	0.05	0.79	0.04	17,506
Food	8	0.70	0.04	0.73	0.08	11,427
Chemicals	17	0.75	0.16	2.16	0.10	16,652
Chemical products	23	0.72	0.13	0.55	0.02	13,294
Plastic	14	0.74	0.12	0.41	0.02	23,567
Rubber	59	0.72	0.14	1.39	0.03	4,739
Skins and leather	35	0.72	0.05	0.39	0.02	10,140
Wood and furniture	26	0.76	0.10	0.68	0.02	29,730
Paper and books	11	0.74	0.14	0.76	0.06	8,436
Textile fibres	13	0.78	0.14	1.49	0.10	16,426
Textile fabrics	34	0.79	0.13	2.23	0.06	8,163
Clothing	32	0.75	0.05	3.82	0.11	57,370
Shoes and hats	28	0.74	0.05	0.80	0.02	13,786
Stone and glass	8	0.69	0.23	0.46	0.04	14,567
Iron and steel	12	0.72	0.05	0.28	0.02	23,231
Basic metal	23	0.72	0.04	0.22	0.01	16,512
Machinery	74	0.67	0.03	0.14	0.0005	55,501
Electrical machinery	19	0.70	0.01	0.01	0.0003	62,199
Vehicles	38	0.71	0.01	0.30	0.004	14,761
Instruments	30	0.63	0.02	0.00	0.00	12,728
Toys	9	0.71	0.14	0.02	0.003	9,483
Miscellaneous	4	0.73	0.07	0.12	0.02	4,879
Overall	21	0.73	0.05	0.41	0.01	445,097

	Output elasticity			Returns to scale	Markup	Marginal cost
	Labor (1)	Capital (2)	Materials (3)	(4)	(5)	(6)
Panel B. Statistics derived from production function estimates.						
Agriculture	0.17	0.05	1.02	1.24	1.33	11
Food	0.25	0.08	1.06	1.38	1.50	5
Chemicals	0.29	-0.11	1.15	1.33	1.54	12
Chemical products	0.31	-0.12	1.10	1.27	1.53	15
Plastic	0.19	-0.09	1.15	1.25	1.57	9
Rubber	0.10	-0.30	1.32	1.12	1.90	29
Skins and leather	0.41	-0.11	0.98	1.29	1.35	24
Wood and furniture	0.19	-0.11	0.98	1.07	1.30	21
Paper and books	0.27	-0.01	1.09	1.35	1.47	7
Textile fibres	0.30	-0.09	1.15	1.37	1.47	9
Textile fabrics	0.08	0.01	1.11	1.20	1.41	25
Clothing	0.04	-0.01	1.14	1.17	1.53	21
Shoes and hats	0.20	-0.05	0.99	1.15	1.35	20
Stone and glass	0.25	-0.09	1.07	1.24	1.56	5
Iron and steel	0.21	0.05	1.07	1.31	1.52	8
Basic metal	0.38	-0.14	1.07	1.31	1.53	15
Machinery	0.45	-0.16	1.00	1.28	1.45	50
Electrical machinery	0.66	-0.07	0.72	1.33	1.01	19
Vehicles	0.18	-0.05	0.79	0.94	1.06	34
Instruments	0.84	-0.28	0.79	1.36	1.23	27
Toys	0.39	-0.15	0.99	1.23	1.39	6
Miscellaneous	0.54	-0.12	0.89	1.32	1.25	3
Overall	0.27	-0.07	1.04	1.24	1.42	15

Notes: This table reports the medians of key variables by industry. Panel A reports statistics observed from our data. Panel B reports statistics derived from production function estimates. The material revenue share is calculated as material expenditure divided by total revenue. Input emission fees are the weighted average of AVE output emission fees, where the weights are input shares from the inter-province input-output table. Output emission fees are the emission costs per unit. The emission cost share of revenue is calculated as emission costs divided by total revenue. This table reports input emission fees, output emission fees, and emission cost share of revenue multiplied by 1000. Output elasticities come from a gross-output translog production function with labor, capital, and materials as inputs. Returns to scale are the sum of the three output elasticities. Markups are estimated as material output elasticities divided by material revenue shares. Marginal costs are recovered as output prices divided by estimated markups. Prices are adjusted to a common 2000 basic using the industry-specific price index.

