Equilibrium Particulate Exposure

Lorenzo Aldeco, Lint Barrage and Matthew A. Turner

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Definitions/Units

Particulates are fine particles of solids or water in the air column. We can measure them three ways,

- Mass. This is useful for describing,
  - Sources; flows in, hydrocarbon combustion, dust, fires, chemistry(ignored).
  - Sinks; flows out, deposition.

  Economic activity/regulation affects the mass of particulates in the air at a point.
- Concentration, Units $\sim$ Mass/Volume, e.g., PM10 $\sim \mu g/m^3$. This is what we often measure as air quality.
- Exposure $=$ people $\times$ concentration. This is what we really care about.

Mass $=$ concentration $\times$ volume, so we can go back and forth between units... but we need to think about the diffusion process.

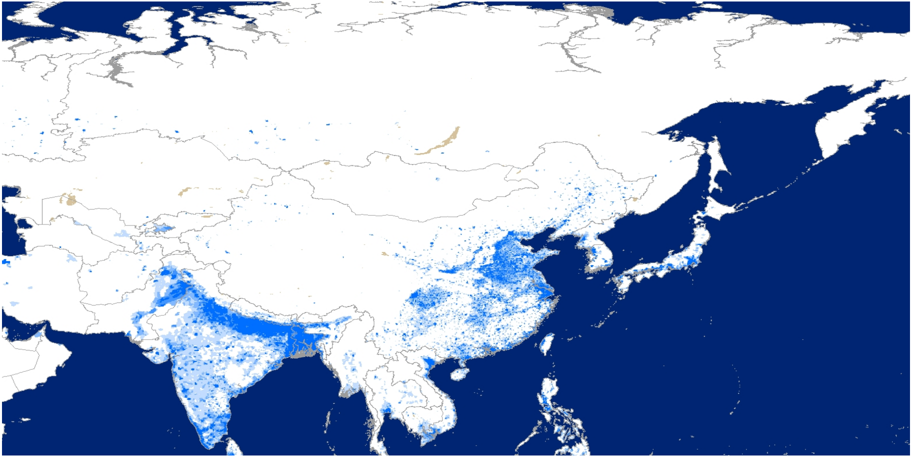
Equilibrium exposure to airborne particulates

- Document levels and changes in particulate concentration and exposure.
- Describe correlations between economic activity, particulate concentration and exposure.
- Develop country level equilibrium model (**SEPIA**) of particulate concentration and exposure, and its implications.

Main contributions: data, facts, model, policy.

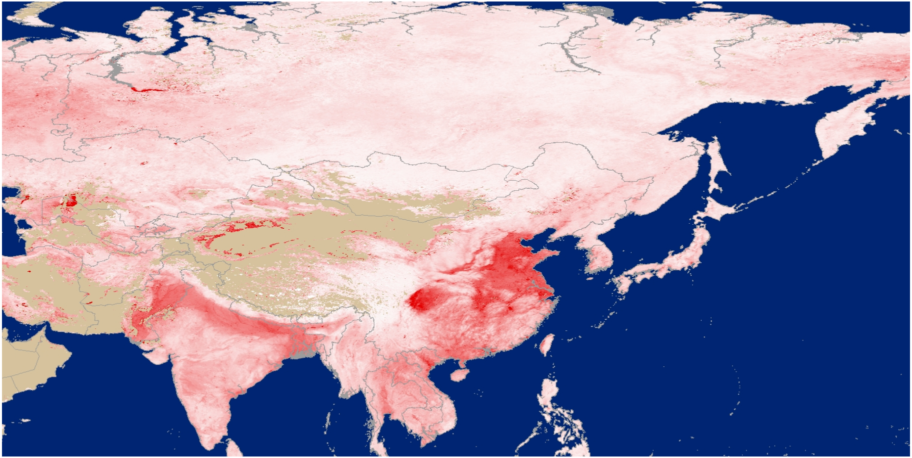
This is important: particulates are poisonous and jointly produced with energy.

Exposure 1: Population in China, Russia and India, 2010.



