The True Cost of Air Pollution:
Evidence from the Housing Market

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Resources for the Future

Camp Resources XXIII
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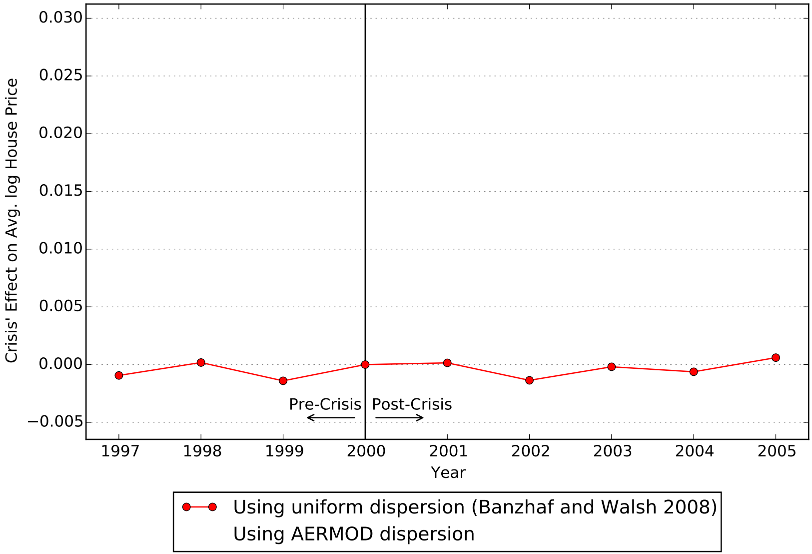
The Puzzle of Clean Air's Value

- Smith and Huang (1995): MWTP from house prices is low
  - \$233–\$260 (TSP), a fraction of mortality cost
- Quasi-experiments and IV's haven't helped.
  - Chay and Greenstone (2005): \$191 (TSP)
  - Bayer, Keohane, and Timmins (2009): \$130 (PM_{10})
- But prices are sensitive to other spatial amenities.
  - School funding (Cellini, Ferreira, and Rothstein 2010)
  - Crime risk (Linden and Rockoff 2008; Pope 2008)
  - Pediatric cancer risk (Davis 2004)
- And people definitely dislike air pollution.
  - Neidell (2009), Moretti and Neidell (2011), and Qin and Zhu (2015)

The problem is how we measure pollution exposure

- Most common (nearly universal) methods are poorly suited to air pollution
  1. Geographic diff-in-diff (often reduced form only)
  2. Monitor averages/interpolation
- Natural experiment does not help.

Effect of Electricity Crisis of 2000 on Prices



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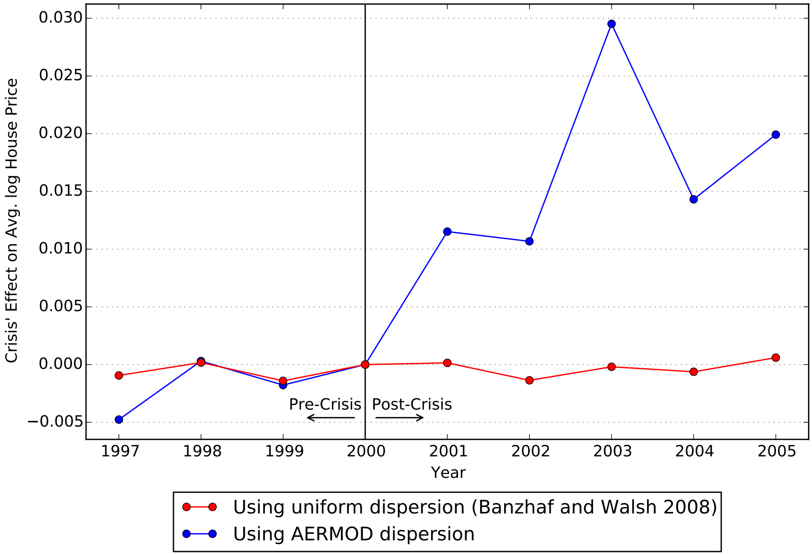


Outline

1. Measuring Pollution Effects
   1. The Problem: Bad exposure data
   2. The Solution: Atmospheric dispersion model
2. Theory and Natural Experiment
3. Estimation
   1. Basic price response and MWTP
   2. Comparison to standard methods
   3. Sorting, home-ownership, and incidence
4. Conclusion

