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Economic Development and the Environment

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ABSTRACT

Economic development relies on and transforms the environment. The transformation is evident in the poor environmental quality in many developing countries. For example, air quality in Southeast Asia is three times worse than in the United States, in sub-Saharan Africa four times worse and in South Asia more than six times worse. We model how environmental quality affects health, productivity and well-being and how individuals privately adapt to environmental hazards. We also model how collective action and formal regulation contribute to environmental quality. We draw three main findings from a review of empirical research on these mechanisms. First, individual adaptation to environmental hazards is both inadequate as a remedy and inefficiently low. Second, collective action, without the state, to manage resources or address externalities has been outstripped by the scale of environmental problems. Third, state action through formal regulation works better than it looks. Many formal regulations are coarse, poorly targeted and inefficient, but nonetheless yield benefits in excess of their costs.

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1 Introduction

Economic development both relies on and transforms the natural world. Relies on, because people depend on nature for their sustenance, health and productivity. We see this reliance at all levels of income, but especially when people cannot afford to buy substitutes for nature from the market. Transforms, because economic development turns nature into an input to production and the environment into a byproduct.

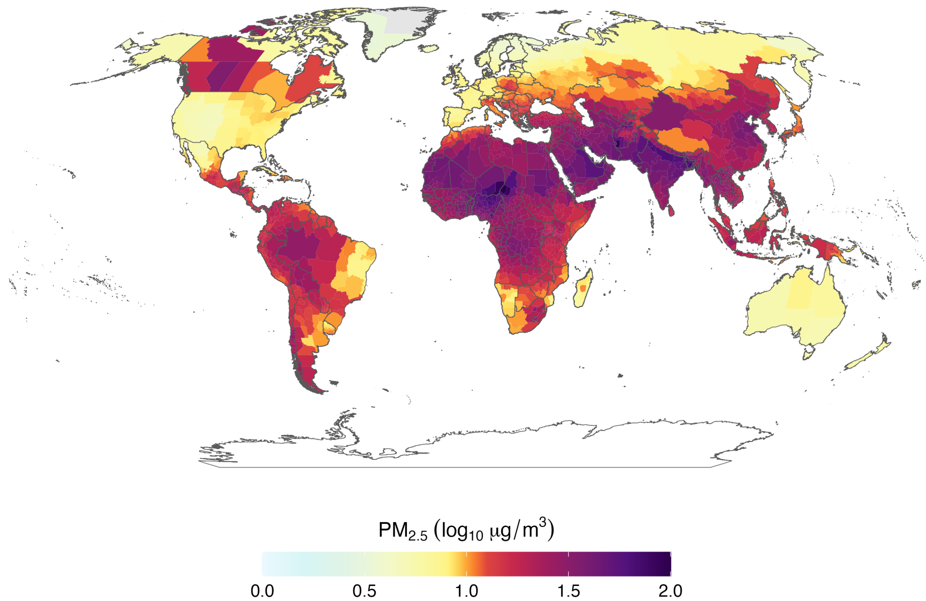
The transformative aspect of economic development for the natural environment is on view in the poor environmental quality in many developing countries. Air pollution is a well-studied example that can be measured consistently around the world (Figure 1). Levels of fine particulates, relative to the United States, are on average three times worse in Southeast Asia, four times worse in sub-Saharan Africa, five times worse in the Middle East and North Africa, and more than six times worse in South Asia (Figure 2, panel a; note the logarithmic scale). In China and India alone, more than two billion people tolerate levels of air pollution that harm health and reduce lifespans by an estimated 2.2 and 3.5 years, respectively (AQLI, 2025). Surface water quality, as in rivers and lakes, is also regularly five times worse in large developing countries than in the United States (Figure 2, panel b).

While air and water quality are signal measures, the environment acts on human well-being through myriad channels. We consider any natural resource or service that bears on human health, productivity or well-being as a dimension of environmental quality. In Brazil and Indonesia, deforestation releases greenhouse gases, changes weather patterns and disrupts water cycles (Araujo, 2023; Sum et al., 2026). In South Asia, rapid depletion of groundwater reservoirs causes economic and social harm (Sekhri, 2014; Blakeslee, Fishman and Srinivasan, 2020). Biodiversity losses expose humans to the spread of disease (Frank and Sudarshan, 2024). In every country, economic growth drives fossil fuel consumption, which emits local air pollutants and the greenhouse gases that cause climate change (Intergovernmental Panel on Climate Change, 2023).

Are these extremes of environmental harm inevitable? Might they even reflect an efficient social choice, for countries to develop first and clean up later?