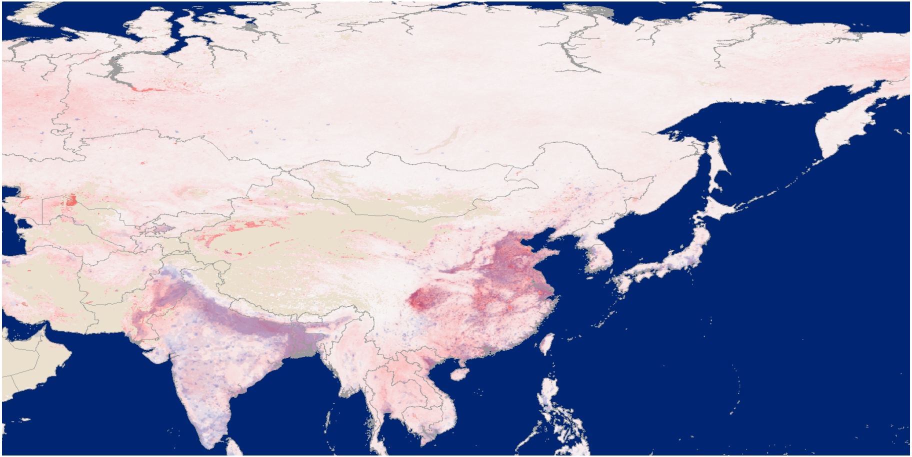
Note: Blue is population.

Exposure 2: Concentration/AOD in China, Russia and India, 2010.



Note: Red is AOD.

Exposure 3: Exposure in China, Russia and India, 2010.



Note: Red is AOD, Blue is population. Purple is exposure. In India, people are more dispersed than pollution. In China, pollution is more dispersed than people. Pollution and population are separate in Russia. What is the effect of an urban coal tax in China?

AOD and Exposure

Levels and changes, selected countries

	AOD 2000	Exposure 2000	%Δ AOD 2000-10	%Δ Exposure 2000-10	$\frac{\%\Delta AOD}{\%\Delta Exposure}$
Indonesia	0.20	0.27	-15.71	-1.83	8.58
Brazil	0.13	0.12	65.55	28.18	2.33
US	0.14	0.20	-20.48	-11.89	1.72
India	0.28	0.36	30.58	29.03	1.05
Russia	0.12	0.17	52.21	72.66	0.72
China	0.31	0.53	13.58	22.96	0.59
Poland	0.20	0.22	-4.46	-8.39	0.53

- Some countries experience high levels of AOD, but relatively lower levels of exposure.
- Some countries experience rapid increases of AOD, but but small increases (or decreases) in exposure.

$\Longrightarrow$ The equilibrium process that selects the locations of people and pollution sources looks important. How important is general equilibrium? For example, how likely is it that taxes on agricultural burning increase exposure?

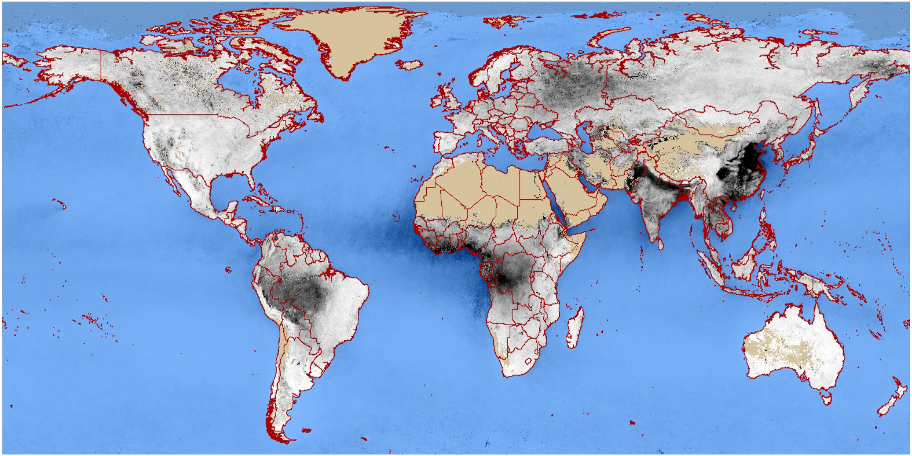
Is the importance of location to exposure surprising? I

