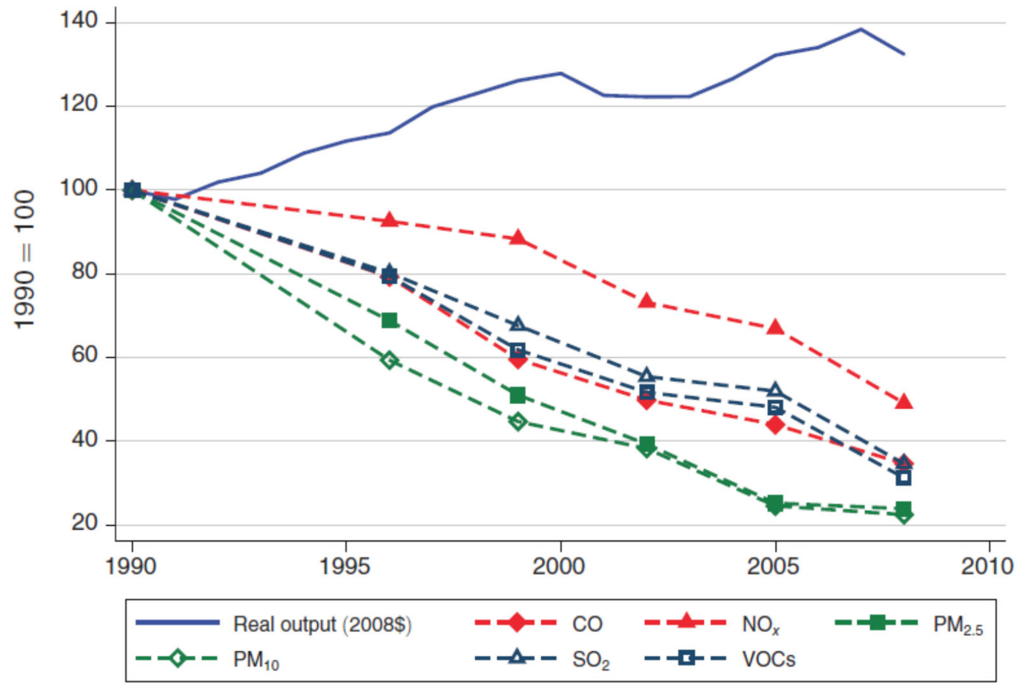

Figure 1. Trends in Manufacturing Pollution Emissions and Real Output

Notes: Real output is measured from the NBER-CES database, using its industry-specific output price deflators and expressed in US$(2008). Emissions come from the EPA's National Emissions Inventory in years 1990, 1996, 1999, 2002, 2005, and 2008. Values are normalized to 100 in 1990.