Geographic diff-in-diff

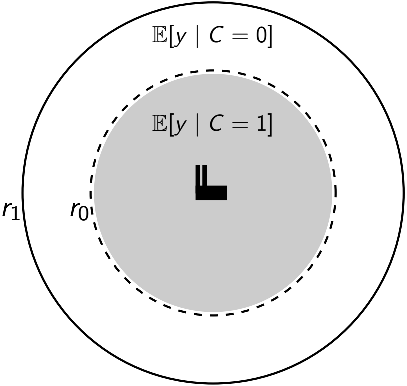
The Setup

$$y_{it} = \alpha N_{it} + \beta X_{it} + \varepsilon_{it}$$

- A firm affects y_{it} through
  - non-pollution (N) effects
  - pollution (X) effects
- Geographic diff-in-diff assumes:
  - "Close" to the firm is exposed to pollution (within r_0).
  - Slightly farther is not exposed (between r_0 and r_1) but is otherwise comparable.
- Use standard diff-in-diff to estimate

$$y_{it} = (\mathrm{Close}_i \times \mathrm{Post}_t) \cdot \gamma_{\mathrm{GD}} + \mathrm{Close}_i \cdot \gamma_1 + \mathrm{Post}_t \cdot \gamma_2 + e_{it}$$

Pollution Exposure and Geographic diff-in-diff



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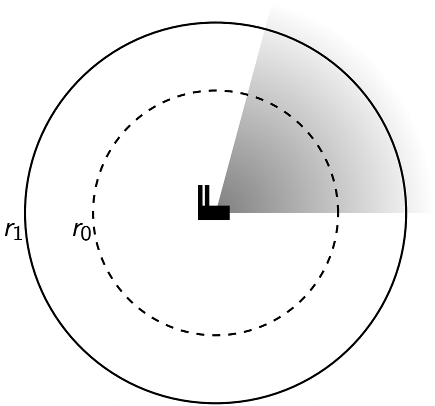
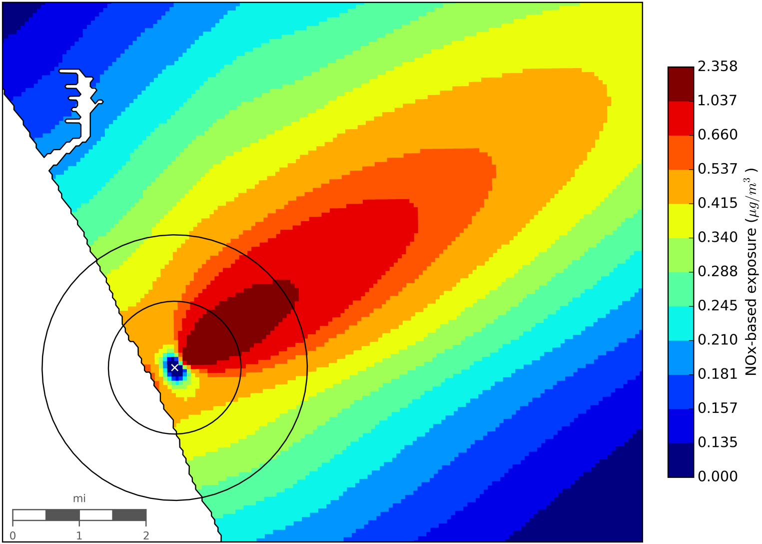
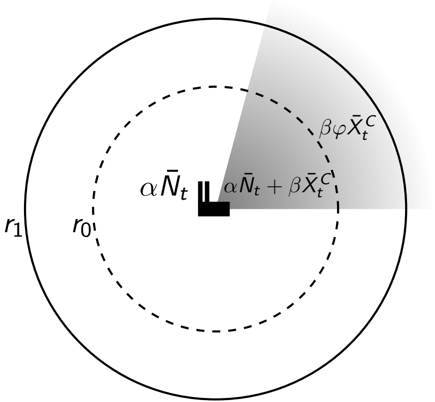


Exposure around a firm (AERMOD dispersion model)

Scatterwood Generation Plant, Los Angeles, 1999



Contaminated Treatment and Control



- $\alpha\bar{N}_t$ is average non-pollution effect at time t.
- $\beta\bar{X}_t^C$ is effect of pollution exposure on treatment group.
- $\beta\varphi\bar{X}_t^C$ is effect of pollution exposure on control group.