The Clean Air Act;

- Reduces TSP in attainment areas by about $30\mu g/m^3$ from a base of $90\mu g/m^3$ (Chay and Greenstone [2005])
- Increases house prices in attainment areas, TSP elasticity of house price $\in [-0.20, -0.35]$ (Chay and Greenstone [2005])
- 600k reduction in non-attainment area employment from 1972-1987 (out of 75-100m national employment) (Greenstone [2002])
- Workers in dirty industries in non-attainment areas displaced to attainment areas/clean industries (Walker [2013])
- Firms in dirty industries migrate to attainment areas, firms in dirty industries shrink (Becker and Henderson [2000]).

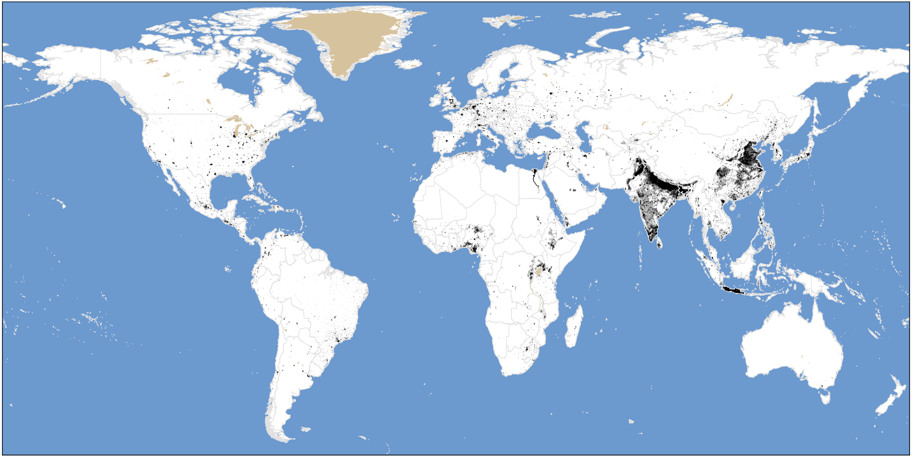
People adjust to regulation of pollution in complicated but intuitive ways.

Aerosol Optical Depth 2010



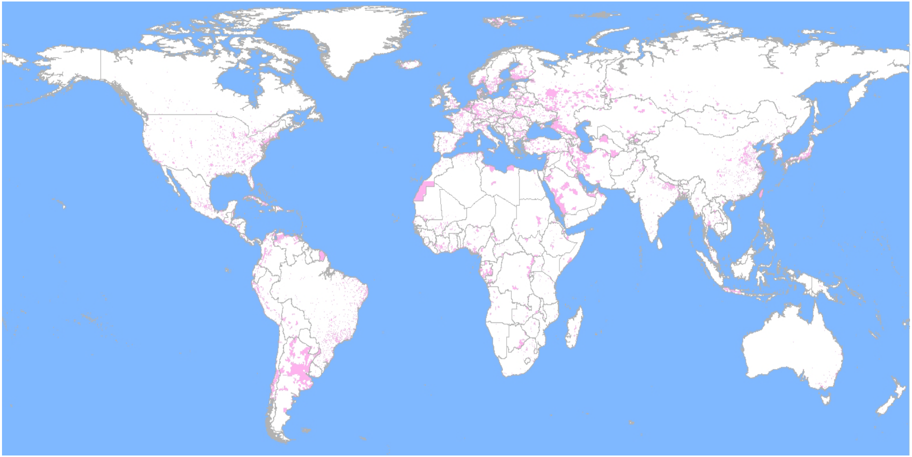
Note: Darker indicates larger AOD value.

Gridded population of the world, 2010.



