

# Growth and Development: Air Pollution

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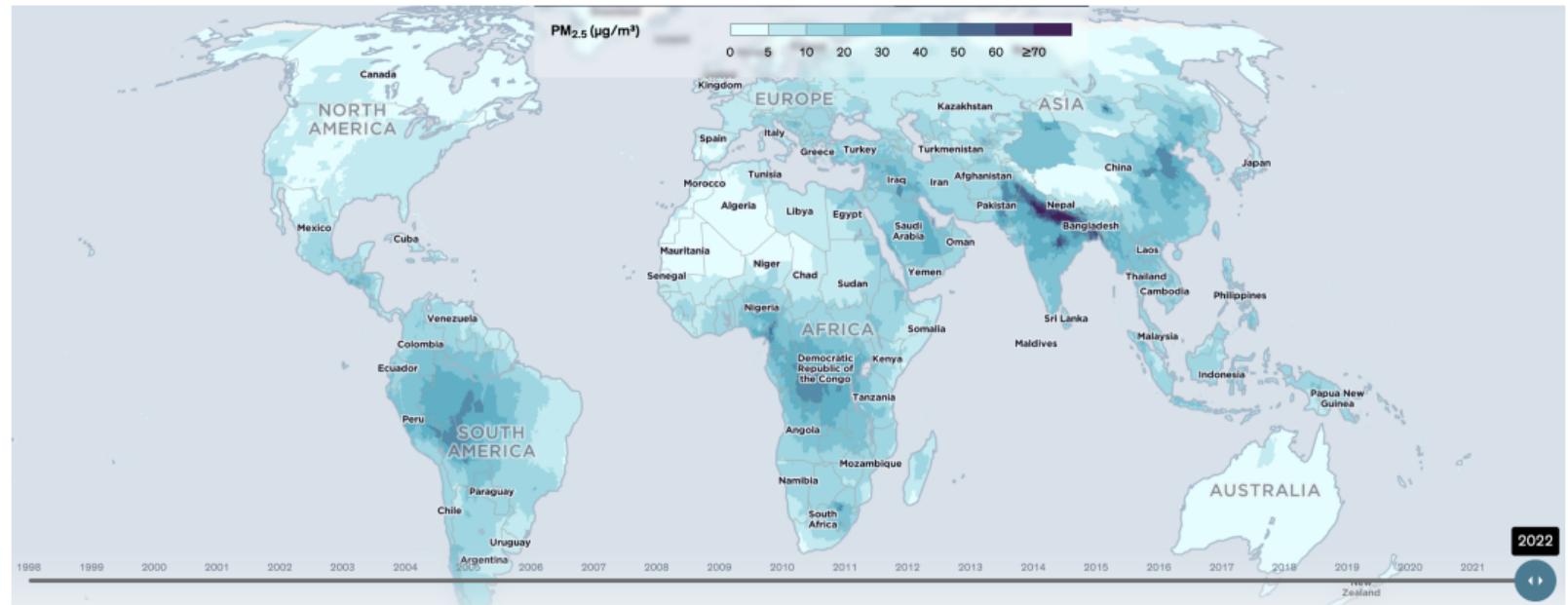
Lecture Notes for PhD Growth and Development (EC8510)



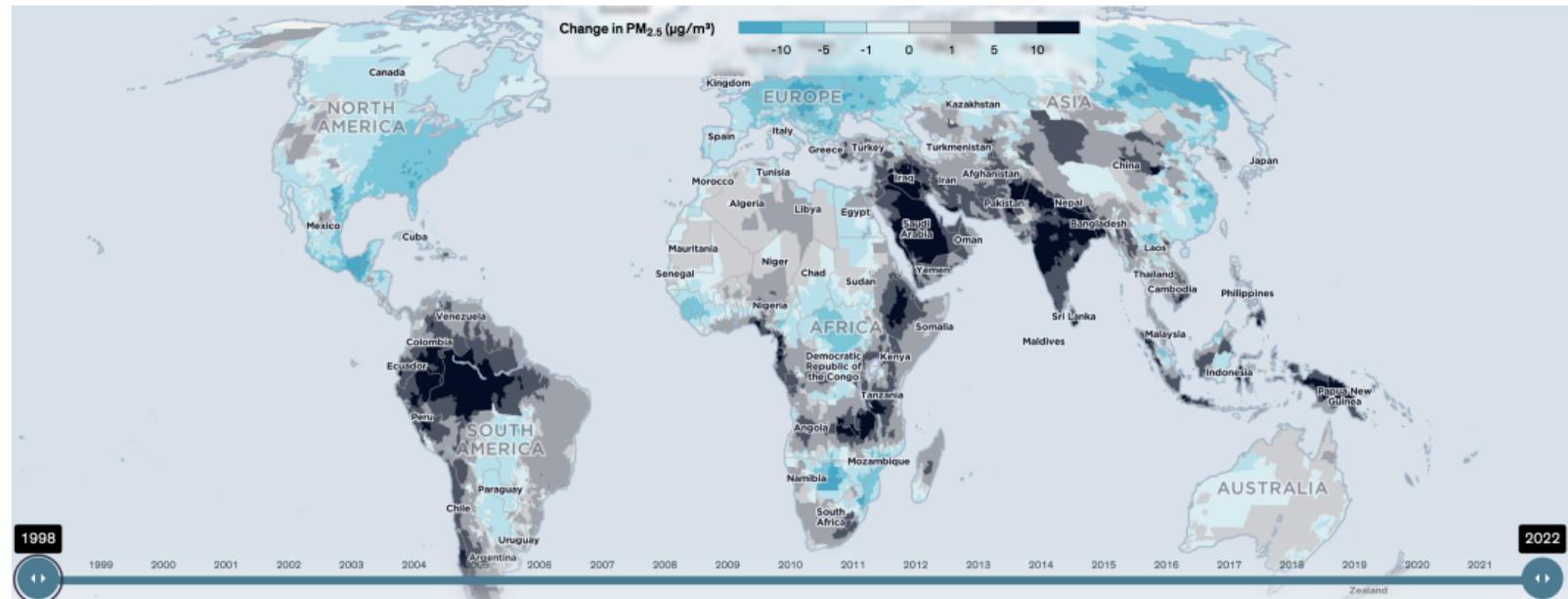
# Motivation

- ▶ **The Problem:** Air pollution has large and persistent negative effects on health, mortality, and human capital around the world.
- ▶ **The Possibility:** Air pollution can be reduced. History has shown that it is possible to significantly reduce air pollution.
- ▶ **(Some) Solutions:** Political will and policy tools such as markets, stringent regulation, and regulatory incentives have been successfully used to address this issue.

In 2022, 98% of the world population lived in areas that did not meet WHO guidelines for fine particulate pollution.