Bias in Geographic diff-in-diff

- Estimated pollution effect is

$$\hat{\gamma}_{\mathrm{GD}} = \underbrace{\alpha\left(\bar{N}_1^C - \bar{N}_0^C\right)}_{\text{Non-pollution Effect}} + \underbrace{(1-\varphi)}_{\text{Wind Bias}} \cdot \underbrace{\beta\left(\bar{X}_1^C - \bar{X}_0^C\right)}_{\text{Pollution Effect}}$$

- As wind speed increases, φ increases.
- If N_t is constant, then $\hat{\gamma}_{\mathrm{GD}} \to 0$ as $\varphi \to 1$.
- If N_t is not constant, $\hat{\gamma}_{\mathrm{GD}}$ primarily recovers *non*-pollution effects.

- Can usually re-scale with 2SLS—why not use poll. monitors?

How correlated are monitors and nearby locations?

It depends on where firms are.

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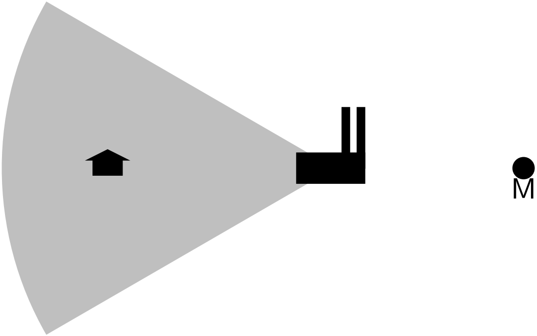

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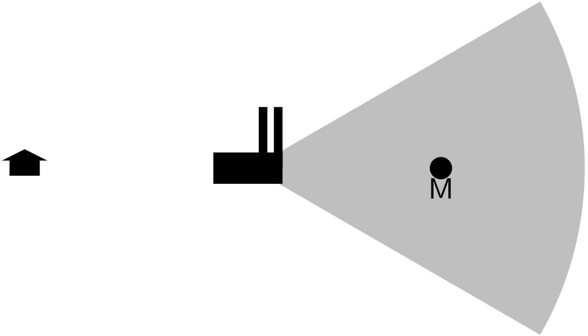
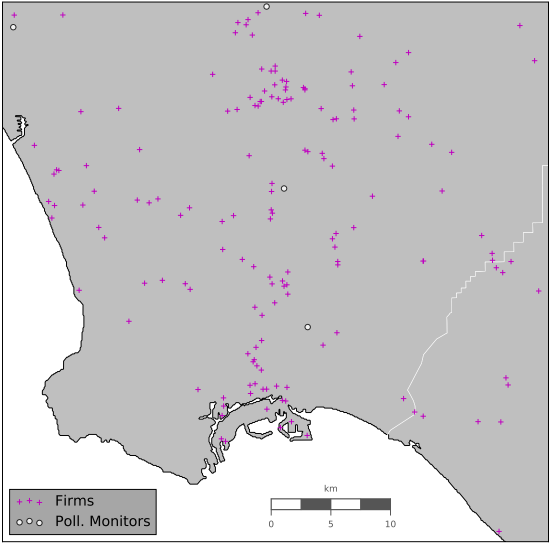
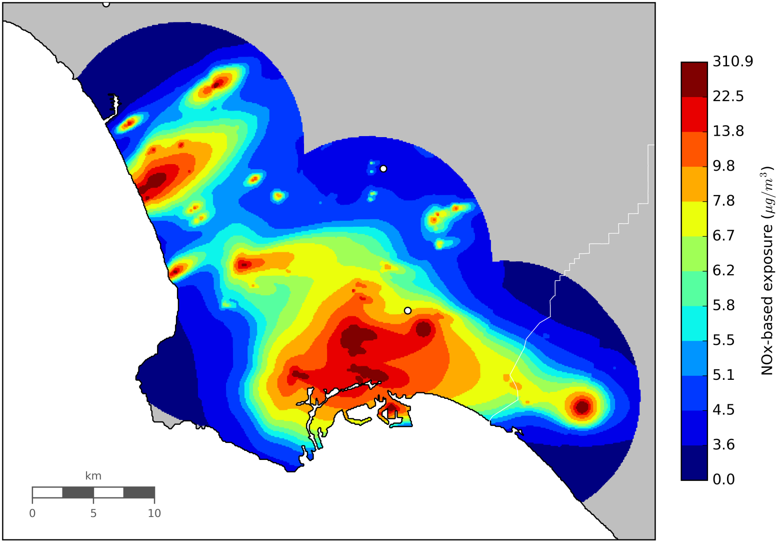