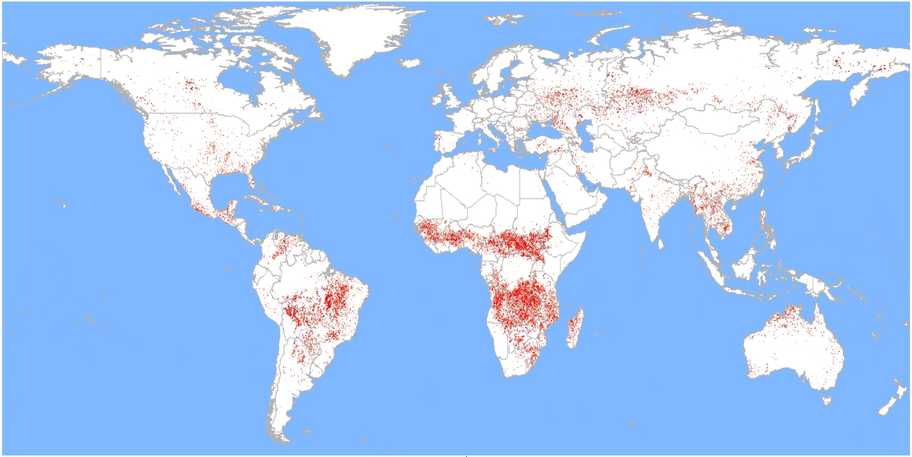
Note: Darker indicates more people per cell.

Urban Areas from GPW and World Bank urban share



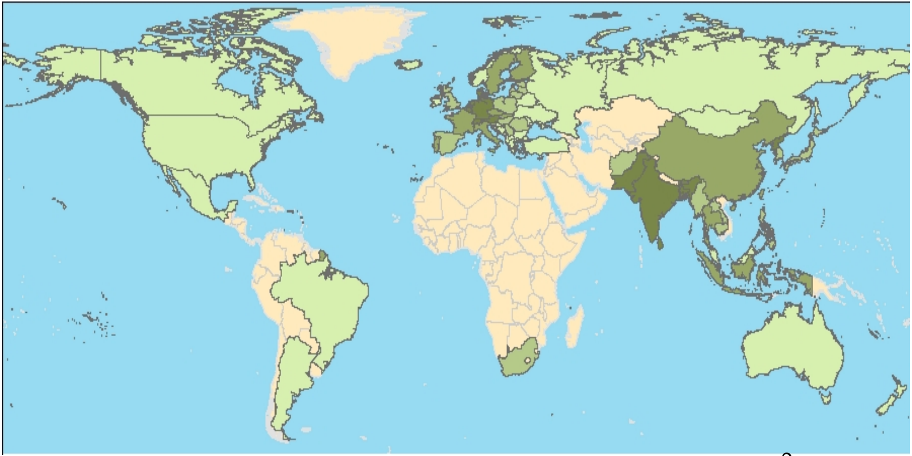
Note: ‘urban regions’ for each country. Model geography is rural, urban, rest-of-world, by country.

MODIS Fires, 2010.



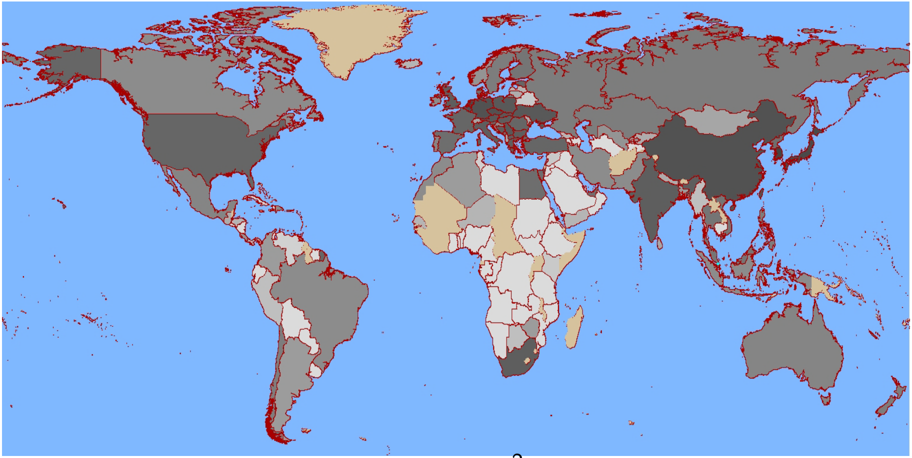
Note: Darker indicates more days/year of fire.