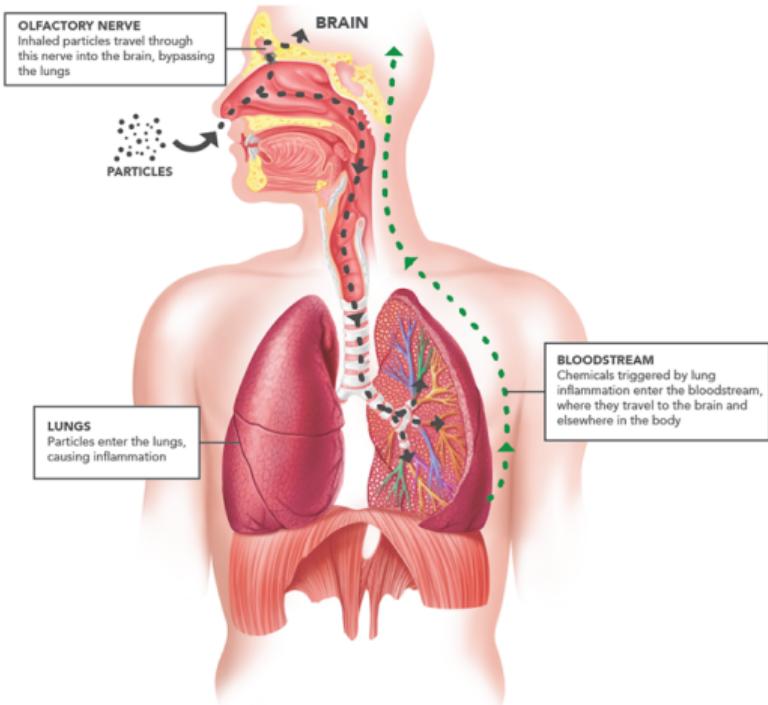


Between 1998 and 2022, fine particulate pollution increased by 13% globally



# What's the Big Deal?

- ▶ Primary consequence of inhaling air pollution is inflammation in the lungs:
  - ▶ Impedes exchange of carbon dioxide and oxygen, affecting cellular function throughout the body.
  - ▶ Chronic exposure leads to chronic inflammation.
  - ▶ Affects cardiovascular function and cognitive function as well as respiratory function.
- ▶ PM is attributed to as many as 9 million premature deaths each year.
  - ▶ 2x more than war, all other forms of violence, HIV/AIDS, tuberculosis, and Malaria combined.



# Evidence on Health Effects

- ▶ Hundreds of studies across disciplines have shown health effects of air pollution
- ▶ Effects on life expectancy, cancer risk, cardiovascular disease, respiratory disease, neurological conditions, immune system disorders, etc.
- ▶ Empirical challenge: Identifying causal effect is challenging.
  - ▶ Sicker people (who are poorer) tend to live in polluted areas.
  - ▶ Are they sicker because of pollution?

**PM<sub>2.5</sub>** ● <2.5  $\mu\text{m}$  combustion particles, organic compounds, metals

**PM<sub>10</sub>** |  | <10  $\mu\text{m}$  dust, pollen, mold

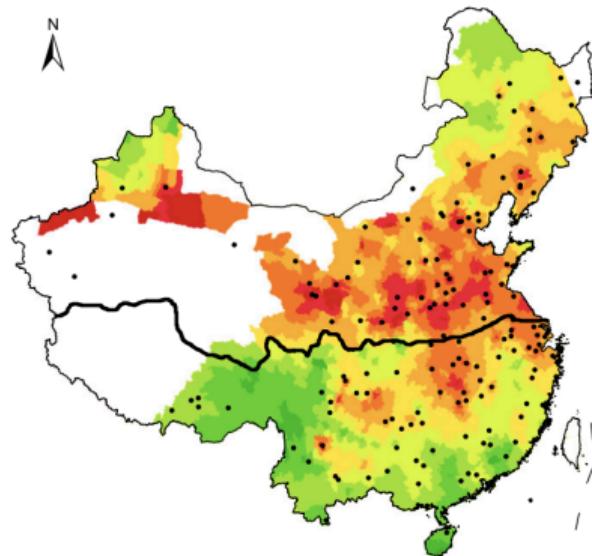
Grain of Beach Sand | ~90  $\mu\text{m}$



**$\mu\text{m}$ :** micrometers in diameter

# Evidence on Health Effects

- ▶ Ebenstein et al., (2017) explores the effect of air pollution on life expectancy using a natural experiment in China
- ▶ **Huai River Winter Heating Policy:**  
Established during the planning period, 1950-1980.
- ▶ Coal-powered municipal heating systems built to provide subsidized heating to homes in winter.
- ▶ Only built municipal heating systems in cities north of the Huai River-Qinling Mountains line.



**Fig. 1.** China's Huai River/Qinling Mountain Range winter heating policy line and  $\text{PM}_{10}$  concentrations. Black dots indicate the DSP locations. Coloring corresponds to interpolated  $\text{PM}_{10}$  levels at the 12 nearest monitoring stations, where green, yellow, and red indicate areas with relatively low, moderate, and high levels of  $\text{PM}_{10}$ , respectively. Areas left in white are not within an acceptable range of any station.

# Air Pollution Concentrations are 40% Higher North of the River

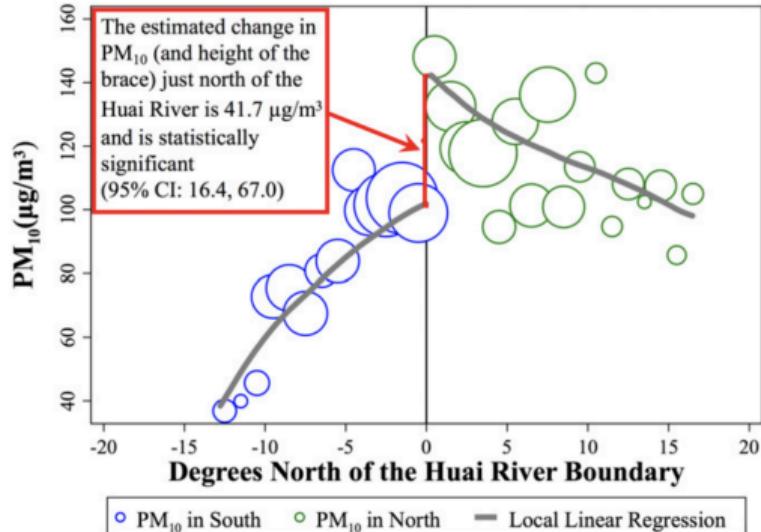
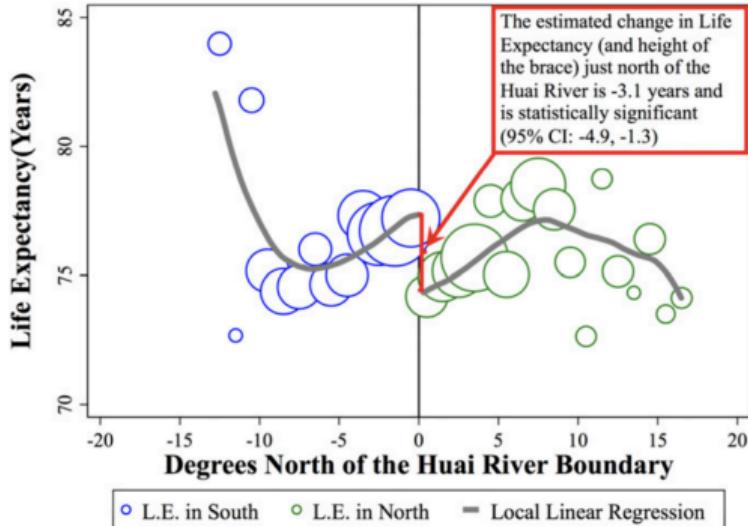