Actual firm and monitor locations



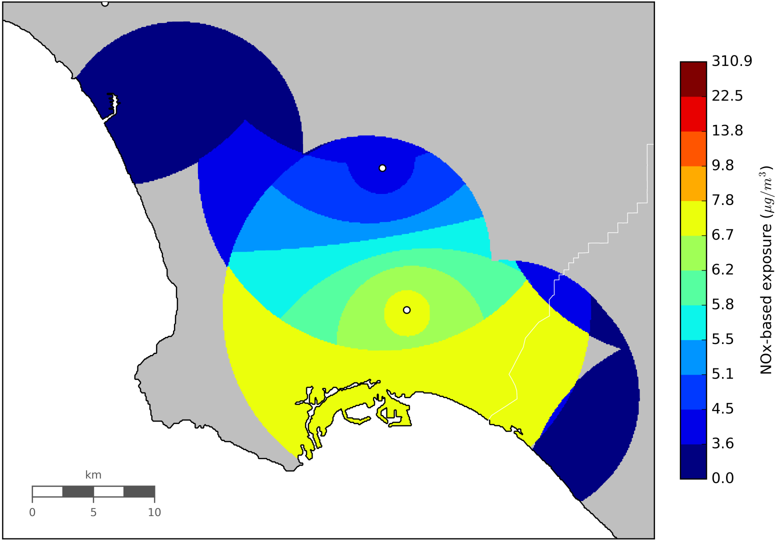
Monitor Locations and AERMOD Exposure

All Firms, 1999



Exposure Interpolated from Monitor Locations

Inverse Distance Weighting, 15 km.



Monitors do not provide enough information

- Systematic over-smoothing leads to non-classical meas. error.
  - Found by Knittel, Miller, and Sanders (2014), but not attributed to smoothing across space.
- When IV's are correlated with meas. error, bias persists in second stage.
  - E.g., IV is "near firm", but smoothing creates spikes in meas. error near firm, so they're correlated.
- Other issues:
  - Monitor's changing relationship to exposure distribution over time.
  - Cross-validation correlation tests usually don't account for seasonal variation common to all monitors.

Outline

Using Atmospheric Chemistry to Solve the Puzzle

- Must account for local spikes around firms and wind dispersion.
- AERMOD (dispersion model) uses
  1. Meteorology (e.g., temperature, wind speed)
  2. Firm emissions and equipment (e.g., stack height)

  and yields aermod_{ift}, exposure to location i due to firm f at time t.
- AERMOD is EPA's legally preferred short-range model.
  - Assessed with tracer chemical (SF_6) and monitor field.

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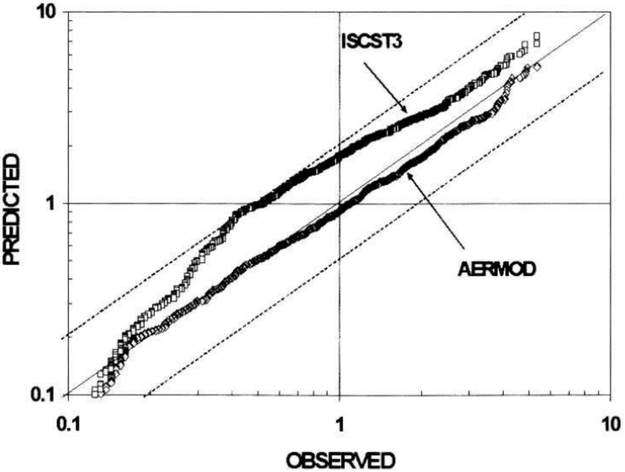
AERMOD Validation with Tracer and Monitors



Source: Perry et al. (2005)

AERMOD Validation with Monitors

Los Angeles, 1997–2005

Figure: Monitor A

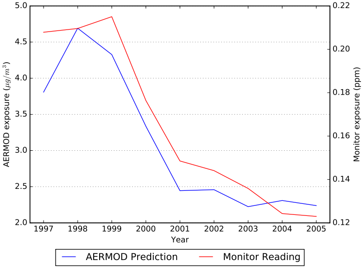
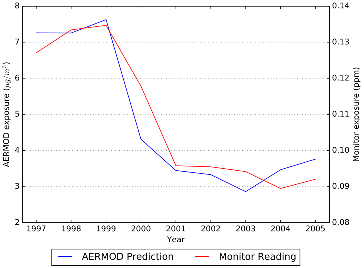


Figure: Monitor B



Note: Monitor readings are average during 4th quarter when atmospheric chemistry is minimal.