Table E3: Translog Production Function Estimates by Industry

	l	k	m	l^2	$l \times k$	$l \times m$	k^2	$k \times m$	m^2
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Agriculture	0.63***	-0.34***	-0.34***	-0.03***	0.01***	-0.02***	-0.01***	0.05***	0.05***
	(1.29E-07)	(1.39E-07)	(1.03E-07)	(1.25E-07)	(1.26E-08)	(1.97E-08)	(5.47E-07)	(3.11E-09)	(3.53E-08)
Food	0.53***	-0.35***	0.06***	-0.03***	0.03***	-0.03***	0.02***	-0.02***	0.06***
	(1.60E-07)	(7.66E-07)	(1.19E-07)	(7.87E-07)	(1.71E-08)	(4.31E-08)	(6.94E-07)	(7.09E-08)	(3.46E-08)
Chemicals	0.75***	-0.90***	0.09***	0.06***	-0.03***	-0.07***	0.003***	0.08***	0.03***
	(2.11E-07)	(1.75E-07)	(9.90E-08)	(2.49E-07)	(1.50E-07)	(6.26E-08)	(1.88E-06)	(8.05E-07)	(3.75E-07)
Chemical products	-0.51***	-0.35***	0.70***	0.06***	0.04***	-0.02***	-0.01***	0.02***	0.01***
	(1.50E-07)	(2.50E-07)	(7.57E-08)	(3.47E-07)	(2.15E-07)	(5.95E-08)	(1.88E-06)	(4.42E-07)	(4.10E-07)
Plastic	0.20***	-0.07***	0.18***	-0.01***	-0.01***	0.02***	0.01***	-0.02***	0.05***
	(1.36E-07)	(1.91E-08)	(7.40E-08)	(3.75E-08)	(1.79E-07)	(2.77E-08)	(6.86E-07)	(4.24E-07)	(5.26E-07)
Rubber	0.60***	0.14***	0.10***	-0.01***	-0.03***	-0.01***	-0.01***	-0.001***	0.06***
	(6.31E-06)	(5.39E-05)	(3.16E-06)	(4.17E-05)	(1.89E-05)	(7.33E-06)	(5.29E-06)	(2.37E-06)	(1.80E-06)
Skins and leather	0.30***	0.27***	1.82***	0.04***	-0.09***	0.05***	0.01***	-0.002***	-0.06***
	(1.70E-07)	(8.14E-07)	(8.40E-08)	(6.28E-07)	(3.88E-08)	(5.33E-08)	(1.60E-06)	(3.90E-07)	(9.10E-08)
Wood and furniture	-0.09***	-0.53***	1.64***	0.07***	-0.01***	-0.04***	-0.02***	0.09***	-0.06***
	(1.05E-07)	(1.99E-07)	(4.75E-08)	(1.81E-07)	(5.72E-08)	(2.82E-08)	(9.21E-07)	(5.43E-07)	(1.25E-08)
Paper and books	0.36***	-0.40***	0.68***	-0.02***	0.04***	-0.02***	-0.02***	0.05***	0.004***
	(5.41E-07)	(9.58E-06)	(1.68E-06)	(1.56E-06)	(9.99E-07)	(4.36E-06)	(4.50E-06)	(4.71E-06)	(6.56E-07)
Textile fibres	-0.07***	-0.11***	1.27***	0.09***	0.004***	-0.06***	-0.02***	0.03***	-0.003***
	(1.24E-05)	(3.07E-07)	(1.28E-05)	(1.83E-07)	(4.73E-07)	(4.34E-07)	(7.62E-07)	(7.06E-07)	(1.40E-06)
Textile fabrics	0.16***	-0.62***	1.29***	-0.03***	0.01***	0.02***	-0.04***	0.13***	-0.07***
	(2.86E-07)	(3.64E-08)	(4.06E-07)	(1.33E-07)	(1.75E-07)	(1.07E-07)	(1.98E-06)	(4.78E-07)	(6.57E-07)
Clothing	0.12***	-0.22***	0.82***	-0.01***	-0.02***	0.02***	0.01***	0.02***	0.0001***
	(1.37E-07)	(4.55E-08)	(1.61E-08)	(1.69E-08)	(9.16E-08)	(1.87E-08)	(5.57E-07)	(6.39E-07)	(1.40E-07)
Shoes and hats	0.02***	0.19***	0.62***	-0.01***	0.02***	0.01***	-0.02***	-0.004***	0.02***
	(1.36E-07)	(7.99E-07)	(6.33E-08)	(6.26E-07)	(4.76E-08)	(3.77E-08)	(1.20E-06)	(6.09E-07)	(1.13E-07)
Stone and glass	0.21***	0.09***	0.30***	0.07***	0.02***	-0.08***	-0.01***	-0.001***	0.06***
	(2.01E-07)	(1.07E-07)	(1.28E-07)	(1.20E-07)	(8.62E-08)	(3.30E-08)	(1.03E-06)	(7.99E-07)	(1.66E-07)
Iron and steel	0.45***	-0.10***	-0.31***	0.04***	0.07***	-0.12***	0.04***	-0.08***	0.13***
	(1.48E-07)	(8.95E-09)	(7.10E-08)	(2.70E-08)	(2.32E-07)	(2.23E-08)	(8.82E-07)	(5.85E-07)	(4.29E-07)
Basic metal	0.88***	-0.21***	-0.21***	0.002***	0.05***	-0.09***	-0.03***	0.04***	0.07***
	(1.23E-07)	(2.89E-07)	(5.87E-08)	(2.67E-07)	(1.01E-07)	(3.35E-08)	(1.13E-06)	(8.16E-07)	(9.28E-08)
Machinery	-0.11***	0.69***	1.21***	-0.004***	-0.06***	0.12***	-0.04***	0.03***	-0.06***
	(1.68E-07)	(1.34E-08)	(8.70E-08)	(6.20E-08)	(1.84E-07)	(3.68E-08)	(1.26E-06)	(2.04E-07)	(2.62E-07)
Electrical machinery	1.11***	-0.51***	1.61***	0.03***	-0.07***	-0.02***	-0.01***	0.10***	-0.08***
	(3.86E-07)	(4.17E-07)	(1.73E-06)	(9.59E-08)	(2.02E-07)	(2.90E-07)	(1.56E-06)	(1.01E-06)	(2.91E-08)
Vehicles	0.94***	0.25***	1.52***	-0.06***	-0.08***	0.06***	-0.06***	0.11***	-0.10***
	(3.90E-07)	(3.27E-06)	(2.73E-06)	(2.14E-07)	(3.20E-07)	(2.71E-06)	(5.03E-06)	(4.39E-06)	(1.20E-06)
Instruments	0.49***	0.37***	1.21***	0.02***	-0.06***	0.06***	-0.06***	0.07***	-0.07***
	(4.46E-07)	(3.82E-08)	(2.41E-07)	(2.19E-07)	(1.29E-07)	(1.17E-07)	(2.65E-06)	(2.64E-07)	(2.89E-07)
Toys	0.48***	0.37***	1.52***	0.09***	-0.04***	-0.07***	-0.01***	-0.01***	-0.003***
	(2.53E-07)	(1.39E-07)	(1.38E-07)	(1.90E-07)	(9.81E-08)	(4.57E-08)	(1.25E-06)	(4.00E-07)	(2.96E-07)
Miscellaneous	-0.46***	0.26***	0.59***	0.17***	0.05***	-0.13***	-0.05***	0.01***	0.04***
	(4.55E-06)	(4.58E-07)	(3.19E-06)	(7.53E-07)	(1.96E-07)	(4.29E-07)	(5.61E-06)	(9.60E-07)	(6.05E-07)