Fig. 2. Fitted values from a local linear regression of PM<sub>10</sub> exposure on distance from the Huai River estimated separately on each side of the river.

Average PM<sub>10</sub> concentrations in China during this period is 103  $\mu\text{g}/\text{m}^3$  (More than 5× WHO standard).

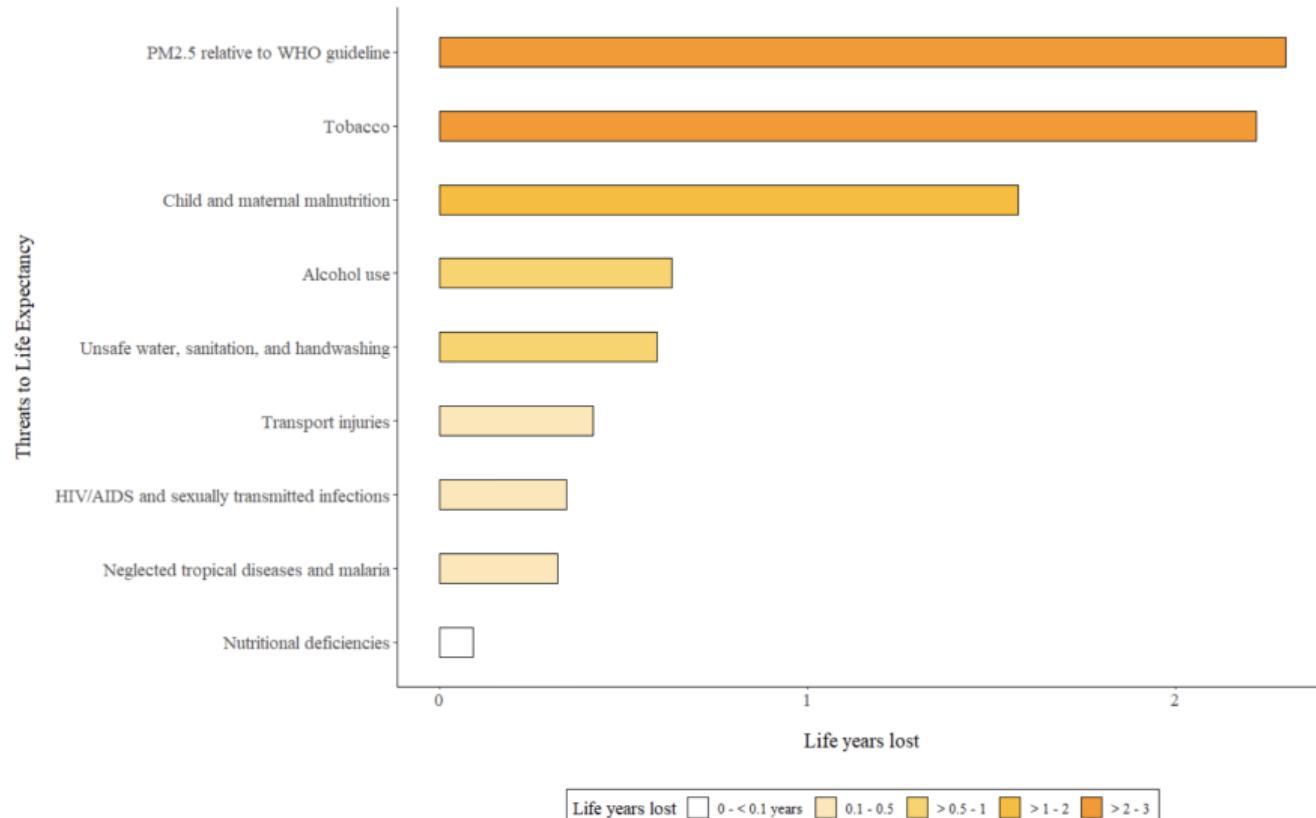
# Life Expectancy is 3 years Lower



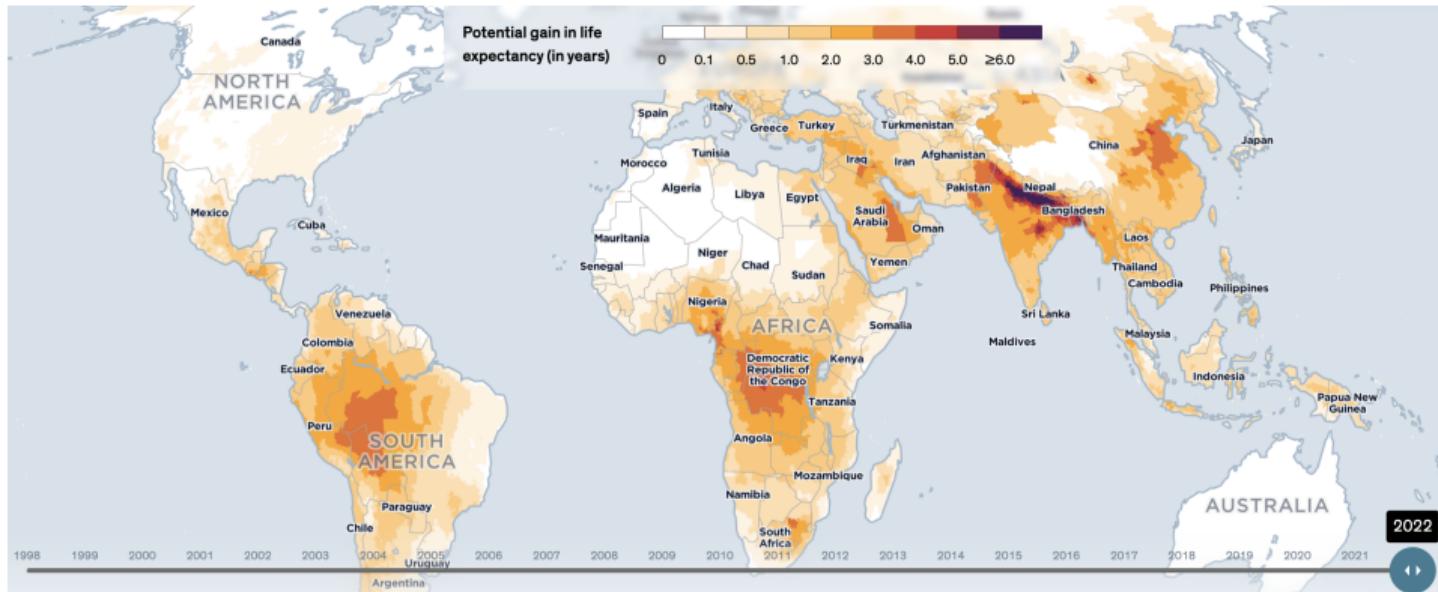
**Fig. 3.** Fitted values from a local linear regression of life expectancy (L.E.) on distance from the Huai River estimated in the same manner as in Fig. 2.