Outline

Estimating demand for air pollution

- When choosing a house, agents solve

$$\max_{c,\boldsymbol{g}} u(c, \boldsymbol{g}; \boldsymbol{\alpha}) \quad \text{s.t.} \quad y = c + P(\boldsymbol{g})$$

  numeraire c, amenities $\boldsymbol{g}$, and preferences $\boldsymbol{\alpha}$.
- At optimum, $\text{MWTP}_{g_k} = P_{g_k}$ for $g_k \in \boldsymbol{g}$ (Rosen 1974).
- Allows us to get MWTP by estimating marginal price.
  - Requires a few assumptions, e.g., constant P over time (Kuminoff and Pope 2014).

- Location choice is endogenous, need an instrument.

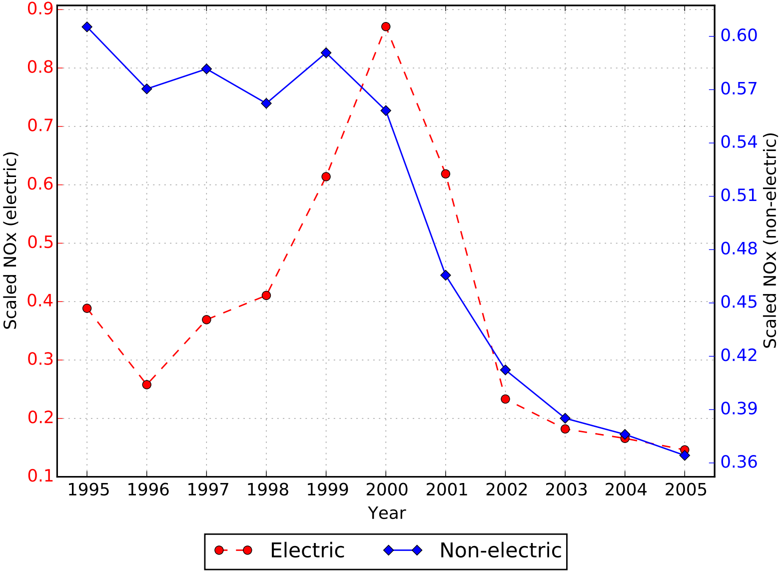
Natural Experiment

Electricity Crisis and Cap-and-Trade

- In 1994, SCAQMD (Southern CA) instituted RECLAIM, a cap-and-trade for NO_x.
    - Cap was very loose, firms did not adapt.
    - No banking of permits.
- Mid-2000, electricity demand exceeded normal supply.
    1. Increase in (inefficient) production caused shortage in permits.
    2. Permit prices skyrocketed. Prices
    3. Firms installed abatement tech.

Drop in firm emissions following the Crisis

Normalized Firm Emissions, Annual



Natural Experiment

Using the Crisis as IV

- Temporary Crisis coordinated permanent abatement.
- Use avg. exposure in 1995–1996 as a measure of Crisis' treatment intensity:

$$\mathrm{aermod\_pre}_i = \frac{1}{8} \cdot \sum_{t=1995Q1}^{1996Q4} \mathrm{aermod}_{it}$$

- Two sets of instruments:
  1. $\mathrm{aermod\_pre}_i \times \delta_y$ for $y \in \{1998, \ldots, 2005\}$
  2. $\mathrm{aermod\_pre}_i \times \mathrm{post}_t$ for $\mathrm{post}_t = \mathbf{1}\{y \geq 2001\}$