Biomass combustion per km^2 2010 (IIASA)



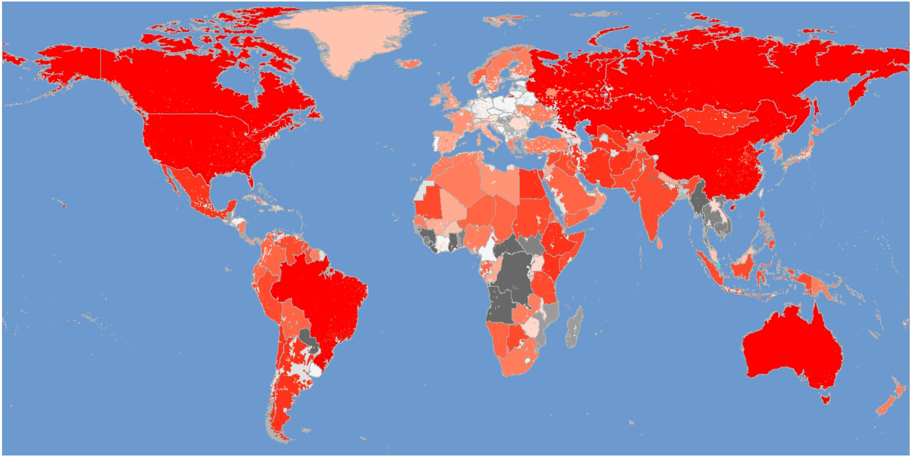
Note: Darker = more biomass fuel and crop burning per km^2 in 2010.

Coal per km^2 2010 (IEA)



Note: Darker = more coal use per km^2 in 2010.

AOD flows per km^2 by country-region, 2010.



Note: Red is flow out of region divided by source country-region area.

Pixel level regressions, AOD 2000-15. 10% sample.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Country FE	Y	.	.	.	Y	.	.
Year FE	.	Y	.	.	.	Y	.
Country × Year FE	.	.	Y	.	.	.	Y
Climate	.	.	.	Y	Y	Y	Y
233 countries							
N	604809	604809	604809	604012	604012	604012	604012
Area wgt R^2	0.388	0.009	0.428	0.178	0.475	0.186	0.512
Pop. wgt R^2	0.485	0.009	0.523	0.131	0.562	0.137	0.595
63 countries							
N	422377	422377	422377	421860	421860	421860	421860
Area wgt R^2	0.298	0.011	0.342	0.115	0.407	0.125	0.447
Pop. wgt R^2	0.467	0.013	0.506	.121	0.553	0.129	0.585

- We explain a lot of variation with country indicators, country-year adds a little.
- We explain more variation in exposure than AOD.
- Climate (cloud cover, rain days, vapor pressure, temperature, and frost days) is important because Satellites have trouble distinguishing water vapor from dust.

Table: Population weighted AOD on sources regressions. Modulo 5 years. Model sample countries. Dependent: Terra AOD

	(1)	(2)	(3)	(4)	(5)	(6)
Density	0.00000709***					0.00000771***
	(0.00000139)					(0.00000141)
Urban		0.0925***				0.0772***
		(0.00352)				(0.00356)
Crops			0.000248***			0.000374***
			(0.0000158)			(0.0000100)
Barren				0.00127***		0.00176***
				(0.000215)		(0.000214)
Fire					0.000469	0.000426
					(0.000243)	(0.000256)
N	421741	421860	421860	421860	421860	421741
R^2	0.596	0.613	0.601	0.588	0.585	0.648

Standard errors in parentheses

Controls for country-year fixed effects and climate.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Baseline population weighted regression with county-year and climate controls has $R^2 = .585$.
Pixel level variables have only a little explanatory power.