Long-term exposure to an additional  $10 \mu\text{g}/\text{m}^3$  is associated with a 0.64-year decline in life expectancy.

# Air Pollution Damages are Leading Cause of Lower Life Expectancy



# Air Pollution Damages are Highly Unequal



## Pollution and Infant Health

- ▶ In the 1950s, epidemiologists believed that a fetus was a “perfect parasite” that was “afforded protection from nutritional damage that might be inflicted upon the mother” (Susser and Stein, 1994)
- ▶ The placenta was regarded as a “perfect filter, protecting the fetus from harmful substances in the mother’s body and letting through helpful ones” (Landro, 2010)
  - ▶ Roughly half of U.S. mothers reported smoking in pregnancy in the 1960s (Aizer, Stroud, and Buka, 2009)
  - ▶ They were told it was fine.

## The “Fetal Origins” Hypothesis

- ▶ However, recent evidence suggests that the 9 months *in utero* are the most critical periods in a person's life, shaping future abilities and health trajectories.
- ▶ The intrauterine environment “programs” the fetus to have particular metabolic characteristics (Barker, 1990)
- ▶ The fetal origins hypothesis combines several key ideas:
  - ▶ The effects of fetal conditions are persistent
  - ▶ The health effects can remain latent for many years
  - ▶ There is a specific biological mechanism — epigenetics (Petronis, 2010)

# The Effects of Early Childhood Exposure

- ▶ The effects of early childhood pollution exposure on adult human capital depends on the short-run effects as well as the propagation of those effects through the life cycle,

$$\frac{dh_A}{dp_E} = \frac{\partial f_A}{\partial h_E} \frac{\partial h_E}{\partial p_E} + \frac{\partial f_A}{\partial h_L} \frac{\partial h_L}{\partial p_E} + \frac{\partial h_A}{\partial p_E}$$

1. The gestation period is critical for physiological and cognitive development

$$\left| \frac{\partial h_E}{\partial p_E} \right| > \left| \frac{\partial h_L}{\partial p_L} \right| \quad \forall p_E = p_L$$

2. Epigenetic impacts – permanent alterations of gene expression – may only appear later in life.

$$\frac{\partial h_E}{\partial p_E} = 0 \quad \text{and} \quad \frac{\partial h_A}{\partial p_E} < 0$$

## The Effects of Early Childhood Exposure

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$$\frac{dh_A}{dp_E} = \frac{\partial f_A}{\partial h_E} \frac{\partial h_E}{\partial p_E} + \frac{\partial f_A}{\partial h_L} \frac{\partial h_L}{\partial p_E} + \frac{\partial h_A}{\partial p_E}$$

- 3) If early childhood exposure is detrimental, then static and dynamic complementarities may be important

$$\frac{\partial h_L}{\partial p_E} \leq 0$$

- ▶ Consequently, parents may engage in compensatory or reinforcing investments.

# The Long-Term Consequences of Early Life Pollution Exposure

- ▶ Much of the focus has been on health effects, but these are the tip of the ice berg.
- ▶ Many less visible “non-health” effects of pollution affect well-being.
- ▶ Even acute exposure to pollution has both immediate and persistent, long-run, effects on educational attainment, learning, decision-making, productivity, criminal activity, labor force participation, and earnings.
- ▶ **Isen et al., (2017):** “... a 10 percent decrease in TSPs in the year of birth is associated with a 1 percent increase in annual earnings at age 30.”
- ▶ **Colmer and Voorheis (2021):** “... first-generation individuals who experienced lower pollution exposure in the gestational environment are more likely to have children who end up attending college 40-50 years later.”
- ▶ **Colmer, Voorheis, and Williams (2023):** “... early life exposure pollution exposure is one of the top five predictors of upward mobility in the United States.”

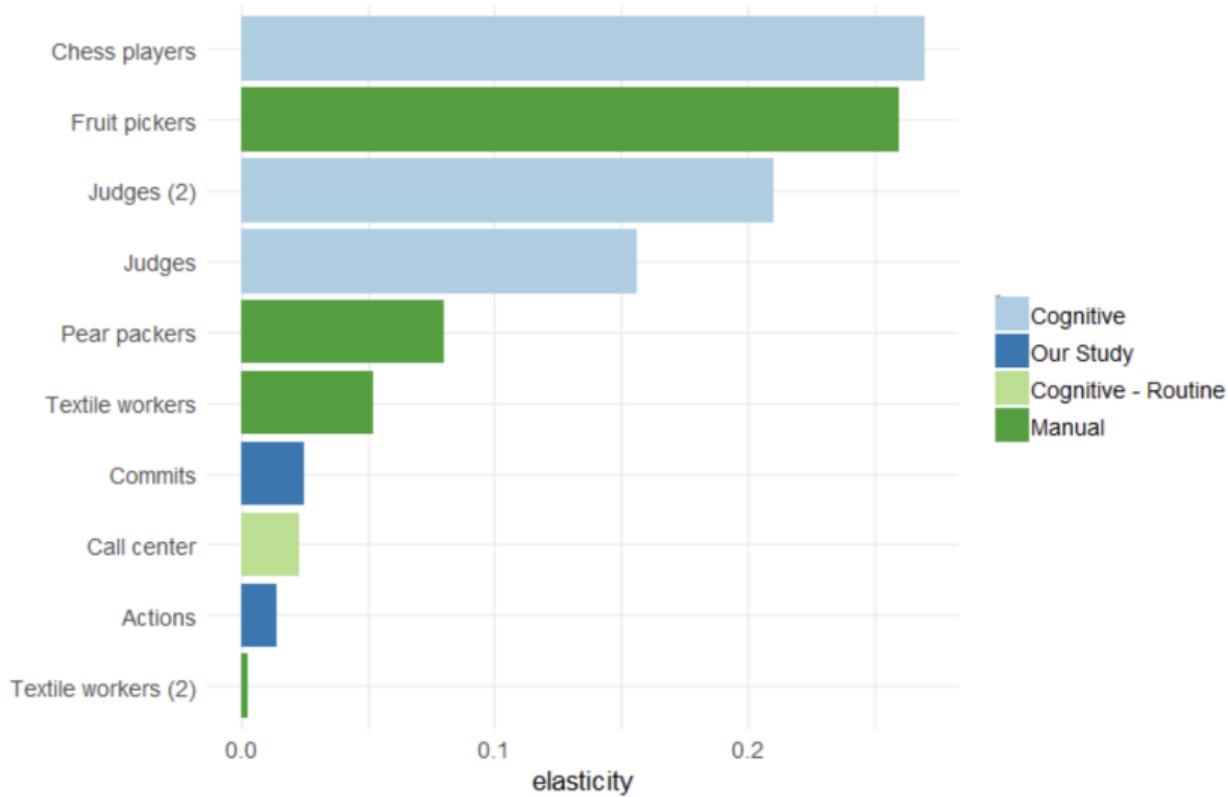
## Reasons for Continued Interest in the Fetal Origins Hypothesis