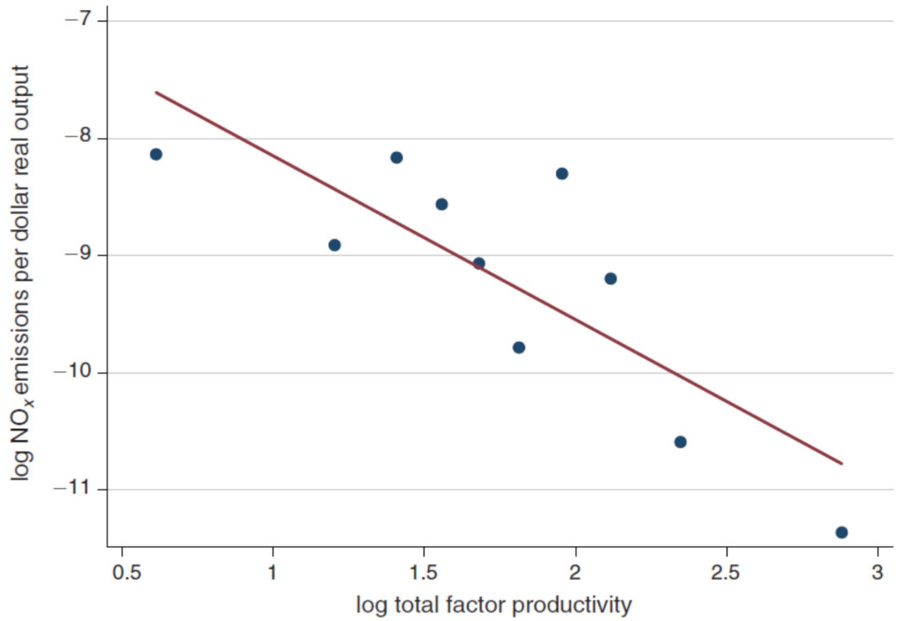

Figure 2. Plant-Level Pollution Intensity vs. Total Factor Productivity

Notes: This figure plots the relationship between plant-level total factor productivity and NO_x pollution per unit of output for US manufacturing in 1990. The plant-level productivity measure is constructed from the US Annual Survey of Manufacturers, using a total factor productivity index measure. We divide the sample into ten deciles based on this plant-level productivity measure. We then compute the mean values of log productivity and log pollution per unit of real output within each decile, weighting the decile mean by plant-level inventory-adjusted, real output. The plot is accompanied by a linear fit, relating plant-specific emissions intensities to total factor productivity at the same plant. The line is fit to the entire sample, not simply the decile means. See online Appendix III.H for additional details.

Consider the following representation of total manufacturing pollution, denoted Z:

$$Z = \sum_s z_s = \sum_s x_s e_s = X \sum_s \kappa_s e_s. \tag{1}$$

Total manufacturing pollution Z equals the sum of pollution from each manufacturing product s, z_s. A manufacturing product in our setting can be thought of as a sub-industry classification, where for example, SIC 3312 (blast furnaces and steel mills) is subdivided into 24 different products ranging from steel wire (33125) to cold rolled sheets and strip (excluding metallic coated and electrical) (33127).[5] Alternatively, we can write manufacturing pollution as equal to the total output of a product x_s multiplied by a product-specific emissions factor e_s. We can also represent manufacturing pollution emissions as the total output shipped by all manufacturing industries, X, multiplied by the sum of each product's share of total output, $\kappa_s \equiv x_s/X$, times an emissions coefficient reflecting pollution per dollar of output shipped of that product ($e_s \equiv z_s/x_s$). In vector notation, we have

$$Z = X\kappa'\mathbf{e},$$

where κ and $\mathbf{e}$ are $S \times 1$ vectors containing the market shares of each of the S products and their pollution intensities, respectively. Totally differentiating then dividing through by Z yields three terms representing the scale, composition, and technique effects:

$$\frac{dZ}{Z} = \underbrace{\frac{dX}{X}}_{\text{scale}} + \underbrace{\frac{d\kappa}{\kappa}}_{\text{composition}} + \underbrace{\frac{de}{e}}_{\text{technique}}. \tag{2}$$

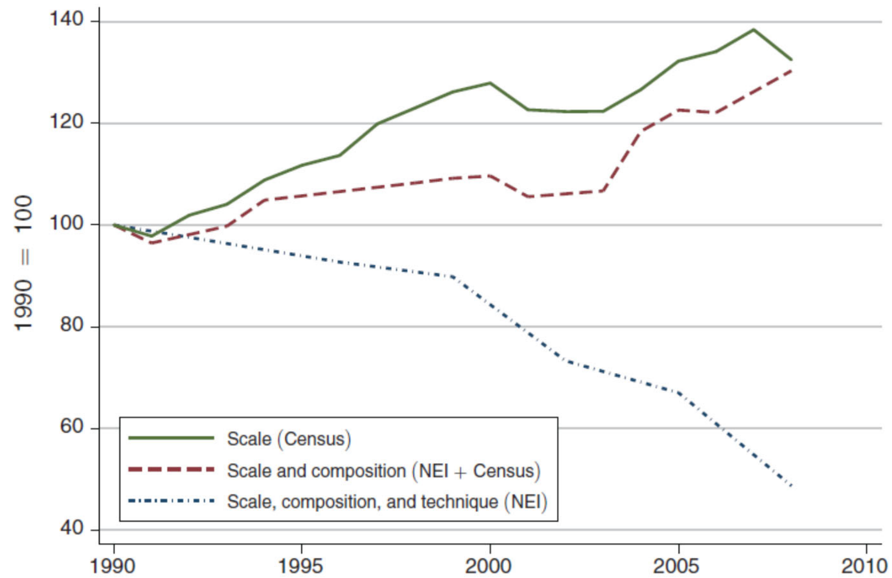

Figure 3. Nitrogen Oxides Emissions from United States Manufacturing

Notes: This figure plots observed and counterfactual trends in NO_x emissions based on the statistical decomposition from equation (2). The top line plots the counterfactual emissions with the same composition of goods and techniques as in 1990. The middle line represents emissions with the same emissions per unit of output as in 1990. The final line represents the actual observed emissions trends, which consists of changes to both the scale, composition, and techniques associated with production since 1990.