Notes: This table reports the results of translog production function estimation for each industry. Standard errors are in parentheses. Significance: * 0.10, ** 0.05, and *** 0.01.

Table E4: Effects of Input and Output Emission Fees (in Arcsinh)

Output prices	(1)	(2)	(3)	(4)
Panel A. Joint effects of input and output emission fees on output prices.				
ec^I	0.020***	0.021***	0.050***	0.046***
	(0.006)	(0.006)	(0.008)	(0.008)
ec^O	0.636***	0.684***	0.684***	0.681***
	(0.034)	(0.036)	(0.036)	(0.035)
N	445,097	445,097	445,097	445,097
Adjusted R2	0.79	0.80	0.80	0.80
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes		
CIC industry-province fixed effects		Yes	Yes	Yes
Province-year fixed effects			Yes	
City-year fixed effects				Yes
Markups	(1)	(2)	(3)	(4)
Panel B. Joint effects of input and output emission fees on markups.				
ec^I	-0.001	-0.021***	-0.021***	-0.019***
	(0.002)	(0.002)	(0.002)	(0.002)
ec^O	-0.044***	-0.023***	-0.021***	-0.020***
	(0.005)	(0.005)	(0.005)	(0.005)
N	445,097	445,097	445,097	445,097
Adjusted R2	0.70	0.73	0.73	0.74
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes		
CIC industry-province fixed effects		Yes	Yes	Yes
Province-year fixed effects			Yes	
City-year fixed effects				Yes