- ▶ The large effects, resulting from short exposure times, suggest that pareto improvements can be made by re-allocating resources from later to earlier in the life cycle.
  - ▶ The literature resonates with a core interest of economists: efficiency
  - ▶ However, it is far from obvious how this potentially high-return reallocation can best be achieved.
- ▶ The FOH is a surprisingly general phenomenon, affecting a wide range of outcomes.
- ▶ Mechanisms and policy implications are still not well understood,
  - ▶ Investments in pregnant women, children, and their environment may counter-balance forces leading to greater inequality.
  - ▶ What are the relevant policy levers?
- ▶ The Missing Middle.

# Pollution and Productivity

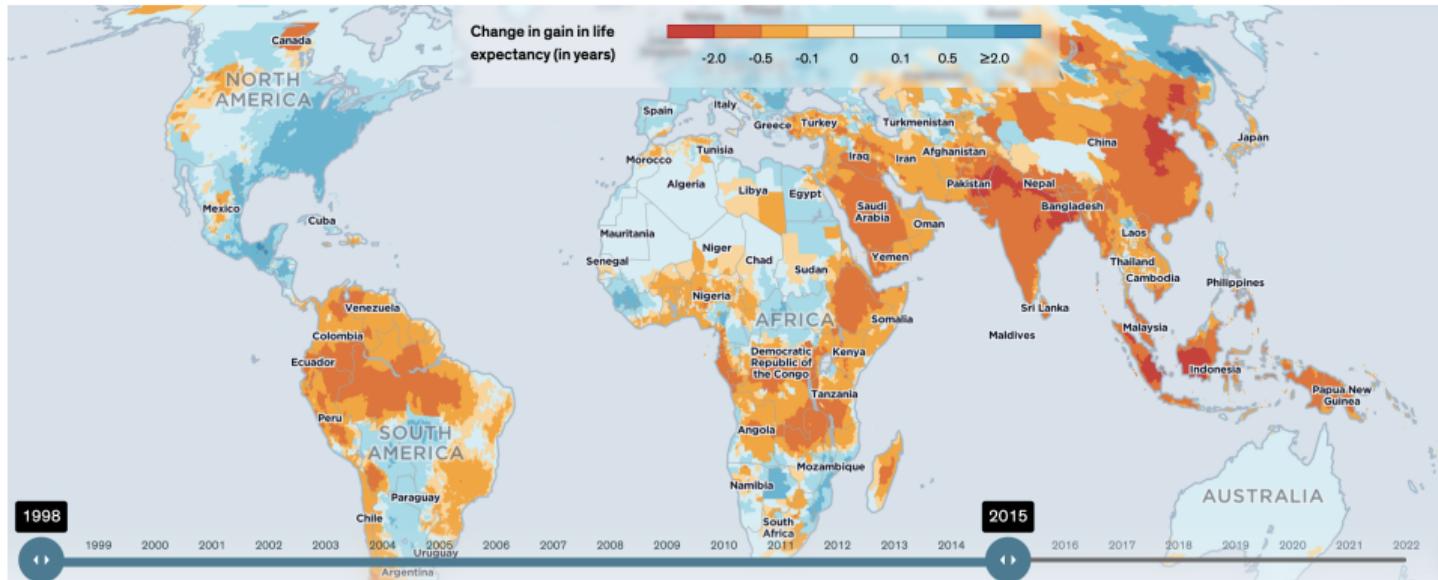
- ▶ Acute exposure has immediate effects on productivity ([Graff Zivin and Neidell, 2012](#); [Chang et al., 2016](#); [Adhvaryu et al., 2022](#)).
  - ▶ At an hourly level, a  $10\mu\text{g}/\text{m}^3$  increase in pollution lowers productivity by 0.5 percent (one percent of average productivity) ([Adhvaryu et al., 2022](#)).
- ▶ Subtlety of physiological effects makes behavioral responses to manage harms more complicated.
  - ▶ Absence of symptoms, or the manifestation of an “off day” makes introspective causal attribution difficult, reducing ex ante avoidance behavior.
  - ▶ But changes in outcomes are visible, which requires costly remediation/compensation.
  - ▶ Environmental regulation often seen as a trade-off between consumption and production that is costly for firms.
  - ▶ However, productivity benefits of air quality mean it could be viewed as an investment contributing to economic growth.