Outline

Data

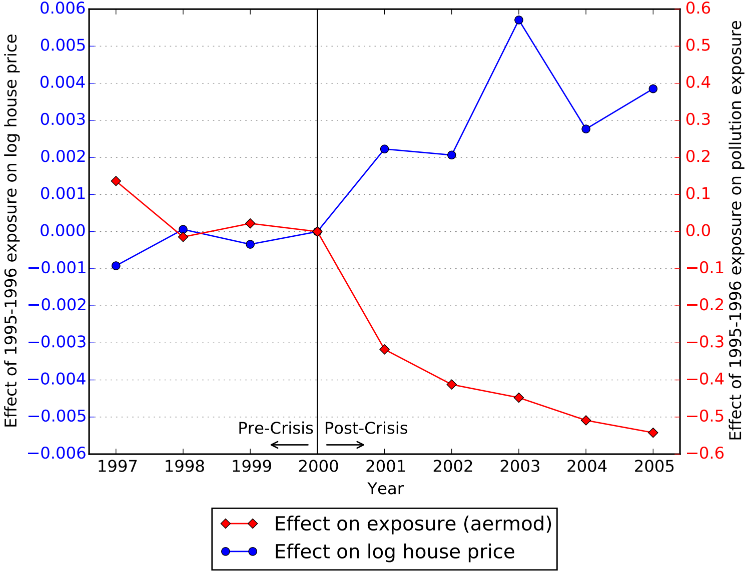
1. House sales and characteristics, 1995–2005 (DataQuick)
2. Firm NO_x emissions, quarterly, 1995–2005 (SCAQMD)
3. Firm equipment data, 1999 & 2002 (NEI)
4. Weather data from 27 stations, hourly, 2009 (SCAQMD)
5. Block group data from 2000 Census and 2005–2009 ACS

Main Estimation Equation

$$\ln p_{it} = \mathrm{aermod}_{it} \cdot \beta + \alpha_i + \delta_t + \left(t \times \boldsymbol{W}_{i,2000}\right) \boldsymbol{\gamma}_1 + \left(t^2 \times \boldsymbol{W}_{i,2000}\right) \boldsymbol{\gamma}_2 + \varepsilon_{it}$$

- α_i and δ_t are property and time (year-quarter) effects.
- $\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2$ are local quadratic time trends by
  - Local geography (10-km grid aligned with local boundaries)
  - Loan-to-value of transacted houses in 2000 (tract)
  - Loan interest rate in 2000 (tract)
  - Median household income in 2000 (block group)
- First stage similar, with RHV $\left(\mathrm{aermod\_pre}_i \times \delta_y\right) \cdot \pi_y$

Event Study around Crisis



Diff-in-diff effect on House Prices

	(1)	(2)	(3)	(4)	(5)	(6)
	ln Price	ln Price	Aermod	ln Price	ln Price	ln Price
Aermod				-0.0073***	-0.0073***	-0.0073***
				[0.0024]	[0.0023]	[0.0024]
Aermod_pre×post	0.0033***	0.0032***	-0.4328***			
	[0.0005]	[0.0008]	[0.0748]			
Aermod_pre	-0.0029**					
	[0.0012]					
Fixed Effects	BG	House	House	House	House	House
Method	OLS	OLS	OLS	2SLS	2SLS	LIML
IV set				Post	Annual	Annual
κ				1	1	1.0003
1st Stage F-stat				6388	932	932
R^2	0.865	0.948	0.911			
N	118,522	41,771	41,771	41,771	41,771	41,771

Notes: Sample average of aermod_pre is 5.172. "Post" IV is aermod_pre × post, "Annual" IV is aermod_pre interacted with year dummies. First-stage F stat assumes homoskedasticity. In addition to fixed effects, controls include year-quarter effects and quadratic time trends by local geography and year 2000 SES variables. Observations absorbed by fixed effects are dropped. Standard errors, clustered at 100-m grid, in brackets: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Summary of Results and Welfare

- Large price response, implies
  - MWTP of \$3,300 per unit of exposure
  - Crisis added \$7,300 to average house, \$3 billion total
- Cost/benefit of RECLAIM (1995 levels to proposed 2005 cap):
  - Annualized benefit to residents $\approx$ \$502 million
  - Annualized cost of abatement $\approx$ \$38 million
- Estimates robust to
  1. Set of instruments and IV method used
  2. Spatially correlated error terms (Conley 1999) Results
  3. Rental price vs. purchase price

Effect on Block Group Rents

	(1)	(2)	(3)	(4)	(5)	(6)
Aermod_pre×post	0.0025	0.0031*	0.0031**			
	[0.0015]	[0.0018]	[0.0015]			
Aermod				-0.0099	-0.0124	-0.0126**
				[0.0062]	[0.0076]	[0.0063]
Method	OLS	OLS	OLS	2SLS	2SLS	2SLS
Weighted by		Pop.	Renters		Pop.	Renters
R^2	0.9160	0.9331	0.9536			

Notes: N=3,162. Excluded instrument in 2SLS regressions is $\text{aermod} \times \text{post}$. Rents with error codes ($0) or top codes ($2,001) are dropped. Sample average of aermod_pre is 6.455.

Outline

What estimates do we get using standard methods?