Role of country year level variation. **Population weighted** regression of Terra AOD, 2000, 2005, 2010, 2015. Model sample of 63 countries, 10% sample. Climate controls.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Green/km^3	-127***										166***
	(7.3)										(23)
Coal/km^3		296***									300***
		(10)									(14)
Oil/km^3			-42***								-111***
			(2.9)								(9.4)
Ag burn/km^3				3042***							586***
				(106)							(113)
Biomass/km^3					50***						.15
					(1.1)						(1.7)
Urb. share						-.005***					-.002***
						(8.2e-05)					(1.9e-04)
Srv GDP/km^3							-.008***				-.02***
							(3.7e-04)				(.002)
Ind GDP/km^3								.01***			38***
								(.0011)			(.0062)
Ag GDP/km^3									.52***		.24***
									(.008)		(.01)
Flow-/km^3										-178***	-3.9
										(6.7)	(10)
Flow+/km^3										160***	4.3
										(5.9)	(9.9)
R^2	0.01	0.11	0.01	0.19	0.14	0.19	0.02	0.00	0.26	0.04	0.40

Notes: Col (1-5) $N = 422377$, Col (6-13) $N = 422345$.Standard errors in parentheses. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

11 country level variables have R^2 of 0.40, versus 0.50 for country × year indicators.

Summary of reduced form results

- Country-year and climate variation explains about 50% of variation in 10 km^2 pixels. This seems remarkable.
- Most variation is at country level. Year effects add little explanatory power.

$\Longrightarrow$ the static, country level problem is economically important.

- Pixel level observables have little explanatory power. This variation is not driven by economics (that we can observe).

$\Longrightarrow$ Coarse model geography seems defensible (and matches energy data).

- Geography is important and a few country-year level variables explain most country-year exposure variation. Order of importance; Ag GDP $>$ Urban Share$>$ Ag Burning $>$ Coal $>$Flows.

$\Longrightarrow$ We know the variables to focus on in our model, and we want to allow people/firms to move.

Causal inference in this context looks really hard. This is macro. We want an 'integrated assessment model'.

SEPIA model goals

Spatial Equilibrium Particulate Integrated Assessment model

- Is importance of, e.g., coal consistent with other basic facts about how economies operate? Are estimated correlations plausibly causal?
- Is it easy to generate complicated general equilibrium responses to particulates regulation? Alternatively, when will partial equilibrium policy analysis be seriously wrong?
- Rank particulates policies and think about the value of better information about structural parameters.

We want to aggregate what we know to make an educated guess. Where relevant, we discipline the model by calibrating it to match certain observed country outcomes for 2010.

SEPIA model, basic structure

Goal: Reflect stylized facts and data limitations, but allow enough margins for adjustment to policy that perverse responses are not ruled out; migration, firm mobility, sector mobility, fuel mix, factor intensity.

- Each country j is a small, open, static economy. Two regions per country:Urban, u, rural/agricultural, a, plus rest of world (ROW)
- Four sectors of production:
  - Industry (I_u, I_a): Urban and agricultural, tradeable
  - Services (S): Urban, non-tradeable
  - Agriculture (M): Rural, tradeable
  - Energy (J): (Rural,Urban) $\times$ sector, non-tradeable
- Equilibrium mobility of labor (agricultural utility premium), industry, AOD
- Fossil energy inputs (coal, oil, gas) imported
- ROW AOD and prices for capital, tradeables, fossil fuels: exogenous

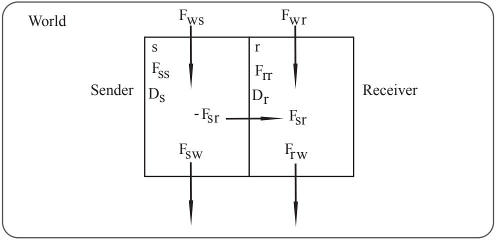
SEPIA model equilibrium

- Profits are maximized in each sector given prices and policies
- Household utility is maximized in each location given prices and policies
- The marginal household with threshold agricultural amenity value ϵ^* is just indifferent between each location
- AOD concentrations obey the laws of nature
- Service sector output market clears
- Labor markets clear
- The aggregate budget constraint is satisfied
- Capital price, ag. output price, manufacturing output price, rest of world AOD all exogenous
- Ag. land rent discarded. Tax revenue discarded or recycled.