# Pollution and Productivity Across Sectors

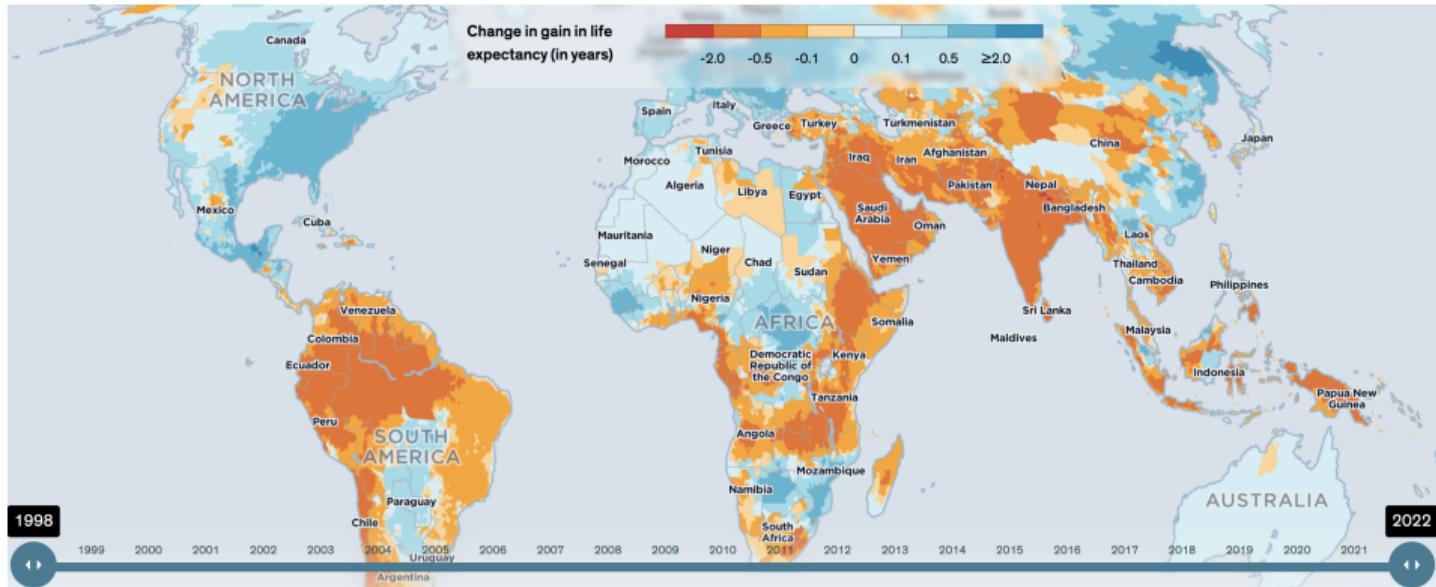


(b) Effects of Air Pollution Across Occupations

# Air Pollution Can Be Reduced



# Air Pollution Can Be Reduced



# China's War on Pollution

## Air pollution concentration in major regions within mainland China

PM 2.5 ( $\mu\text{g}/\text{m}^3$ )\*

— China — Yangtze River Delta — Pearl River Delta — Beijing-Tianjin-Hebei region



Source: China's National Air Quality Monitoring Network  
© FT

\* One-millionth of a gram, per cubic metre air

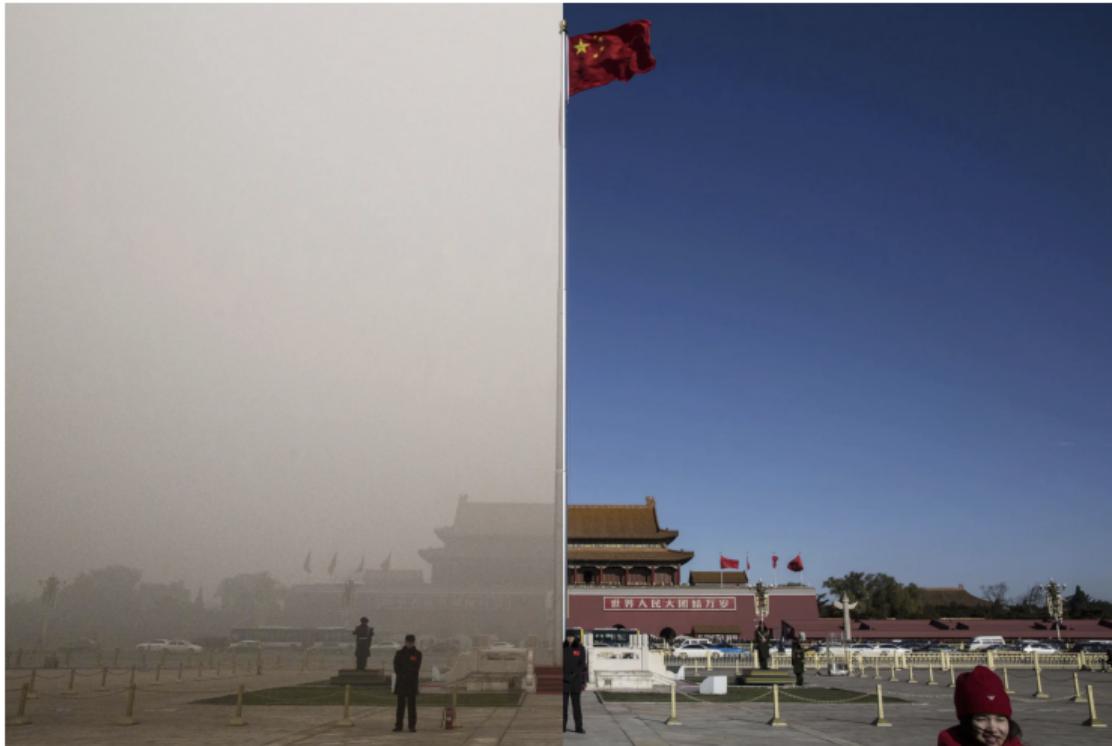
# China's War on Pollution



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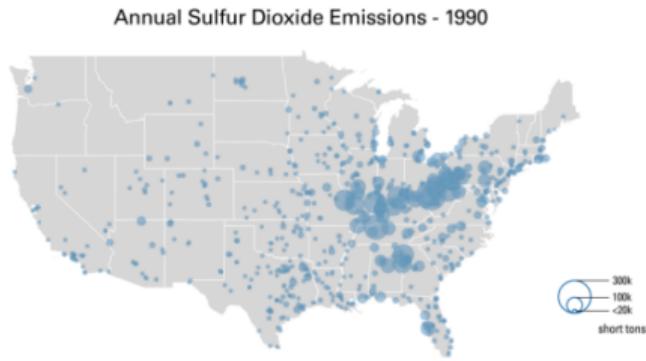
# Political Will

- ▶ Very few (if any) instances of meaningful improvements in environmental quality without strong political will.
- ▶ Nearly all successful cases preceded by consistent public demand.
- ▶ UK:
  - ▶ In 1306, King Edward I issued a ban on burning sea coal because it was "prejudicial to health", but was ignored by population despite threat of torture or hanging.
  - ▶ London Smog led to death of 4,000–12,000 people in one week in 1952, increasing public and political awareness ⇒ Clean Air Act (1956)
- ▶ US:
  - ▶ Rachel Carson publishes "*Silent Spring*" (1962), 20 million demonstrate for Earth day (1970) ⇒ Clean Air Act (1963), EPA created (1970).
- ▶ China:
  - ▶ US embassy tweets hourly pollution in Beijing (2008) → widespread public criticism in print and social media → China premier 'declares war' on pollution (2014).