Notes: This table reports the effects of input and output emission fees on output prices and markups. Panel A reports the price transmission estimates, which are the results of regressing log output prices on log input emission fees and arcsinh output emission fees. Panel B reports a similar set of regressions, using markups as the dependent variable. Standard errors in parentheses are clustered at the firm level.
Significance: * 0.10, ** 0.05, and *** 0.01.

Table E5: Effects of Emission Fees on Prices and Marginal Costs by Industry

Output prices	ec^O (1)	SE (2)	ec^I (3)	SE (4)
Panel A. Effects of input and output emission fees on output prices by industry.				
Agriculture	0.004**	0.002	0.133	0.096
Food	0.004**	0.002	0.036	0.115
Chemicals	0.006***	0.002	0.111	0.091
Chemical products	0.004**	0.002	0.064	0.048
Plastic	0.003*	0.001	0.002	0.048
Rubber	0.040***	0.007	0.299	0.188
Skins and leather	-0.002	0.002	-0.056	0.075
Wood and furniture	0.005***	0.002	-0.084**	0.035
Paper and books	-0.001	0.002	0.072	0.132
Textile fibres	0.002	0.002	0.221***	0.07
Textile fabrics	0.005*	0.003	0.097	0.067
Clothing	0.005***	0.002	-0.018	0.028
Shoes and hats	-0.002	0.002	0.041	0.047
Stone and glass	0.014***	0.002	0.124	0.077
Iron and steel	0.003*	0.002	-0.017	0.017
Basic metal	0.004**	0.002	0.073***	0.022
Machinery	0.007***	0.002	0.059	0.045
Electrical machinery	0.002	0.001	-0.013	0.03
Vehicles	0.014***	0.003	-0.014	0.068
Instruments	0.003	0.002	0.051	0.032
Toys	0.002	0.002	0.077	0.071
Miscellaneous	0.002	0.004	-0.166*	0.098

Marginal costs	ec^I (1)	SE (2)
Panel B. Effect of input emission fees on marginal costs by industry.		
Agriculture	0.091	0.099
Food	-0.197*	0.113
Chemicals	0.243**	0.105
Chemical products	0.091*	0.054
Plastic	0.071	0.048
Rubber	0.477***	0.184
Skins and leather	-0.022	0.082
Wood and furniture	-0.035	0.037
Paper and books	0.113	0.131
Textile fibres	0.291***	0.072
Textile fabrics	0.145*	0.078
Clothing	0.050*	0.028
Shoes and hats	0.063	0.051
Stone and glass	0.140	0.090
Iron and steel	0.014	0.020
Basic metal	0.130***	0.025
Machinery	0.102**	0.047
Electrical machinery	-0.002	0.033
Vehicles	0.038	0.080
Instruments	0.096***	0.036
Toys	0.041	0.087
Miscellaneous	-0.050	0.096

Notes: Panel A reports the results of regressing log output prices on log output and input emission fees for each industry when controlling for the firm, 4-digit CIC industry-province, and city-year fixed effects. Panel B reports similar results of regressing log marginal costs on log input emission fees. SE represents the standard errors clustered at the firm level.
Significance: * 0.10, ** 0.05, and *** 0.01.

Table E6: Demand Elasticity by Industry

	Demand elasticity (1)	SE (2)	Observations (3)
Agriculture	-1.088***	0.094	2,918
Food	-1.372***	0.122	2,659
Chemicals	-0.685***	0.056	3,299
Chemical products	-1.147***	0.136	2,581
Plastic	-1.275***	0.149	2,018
Rubber	-0.771***	0.051	1,277
Skins and leather	-0.661***	0.157	1,431
Wood and furniture	-0.401***	0.113	2,366
Paper and books	-1.438***	0.348	1,503
Textile fibres	-0.983***	0.104	2,504
Textile fabrics	-1.161***	0.171	1,381
Clothing	-0.256	0.165	2,890
Shoes and hats	-0.491**	0.242	1,391
Stone and glass	-0.413***	0.108	2,229
Iron and steel	0.142	0.344	2,644
Basic metal	-0.944***	0.168	2,384
Machinery	-0.217***	0.056	3,091
Electrical machinery	-0.219***	0.066	2,815
Vehicles	-0.218***	0.043	2,080
Instruments	-0.869***	0.089	1,722
Toys	-0.253	0.360	1,239
Miscellaneous	-0.872***	0.156	1,029