Sources: NBER-CES database, CMF, ASM, and NEI

Model: Shapiro and Walker

- Preferences Armington trade model

$$U_d = \prod_s \left(\left[\sum_o \int_{\omega \in \Omega_{o,s}} q_{od,s}(\omega)^{\frac{\sigma_S - 1}{\sigma_S}} \right]^{\frac{\sigma_S}{\sigma_S - 1}} \right)^{\beta_{d,s}}$$

- Production

$$q_{od,s} = \left(z_{od,s} \right)^{\alpha_s} \left(\phi l_{od,s} \right)^{1 - a_s}$$

  - $z_{od,s}$ emissions
  - $l_{od,s}$ labor input

- Another version

$$q_{od,s}(\phi) = (1 - a(\phi))\, \phi l_{od,s}(\phi)$$

where $a(\phi)$ is abatement

- Another version

$$z_{od,s}(\phi) = (1 - a(\phi))^{\frac{1}{\alpha_s}} \phi l_{od,s}(\phi)$$

- 3 ways to think about it, all the same
  - Is pollution a second output on which price is negative
  - An input to production which has a price
  - Optimizing standard production decisions subject to a constraint on pollution emmisions

Firms and Market Structure

- Pay sunk entry cost $f^e_{o,s}$ to draw a productivity ϕ from Pareto

$$G(\phi, b_{o.s}) = 1 - \left(\frac{\phi}{b_{o,s}}\right)^{-\theta}$$

- then have to pay a separate fixed cost $f_{od,s}$ per market

- Profit in a market is

$$\pi_{o,s}(\phi) = \sum_d \pi_{od,s}(\phi) - w_o f^e_{o,s}$$

where

$$\pi_{od,s}(\phi) = p_{od,s}(\phi) q_{od,s}(\phi) - w_o l_{od,s}(\phi) \tau_{od,s} - t_{o,s} z_{od,s}(\phi) \tau_{od,s} - w_d f_{od,s}$$

- $t_{o,s}$ pollution tax
- $\tau_{os,s}$ iceberg cost

- Usual competitive equilibrium

$$L_O = L_o^e + L_o^p + L_o^t + L_o^m + L_o^{nx}$$

first term recourse in fixed cost, second production, third abatement (thrown away) fourth market entry costs, fifth net trade.

- Pollution taxes, productivity, trade liberalization effects on pollution intensity

$$i_{o,s}(\phi) = \frac{\sum_j z_{o,j,s}(\phi)}{\sum_j q_{oj,s}}$$

- Results:

PROPOSITION 1: *Pollution intensity of a firm is locally decreasing in productivity. Pollution intensity of a sector is locally decreasing in pollution taxes, in productivity, and in trade liberalization.*

PROOF:

For a firm with productivity φ, pollution intensity and its derivative are

$$i_{o,s}(\varphi) = \frac{\alpha_s}{\varphi^{1-\alpha_s}} \frac{(t_{o,s})^{\alpha_s - 1}(w_o)^{1-\alpha_s}}{(\alpha_s)^{\alpha_s}(1-\alpha_s)^{1-\alpha_s}} \frac{\sum_j \tau_{oj,s}^{1-\sigma_s} A_{d,s}}{\sum_j \tau_{oj,s}^{-\sigma_s} A_{d,s}}, \quad \frac{\partial i_{o,s}(\varphi)}{\partial \varphi} = (\alpha_s - 1)\frac{i_{o,s}(\varphi)}{\varphi}.$$

Noting that $\alpha_s \in (0,1)$ and that $\varphi, i_{o,s}(\varphi) > 0$ implies the conclusion. Sector-level pollution intensity and its derivatives are

$$I_{o,s} = \frac{\alpha_s}{t_{o,s}} \frac{\sigma_s - 1}{\sigma_s} P_{o,s}, \quad \frac{\partial I_{o,s}}{\partial t_{o,s}} = \frac{I_{o,s}}{t_{o,s}}[\alpha_s \lambda_{oo,s} - 1],$$

$$\frac{\partial I_{o,s}}{\partial b_{o,s}} = -(1-\alpha_s)\frac{I_{o,s}}{b_{o,s}} \lambda_{oo,s}, \quad \frac{\partial I_{o,s}}{\partial \tau_{do,s}} = \frac{I_{o,s}}{\tau_{do,s}} \lambda_{do,s},$$

$$\frac{\partial I_{o,s}}{\partial f_{do,s}} = \frac{1-\alpha_s}{\theta_s}\left(\frac{\theta_s}{(\sigma_s - 1)(1-\alpha_s)} - 1\right)\frac{I_{o,s}}{f_{do,s}} \lambda_{do,s}.$$