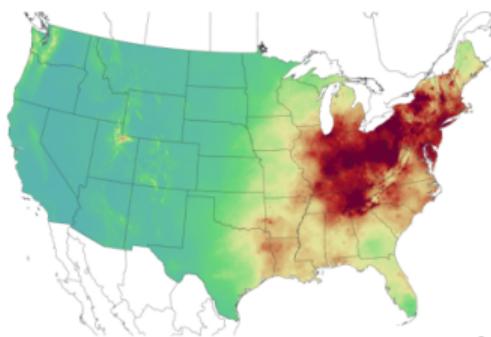
## US Emissions Trading Schemes Have Been Successful

- ▶ Over the past four decades, the US has implemented a number of emissions trading programs
  - ▶ Lead Gasoline Phasedown (1980s)
  - ▶ Acid Rain SO<sub>2</sub> Allowance Trading (1990s)
  - ▶ RECLAIM SO<sub>2</sub> and NO<sub>x</sub> Markets (1990s)
  - ▶ Northeast NO<sub>x</sub> Trading (1990s)
- ▶ Flexibility of trading schemes yielded cost savings of as much as 50% and successfully achieved environmental goals.

The Acid Rain Program showed the potential for market-based regulations to reduce pollution at low cost

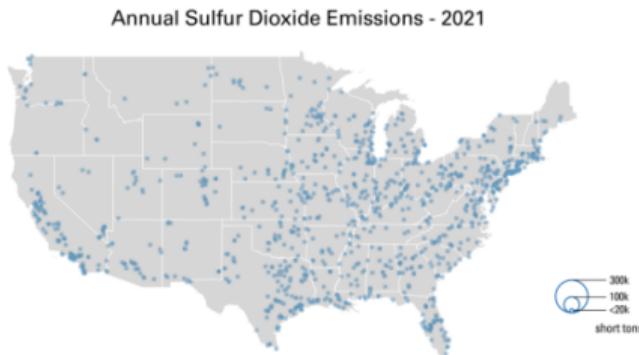


Annual Wet Sulfate ( $\text{SO}_4^{2-}$ ) Deposition — 1989-1991

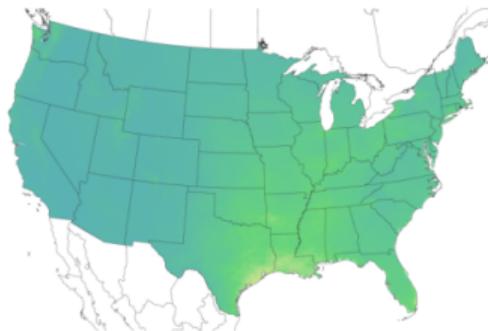


Source: NADP, PRISM  
USEPA, 2022

The Acid Rain Program showed the potential for market-based regulations to reduce pollution at low cost



Annual Wet Sulfate ( $\text{SO}_4^{2-}$ ) Deposition — 2019-2021



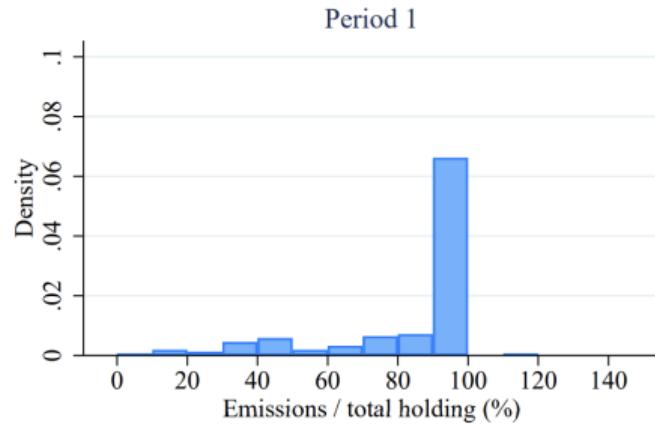
## Emissions Markets in India (Greenstone et al., 2023)

- ▶ Air Act of India (1981): Established Command Control Regime
- ▶ **Command:** Mandate for plants to install air pollution control devices (APCDs)
  - ▶ This is effective: every plant in sample had at least 1 piece of abatement equipment
- ▶ **Control:** Plants sanctioned if manually sampled emissions exceed specified concentrations limit (150 mg/NM<sup>3</sup>)
  - ▶ This is ineffective: Significant non-compliance across sample
  - ▶ Financial sanctions largely unavailable, so sanctions generally involve shutting plants entirely.

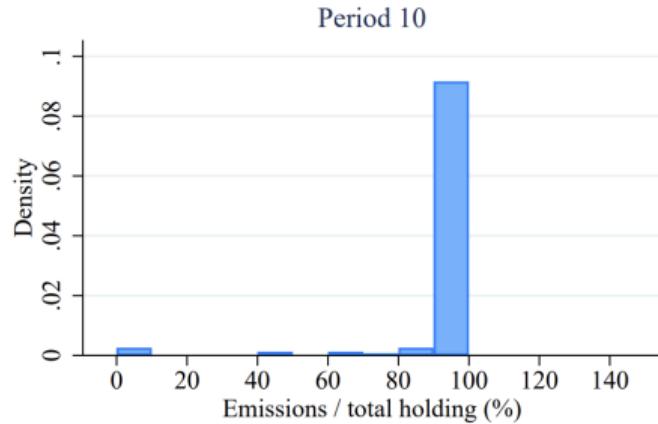
## Market Design Leveraging CEMS Devices

- ▶ **Cap** total pollution (PM2.5) from all plants
- ▶ **Allocate** 80% of permits given to plants, the remaining 20% auctioned by the regulator
- ▶ Plants **trade** at weekly auctions with uniform prices
- ▶ **Compliance:** Plants subject to a severe fine if they emit in excess of permit holdings

# Learning-by-Doing



(a) Period 1



(b) Period 10

- ▶ Permits unspent as a percentage of the period cap
  - ▶ Period 1: 12.5% (35 tons/280 tons)
  - ▶ Period 10: 2.8% (4.8 tons/170 tons)

## Markets Reduced Abatement Costs and Emissions

- ▶ Trading reduced emissions by 20-30% relative to control firms.
- ▶ At the market cap of 170 tons, total abatement costs within the trading market were 12% lower than under command and control.
- ▶ Expanding the ETS for one year to all industrial plants in Surat would result in a benefit-cost ratio of 215:1

## Aligning Non-Market Incentives

- ▶ Many firms misreport PM emissions
- ▶ Plants tend to get to choose their auditor and pay their auditor.
- ▶ One might be concerned about incentives...
- ▶ Duflo et al., (2013) randomly assigned firms to a new auditing mechanism, where polluters paid into a central fund which randomly assigned auditors.
- ▶ Treatment auditors reported emissions that more closely matched “back-checks”.
- ▶ Treated firms reduced pollution by 28%.

# Designing Payment Schemes to Reduce Crop Burning

- ▶ Farmers in Northern India burn stalks to clear fields, with significant health externalities for downwind cities.
- ▶ Every 50 acres burned causes a single death ([Jack et al., 2022](#))
- ▶ Crop residue burning caused 86,000 premature deaths in India in 2018 ([Lan et al., 2022](#))
- ▶ Bans on burning residue have been ineffective due to lack of compliance.