To confirm new results are due to new methods, re-estimate using

1. Geo diff-in-diff
   - 1- and 2-mile treatment radii
   - cf. Currie and Walker (2011), Currie et al. (2015), Hanna and Oliva (2015), Schlenker and Walker (2016)
2. Uniform kernel
   - 2-km bandwidth (Banzhaf and Walsh 2008)
3. Triangle kernel
   - 5-km bandwidth

Comparing Methods

Model/Paper	Crisis' Effect on Avg. Price	MWTP
	Standard models	
Geo DD (1 mile)	\$1,438	
Geo DD (2 miles)	−\$589	
Triangle kernel	−\$217	−\$246
Uniform kernel	\$95	\$138
	Prior Research	
SH 1995 (3rd q-tile)[1]		\$233**
SH 1995 (mean)[2]		\$260**
CG 2005[3]		\$191**
BKT 2009[4]		\$130***
BKT 2009 (w/ moving)[5]		\$350**
	Wind-based model	
Aermod	\$7,324***	\$3,272***

Notes: Each row is taken from a different research design. Significance levels taken from original sources: ** $p < .05$, *** $p < .01$

[1] Smith and Huang (1995), 3rd quartile of meta-anlaysis sample

[2] Smith and Huang (1995), mean of meta-anlaysis sample

[3] Chay and Greenstone (2005), Table 5A, col 4

[4] Bayer, Keohane, and Timmins (2009), Table 6, col 2

[5] Bayer, Keohane, and Timmins (2009), Table 6, col 4; structural

Outline

Sorting, Home-ownership, and Incidence

Basic theory and estimation

- Location choice induces spatial equilibrium. Should see
  - population flow into areas after improvements.
  - stratification by income and amenities.
  - Tiebout (1956); Epple and Sieg (1999); Banzhaf and Walsh (2008)
- But single-crossing predicts that low-income incumbents may leave in response to amenity improvement.
- Estimation same as before, but with Census data at block group level.
  - Calculate aermod for constituent blocks, use pop-weighted average for block group.
  - Two years of data: 2000 Census and 2005–2009 ACS
  - Control for year 2000 values of all outcome variables (pop, income, etc.).

Changes in Neighborhood Demographics

Tiebout Sorting

	ln Income	% No HS	ln Pop.	ln H-holds	ln H. Units
Aermod_pre×post	0.0036	-0.0020***	-0.0027**	-0.0024*	-0.0031**
	[0.0026]	[0.0006]	[0.0014]	[0.0014]	[0.0015]
R^2	0.93	0.96	0.95	0.97	0.98

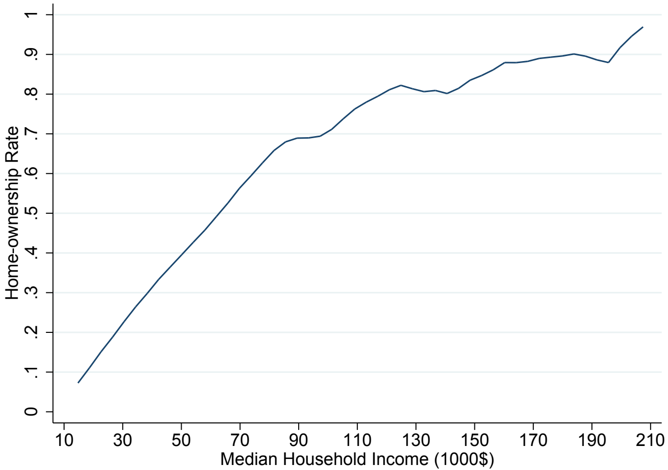
Notes: N=3,868. Sample periods are 2000 and 2005–2009 using data from the 2000 Census and 2005–2009 ACS, respectively. Educational attainment variables are restricted to the sample of people who are at least 25 years old. Block groups with fewer than 400 people in 2000 are dropped. Sample average of $\mathrm{aermod\_pre}$ is 6.560. Standard errors, clustered by tract, in brackets: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Population Change by Education

	(1)	(2)	(3)	(4)	(5)	(6)
	log Less than HS		log High School		log More than HS	
Aermod_pre×post	-0.021***		0.005**		-0.002	
	[0.005]		[0.002]		[0.004]	
Aermod_pre×post×						
% Less than HS in 2000		-0.0158		0.0196**		-0.0252
		[0.0250]		[0.0084]		[0.0222]
% High School in 2000		-0.0243		-0.0149		0.0747***
		[0.0284]		[0.0103]		[0.0221]
% More than HS in 2000		-0.0204		0.0234*		-0.1025***
		[0.0343]		[0.0128]		[0.0266]
R^2	0.936	0.936	0.938	0.938	0.937	0.938
N	3,592	3,592	3,868	3,868	3,718	3,718