Notes: This table reports the estimated industry-specific demand elasticity. The dependent variable is the city-level log aggregate quantity. The independent variable is the city-level log market price, which is the revenue-weighted geometric average of firm-level output prices in the given city. The market price is instrumented by the regional emission fees imposed by local governments, the revenue-weighted average pollution intensity, and their interaction. The regressions also include city fixed effects and a time trend as controls.

Table E7: Effects of Input and Output Emission Fees in More Homogeneous Industries

Marginal costs	(1)	(2)	(3)	(4)
Panel A. Effects of input emission fees on marginal costs.				
ec^I	0.027***	0.067***	0.125***	0.124***
	(0.009)	(0.009)	(0.013)	(0.013)
N	227,719	227,719	227,719	227,719
Adjusted R2	0.83	0.83	0.84	0.84
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes		
CIC industry-province fixed effects		Yes	Yes	Yes
Province-year fixed effects			Yes	
City-year fixed effects				Yes
Output prices	(1)	(2)	(3)	(4)
Panel B. Joint effects of input and output emission fees on output prices.				
ec^I	0.021**	0.028***	0.075***	0.074***
	(0.008)	(0.009)	(0.012)	(0.012)
ec^O	0.006***	0.006***	0.007***	0.006***
	(0.001)	(0.001)	(0.001)	(0.001)
N	227,719	227,719	227,719	227,719
Adjusted R2	0.83	0.83	0.83	0.83
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes		
CIC industry-province fixed effects		Yes	Yes	Yes
Province-year fixed effects			Yes	
City-year fixed effects				Yes
Markups	(1)	(2)	(3)	(4)
Panel C. Joint effects of input and output emission fees on markups.				
ec^I	0.003	-0.028***	-0.039***	-0.039***
	(0.002)	(0.002)	(0.003)	(0.003)
ec^O	-0.0003	-0.00004	-0.0001	-0.0002
	(0.0002)	(0.0002)	(0.0002)	(0.0002)
N	227,719	227,719	227,719	227,719
Adjusted R2	0.69	0.73	0.73	0.74
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes		
CIC industry-province fixed effects		Yes	Yes	Yes
Province-year fixed effects			Yes	
City-year fixed effects				Yes
Output prices	(1)	(2)	(3)	(4)
Panel D. Marginal cost pass-through				
Marginal costs	1.109***	0.581***	0.684***	0.680***
	(0.104)	(0.060)	(0.035)	(0.035)
N	227,719	227,719	227,719	227,719
Adjusted R2	0.92	0.81	0.88	0.87
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes		
CIC industry-province fixed effects		Yes	Yes	Yes
Province-year fixed effects			Yes	
City-year fixed effects				Yes

Notes: This table reports baseline regression results in the subsample of 11 less differentiated industries. Panel A reports the results of regressing log marginal costs on log input emission fees. Panel B (C) reports the results of regressing log output prices (markups) on log input and output emission fees. Panel D reports the marginal cost pass-through estimates. Standard errors in parentheses are clustered at the firm level.

Significance: * 0.10, ** 0.05, and *** 0.01.