Calibration Summary I

- Literature: Production factor shares, fuel substitution elasticity, fire abatement costs
- Directly from data: Fire intensity, fossil energy prices (in progress: tax wedges), consumer expenditure shares
- All remaining parameters: Simultaneously match model's initial equilibrium conditions and data moments:
  - Sectoral outputs: World Bank WDI
  - Initial population distribution (u, a): GPW
  - Initial agricultural labor share: ILOSTAT
  - Sectoral coal, petroleum, gas inputs: IEA
  - Willingess to pay for AOD reduction: Ito and Shuang (2016)

SEPIA steady state particulate transport model I



'Sending region' (agricultural or urban) exports to 'Receiving region'. In a steady state the conservation of mass requires,

$$0 = F_{ss} - D_s + F_{ws} - F_{sw} - F_{sr}$$
$$0 = F_{rr} - D_r + F_{wr} - F_{rw} + F_{sr}.$$

$F_{kk} \sim$ source in region k, $D_k \sim$ deposition in region k, $F_{kk'} \sim$ flow from region k to k'.
N.B.: Two types of economy, urban-sender, urban-receiver.

Counterfactual policy evaluation

We use our model to evaluate three counterfactual policies,

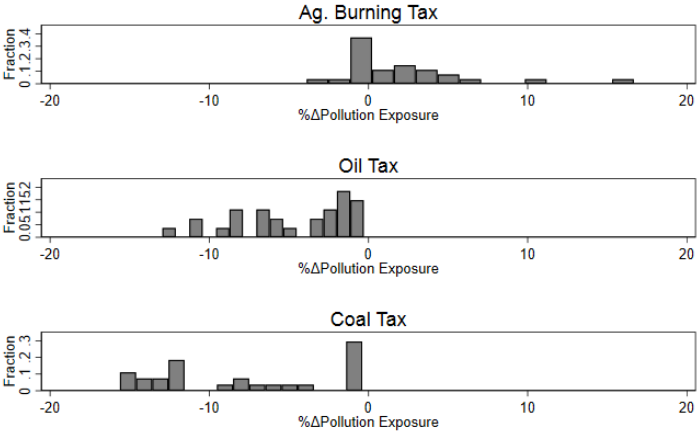
1. 15% tax on coal.
2. 15% tax on petroleum.
3. 300$/Mt on Ag. Burning Emissions.

We want to address three questions.

1. Is partial equilibrium good enough?
2. Which policy, where?
3. What happens in response to policy?

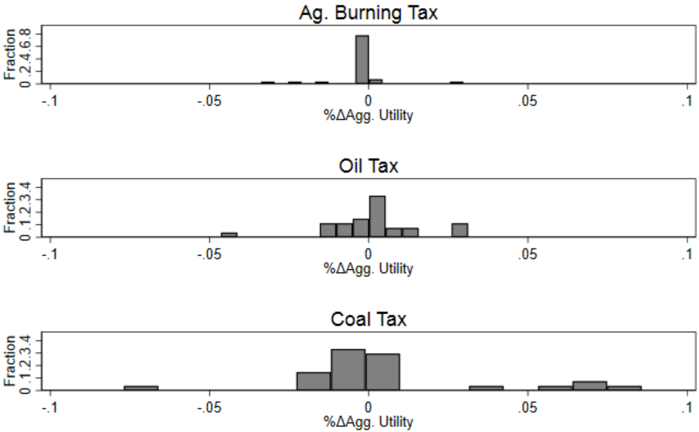
Distribution of Policy Impacts Across Countries: Exposure

Without Lump Sum Rebates

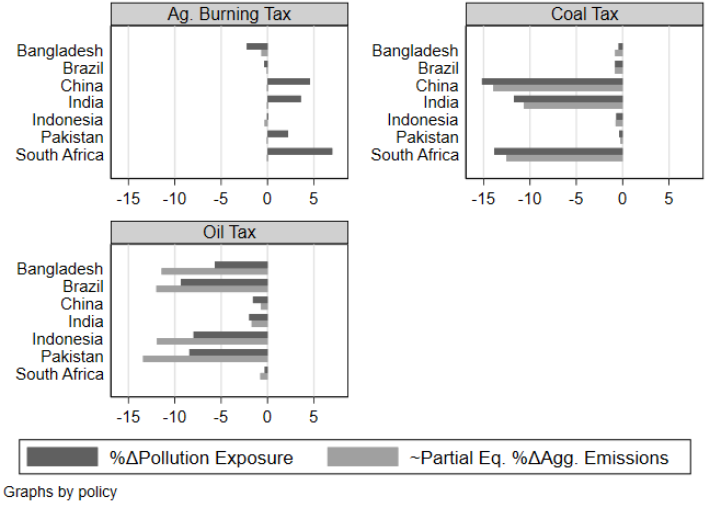


Distribution of Policy Impacts Across Countries: Welfare

Without Lump Sum Rebates



Partial vs. general equilibrium



'Partial equilibrium' response to regulation:

$$\%\Delta\text{Agg. Emissions}_j = \%\Delta\text{Emissions}_j \cdot \text{Emissions Share}_{j,Baseline}$$