Data
Annual Survey of Manufacturing
input costs, plus value of total sales

Pollution elasticity:
Pollution abatement expenditures (PACE survey)
Air pollution emission for EPA National Emissions Inventory

A. *Estimating Parameters*

We first describe estimation of pollution parameters, then trade and macro parameters. To estimate the pollution parameters, we divide $z_{od,s}(\varphi) = (1 - a(\varphi))^{1/\alpha_s}\varphi l_{od,s}(\varphi)$ from Assumption 3 by equation (6) from Assumption 2 to show that pollution intensity is a function of abatement investments:

$$\frac{z}{q} = (1 - a)^{(1-\alpha)/\alpha}. \tag{16}$$

Taking logs of equation (16), taking first differences Δ over time, and allowing for national trends η_t in emissions intensity and idiosyncratic disturbances $\epsilon_{i,t}$ to pollution intensity gives

$$\Delta \ln\left(\frac{z_{i,t}}{q_{i,t}}\right) = \frac{1-\alpha}{\alpha} \Delta \ln(1 - a_{i,t}) + \eta_t + \epsilon_{i,t}. \tag{17}$$

Next, we estimate the shape parameter of the Pareto distribution of firm productivities. We rely on the fact that if the distribution of firm productivities is Pareto with shape parameter θ_s, then the distribution of firm sales is Pareto with shape parameter $\theta_s/(\sigma_s - 1)$. The Pareto tail cumulative distribution function is $\Pr\{x > X_{i,s}\} = (b_{i,s}/X_{i,s})^{\theta_s/(\sigma_s-1)}$ for $X_{i,s} \geq b_{i,s}$. Taking logs gives

$$\ln(Pr\{x > X_{i,s}\}) = \gamma_{0,s} + \gamma_{1,s} \ln(X_{i,s}) + \epsilon_{i,s} \tag{39}$$

We estimate equation (39) separately for each sector s, and the coefficient $\gamma_{1,s}$ in each regression is generally close to negative one. The Pareto shape parameter is then given by $\theta_s = \gamma_{1,s}(1 - \sigma_s)$.

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We use a subset of the firm level data to estimate equation (39). Because selection into exporting can

Table 2—Parameter Estimates

Sector	Tons pollution per dollar costs (1)	Pollution elasticity (α) (2)	Input share (3)	Elasticity of substitution (σ) (4)	Pareto shape parameter (θ) (5)	Shape parameter standard error (6)
Food, beverages, tobacco	2.60	0.0040	0.74	3.79	3.89	(0.13)
Textiles, apparel, fur, leather	1.44	0.0022	0.79	4.87	4.80	(0.10)
Wood products	6.75	0.0103	0.83	5.94	6.20	(0.17)
Paper and publishing	14.61	0.0223	0.79	4.80	5.21	(0.10)
Coke, refined petroleum, fuels	13.88	0.0212	0.88	8.18	9.91	(1.67)
Chemicals	13.42	0.0205	0.70	3.28	3.50	(0.08)
Rubber and plastics	3.13	0.0048	0.78	4.59	4.62	(0.08)
Other non-metallic minerals	19.91	0.0303	0.73	3.66	4.05	(0.11)
Basic metals	36.57	0.0557	0.85	6.66	10.01	(0.50)
Fabricated metals	1.24	0.0019	0.79	4.77	4.80	(0.06)
Machinery and equipment	1.00	0.0015	0.76	4.25	4.19	(0.14)
Office, computing, electrical	1.52	0.0023	0.81	5.24	5.32	(0.15)
Radio, television, communication	0.32	0.0005	0.79	4.66	4.77	(0.23)
Medical, precision, and optical	0.94	0.0014	0.65	2.89	2.86	(0.06)
Motor vehicles, trailers	1.03	0.0016	0.82	5.62	5.60	(0.18)
Other transport equipment	1.26	0.0019	0.74	3.88	3.87	(0.13)
Furniture, other, recycling	3.06	0.0047	0.73	3.77	3.75	(0.03)
Mean across industries	7.22	0.011	0.77	4.76	5.14	(0.23)