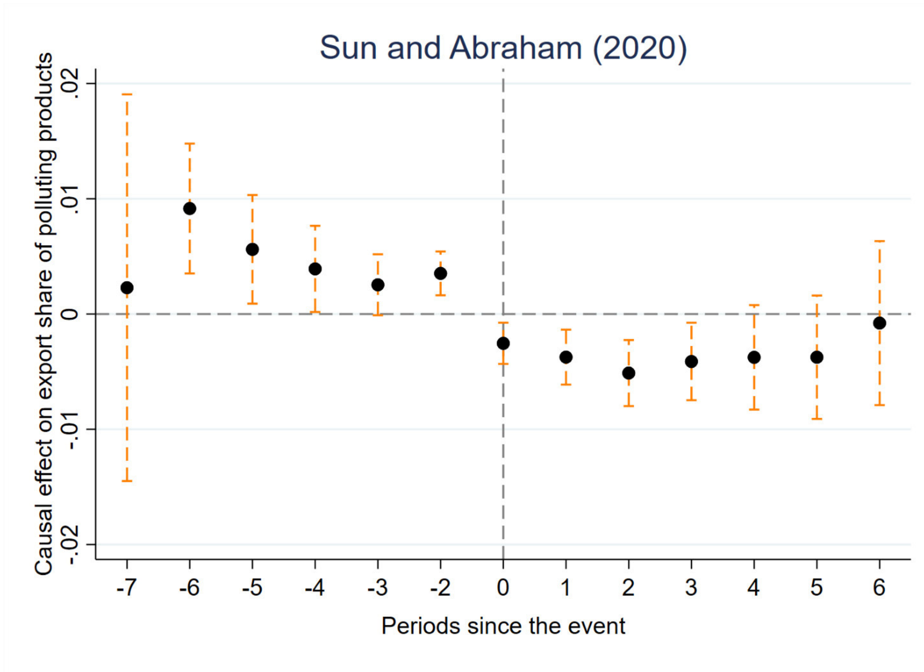


Figure E2: Dynamic Effects on Export Share of Pollution-Intensive Products
Note: This figure adopts the efficient DID estimator proposed by Sun and Abraham (2021). 95% confidence bands are shown, using standard errors clustered by firm.

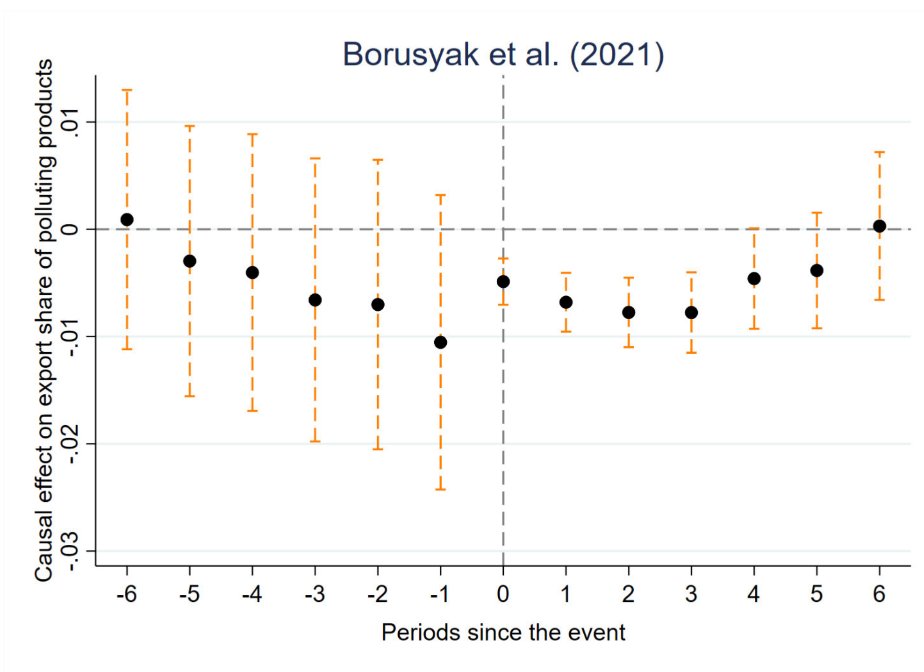


Figure E3: Dynamic Effects on Export Share of Pollution-Intensive Products
Note: This figure adopts the efficient DID estimator proposed by Borusyak et al. (2021). 95% confidence bands are shown, using standard errors clustered by firm.

E2 Further Details on the Settings

In this subsection, we provide more detailed explanations of the settings. First, the "consumer surplus" in this paper does not refer to the surplus of final consumers unless the downstream markets are perfectly competitive. Usually, manufacturing buyers are not consumers of final goods, nor does the market structure guarantee an identical incidence of intermediate and final goods. Second, our derived incidence formulas rely on the assumption of symmetric firms, which simplifies incidence estimates and avoids the difficulty in estimating firm-level demand elasticity. As firms in our data have different capacity levels, they are not symmetric. We leave incidence analyses with asymmetric firms for future work. Finally, we treat the emission fees directly paid by firms as an output tax and ignore firms' upgrade of green technology in the short term. An important question that remains open to future work is allowing investments in cleaner technology for long-term analysis.