Notes: Sample average of aermod_pre is 6.224. Outcome is the log of the number of people with the given educational attainment who are at least 25 years old. Block groups with an undefined logarithm in either year are dropped. Regressions weighted by block group population in 2000. Standard errors, clustered by tract, in brackets: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

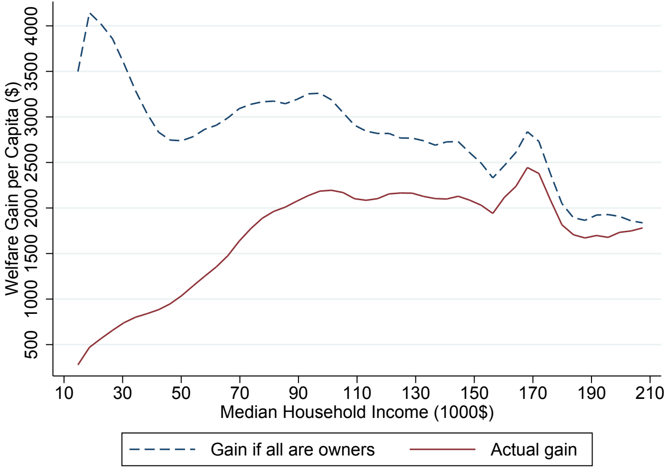
Home-ownership Rate by Income



Notes: Plot is the result of a local linear regression using an Epanechnikov kernel with bandwith of 5. Sample is Census 2000 block groups, weighted by population.

Price Windfall

By income and home-ownership



Summary of Incidence

- 13% (60,000 people) of low-ed adults left sample area after clean-up.
- Very low rate of home-ownership among low-income.
    - Emigration more likely due to welfare loss than wealth shock.
- Raises concerns about equity/efficiency trade-off.
    - But hard to make strong conclusions without household-level panel data.

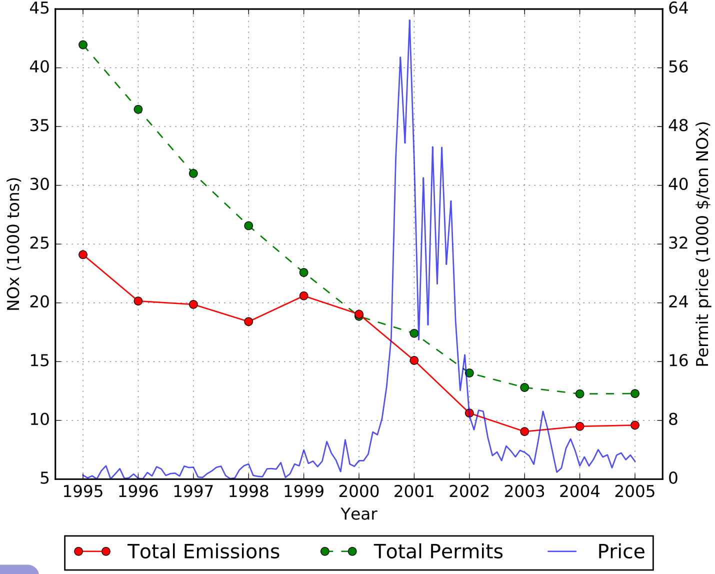
Conclusion

- Large welfare gains from reducing air pollution.
- These gains only detectable when accounting for wind, etc.
  - More firm-level monitoring
  - More monitors, mobile monitors
- However, low-income households may not benefit much.
  - Equity vs. Efficiency

APPENDIX

Natural Experiment

RECLAIM Market



Return

Robustness to Spatially Correlated Errors

	Std. Err.	p-value
Baseline (clustered)	0.0024	0.0022
SHAC by Bandwidth (m)		
200	0.0025	0.0036
400	0.0028	0.0086
600	0.0031	0.0178
800	0.0033	0.0279
1000	0.0035	0.0362
1200	0.0036	0.0414
1400	0.0037	0.0452
1600	0.0037	0.0480

Notes: N=41,771. Each row re-estimates the standard error of aermod in the main 2SLS regression using the non-parametric Spatial HAC (SHAC) method of Conley (1999) and Kelejian and Prucha (2007). Kernel used is a triangle with the listed bandwidth.

◂ Return