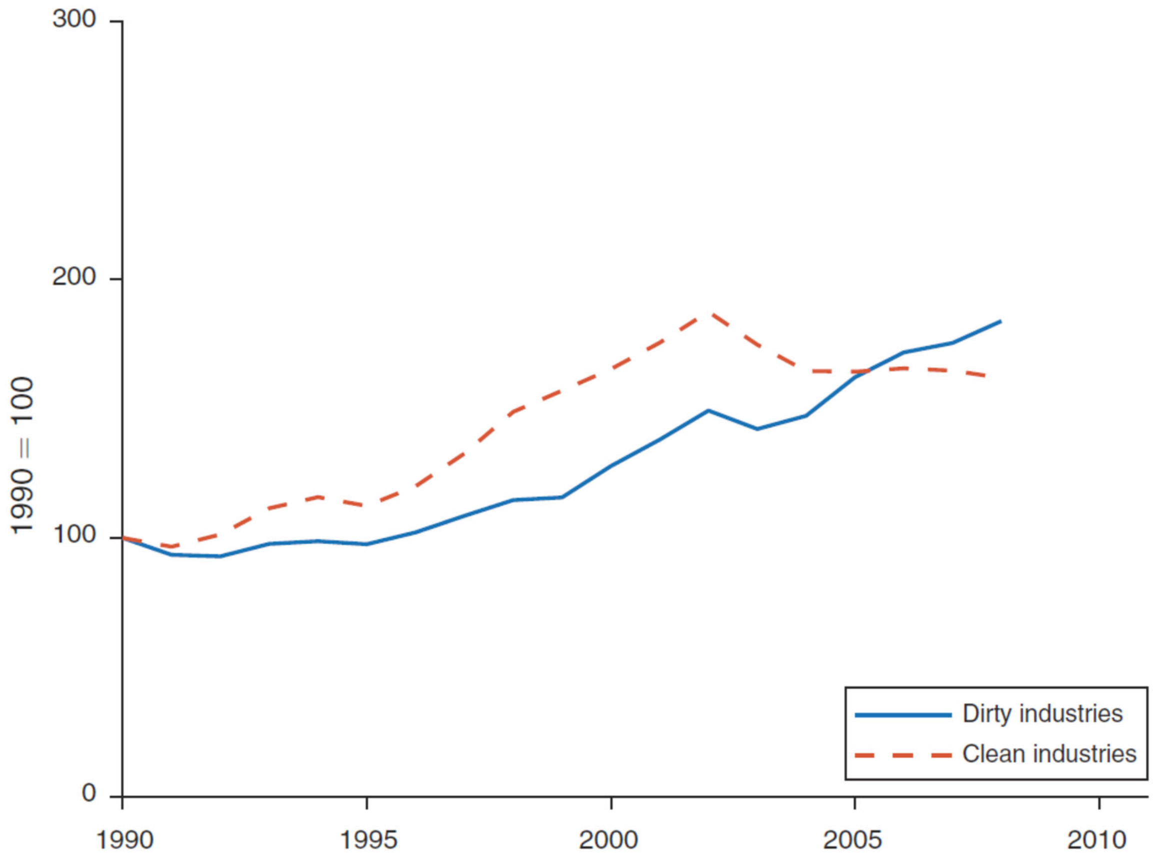

Figure 4. Shocks to Implicit NO_x Pollution Tax, 1990–2008

to the NBP.

We explore how our model-driven measure of pollution taxes corresponds with the NBP by using the following difference-in-difference-in-differences regression model:

$$(24) \qquad \ln(t_{rst}) = \beta_1(\mathbf{1}[NBP_r] \times \mathbf{1}[NBPIndustry_s] \times \mathbf{1}[Year > 2002]) + \eta_{rt} + \gamma_{st} + \psi_{rs} + \epsilon_{rst}.$$

We regress our measure of implied pollution taxes, t, as defined in equation (23), in sector s of NBP region r and year t, on a three-way interaction term describing the effect of being in an NBP-regulated sector in an NBP state in the years after the regulation went into place. We aggregate the data to the sector × region × year level, where a region is defined as inside/outside the NBP region, and sectors are defined by the 17 manufacturing sectors defined in Table 2.[35] We control for region × year fixed effects η_{rt}, sector × year fixed effects γ_{st}, and region × sector fixed effects ψ_{rs}. With these sets of fixed effects, the model effectively controls for time-invariant observed or unobserved determinants of pollution taxes by sector × region, common transitory shocks to sectors across regions, and transitory shocks within a region that affect all sectors similarly. The identifying assumption of the model is that there exist no transitory shocks specific to regulated sectors in the NBP region in the years after the NBP went into place. While this assumption is inherently untestable, the data permit some indirect tests. For example, data from years prior to the change in regulations permit the analysis of pretrends across treatment and control groups prior to the change in policy. The coefficient of interest, β_1, describes how the NBP affected pollution taxes in polluting sectors of regulated states.