## Designing Payment Schemes to Reduce Crop Burning (Jack et al., 2022)

- ▶ Experiment with three farmer groups:
  - ▶ Farmers who were not offered a contract and received **no** payments.
  - ▶ Farmers who were offered a contract for **conditional** payments if they didn't burn
  - ▶ Farmers who were offered an **unconditional** partial upfront payment with the remaining balance given after verification of compliance.

## Designing Payment Schemes to Reduce Crop Burning (Jack et al., 2022)

- ▶ Farmers given **upfront payment were twice as likely to not burn crops** compared to farmers offered standard PES contract.
- ▶ Standard PES contract had no effect on burning compared to control group.
- ▶ Mortality damages are 150-230 times the per-acre cost of reducing burning through upfront PES.

## Distributional Considerations

- ▶ Policy and public discourse around air quality have two targets:
  - 1) Absolute levels of ambient pollution
  - 2) The distribution of pollution between groups
- ▶ Substantial progress on (1)
- ▶ Progress on (2), but a way to go.
- ▶ Efficiency and equity are only separable in a first-best world.

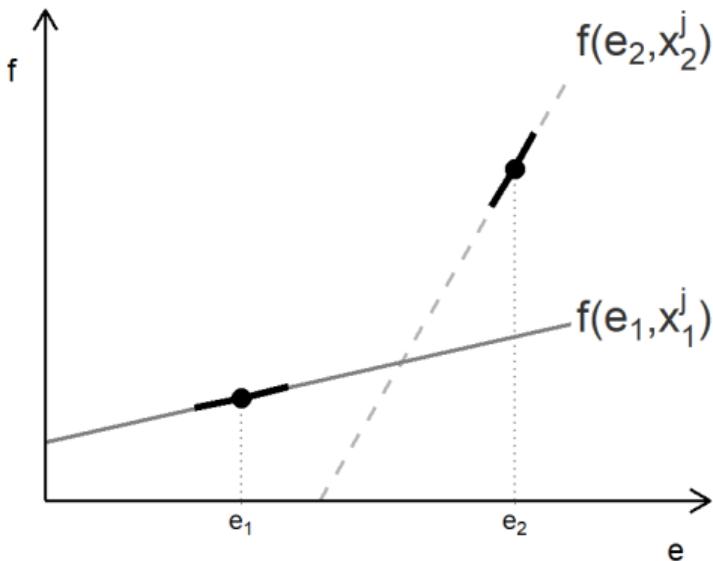
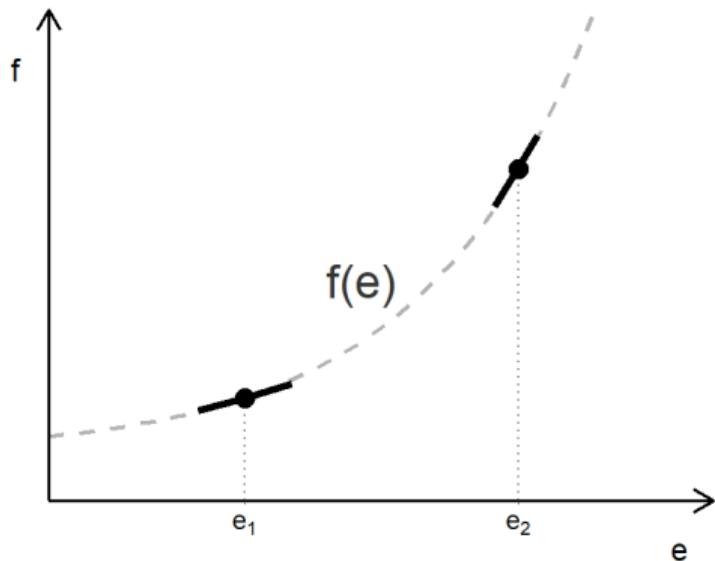
# Environmental Inequality

- ▶ The existence of environmental disparities is well established (UCC, 1987; USGAO, 1983; Bullard et al., 2007; Mohai, et al., 2009; Brulle and Pellow, 2018; Banzhaf et al., 2019; Colmer et al., 2020; Currie, Voorheis, and Walker, 2023; Colmer et al., 2024, etc.).
- ▶ However,
  - 1) We know far more about *where* environmental risks are than *who* is exposed to them.
    - ▶ Places aren't people
  - 2) We know very little about the *causes* or *consequences* of environmental inequality.
  - 3) Do disparities in outcomes reflect *disparate exposures* or *disparate vulnerability*?

*"Any specific prescription is contingent upon how inequities arise. Tackling the remaining uncertainty about the relative importance of such causes is critical if we hope to address environmental injustice at a fundamental level."*

– (Banzhaf, Ma, and Timmins, 2019)

## Differences in Marginal Damages



- ▶ Differences in exposure:  $\frac{\partial^2 f(e,x)}{\partial e^2} > 0$
- ▶ Differences in vulnerability:  $\frac{\partial^2 f(e,x)}{\partial e \partial x_j} > 0$

# Conclusions

- 1) **The Air Pollution Problem:** Air pollution has a variety of deleterious effects on health and non-health human outcomes. The burden is unequal within and between countries.
- 2) **Air Pollution can be Reduced:** History shows that we can reduce pollution and have done so effectively in the past.
- 3) **How to Reduce Air Pollution:** Political will combined with markets, stringent regulations, and other incentives have been successfully used to address this issue.

## Directions for Research

- ▶ Most regulation is second-best (or third-best, or fourth-best...):
  - ▶ What are the constraints?
  - ▶ What are the benefits and costs of the actual regulations?
  - ▶ What is the efficiency loss?
  - ▶ What are the feasible gains from reform?
  - ▶ What are the equilibrium consequences of regulations?
  - ▶ What are the distributional consequences?
- ▶ Frontier research has several common features:
  - ▶ Clear institutional understanding of a generally relevant problem
  - ▶ Data that is novel or exceptional in coverage or depth
  - ▶ Policy, quasi-experimental, or experimental variation to estimate key parameters or validate model predictions

# Directions for Research

## 1. Better data.

- ▶ Remote sensing for air pollution, water extraction, land use, etc.
- ▶ Regulatory and government partnerships for administrative records
- ▶ Wide-scale and personal monitoring of heterogeneous damages

## 2. More of the world

- ▶ Geographic scope is heavily weighted towards major US regulations like the Clean Air Act
- ▶ There are many heterogeneous regulatory regimes around the world to learn from and pollution is much higher in low-income countries.
- ▶ The constrained optimal regulatory regime will differ with pre-existing market failures, which are the object of study in development

## 3. Micro-foundations of responses to regulation

- ▶ Approach regulation as a mechanism design problem.
- ▶ Identify and estimate constraints and find the constrained optimum.
- ▶ Environmental regulation seems behind the comparable literatures on market design in education, health, etc. *We know the status quo is inefficient – what to do instead?*