Table: Counterfactual results for China in base year 2010 with policy revenue discarded.

Panel A: Aggregate effects

	Agg. Exposure (AOD/bil.)	Agg. Exposure %Δ	Urban Emiss. (MT/yr)	Urban Exposure %Δ	Rural Emiss. (MT/yr)	Rural Exposure %Δ	Welfare: Agg. %Δ	Welfare: Avg. Urban %Δ	Welfare: Avg. Rural %Δ
Baseline	0.693	-	4776.0	-	963.6	-	-	-	-
Oil Tax	0.682	-1.56	4714.2	-1.17	941.5	-2.41	-.0091	-.0015	1.3917
Burning Tax	0.724	4.56	4777.4	0.05	1100.8	14.21	-.0007	-.0000	1.3936
Coal Tax	0.587	-15.17	4165.5	-11.8	756.9	-22.24	-.0769	-.0130	1.3762

Panel B: Rural Impacts

	Industry Output ($bil.)	Industry Empl. (bil.)	Ag. Output ($bil.)	Ag. Empl. (bil.)	Ag. Burning (MT)	Coal Use (ktoe)	Oil Use (ktoe)	AOD
Baseline	1168.9	0.3462	5918.9	0.3256	131.4	469.2	51.7	0.328
Oil Tax	1145.7	0.3408	5975.0	0.3301	132.7	460.6	44.7	0.321
Burning Tax	1384.1	0.4099	4901.7	0.2617	98.87	538.0	55.7	0.375
Coal Tax	1022.3	0.3092	6331.6	0.3557	140.6	365.2	47.8	0.258

Panel C: Urban Impacts

Policy	Industry Output ($bil.)	Industry Empl. (bil.)	Services Output (tril.units)	Services Empl. (bil.)		Coal Use (ktoe)	Oil Use (ktoe)	AOD
Baseline	4495.5	0.2736	52.01	0.3779	.	2274.8	421.6	0.724
Oil Tax	4483.6	0.2741	51.76	0.3782	.	2263.9	367.0	0.715
Burning Tax	4497.0	0.2737	52.02	0.3779	.	2275.4	421.7	0.724
Coal Tax	4469.9	0.2779	51.75	0.3805	.	1965.9	415.2	0.631

Conclusion

- Country-year level variation in exposure and concentration is important and easy to explain statistically with economic fundamentals.
- Fine scale spatial variation is about half of variation and is hard to explain with economic fundamentals.
- Cross-country variation in the relationship between concentration and exposure is economically important: Spatial equilibrium processes seem important for exposure (and previously unstudied).
- Reduced form importance of interventions, Ag GDP $>$ Urban Share$>$ Ag Burning $>$ Coal $>$Flows.
- Our spatially integrated model of particulates and the economy exhibits counter-intuitive general equilibrium effects of regulation. We didn't look hard to find them.

Bibliography I

Kenneth Y Chay and Michael Greenstone. Does air quality matter? evidence from the housing market. *Journal of political Economy*, 113(2):376–424, 2005.

Michael Greenstone. The impacts of environmental regulations on industrial activity: Evidence from the 1970 and 1977 clean air act amendments and the census of manufactures. *Journal of political economy*, 110(6):1175–1219, 2002.

W Reed Walker. The transitional costs of sectoral reallocation: Evidence from the clean air act and the workforce. *The Quarterly journal of economics*, 128(4):1787–1835, 2013.

Randy Becker and Vernon Henderson. Effects of air quality regulations on polluting industries. *Journal of political Economy*, 108(2):379–421, 2000.