This chapter reviews research on the environment and economic development. Our goal is to explain how the environment matters for development and why collective action to improve envi-

Figure 1. Particulate matter air pollution levels



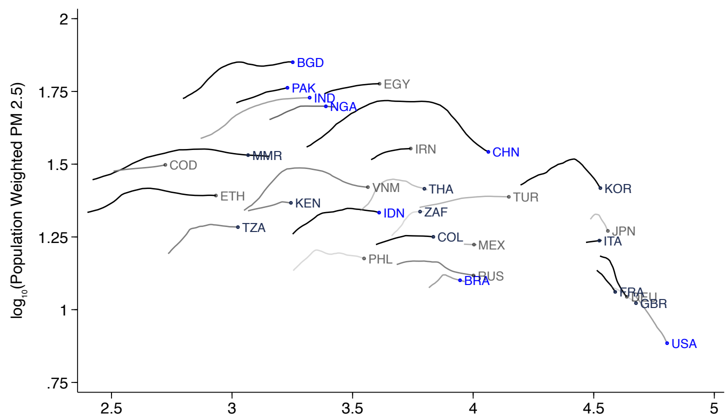
This figure shows the logged fine particulate matter air pollution levels in provinces around the world in 2023. The data come from multiple satellite based NASA instruments, including MODIS and VIIRS, in conjunction with ground-based measurements (van Donkelaar et al., 2024). We plot the map at the Global Administrative Areas (GADM) database level 1.

ronmental quality is difficult in developing countries. The chapter covers both the "demand" side of environmental quality—the ways people enjoy benefits of the environment or suffer damages from pollution—as well as the "supply" side—the collective choices and regulations that determine environmental quality. Throughout the chapter, we draw on a large recent literature on economic development and the environment to gather three main findings.

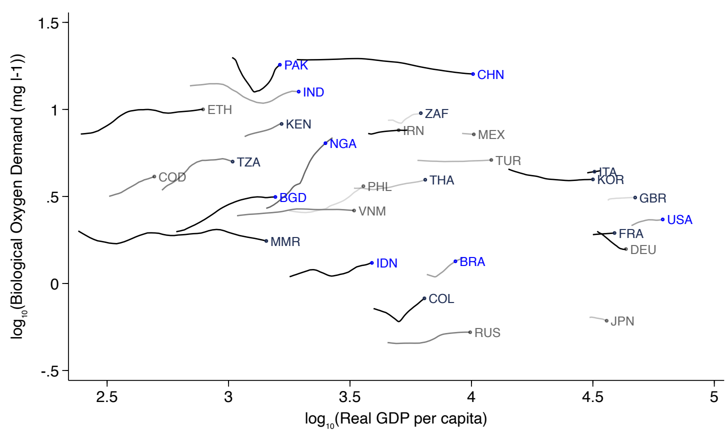
First, individual adaptation to environmental harms is inadequate. In principle, people can protect themselves from environmental harm, like poor ambient air or water quality, through adaptive actions or expenditures. In practice, people in poor countries are more exposed to environmental harms, because they depend more on nature and have lesser means to protect themselves. We document that adaptation does occur in response to many environmental harms, such as poor drinking water quality, air pollution, resource depletion and climate change. However, adaptation is woefully incomplete: it does not restore people anywhere close to the welfare they would enjoy if the harm were either removed altogether or only reduced to the level observed in rich countries.

Figure 2. Environmental quality across countries

(a) Air quality and income per capita



(b) Surface water quality and income per capita



The figure plots environmental quality measures against real income for the most populated countries in the world. Each curve represents a value for a country over the last two decades with a small circle fixed at the most recent year in the data. The countries in blue have populations of over 200 million people. Panel 2a plots the log of fine particulate matter air pollution against real income per capita from 1999 to 2023 (van Donkelaar et al., 2024). Panel 2b shows the log of biochemical oxygen demand against real income per capita from 1999 to 2019 (Jones et al., 2023).

A cascade of reasons explains this shortfall. First, most plainly, the actions an individual can take to protect themselves are limited by technology and cost. For many environmental hazards, there are simply no good private substitutes for public action to improve environmental quality. In developing country cities, the rich buy clean water more than the poor do, yet the rich and poor alike suffer from air pollution, which is hard to buy private protection against. Second, poor people are credit constrained, and cannot afford to buy the efficient level of adaptation from the technology that is available. Third, and more surprising, adaptation seems inadequate even given what technology is both available and affordable. A lack of information compromises demand for adaptive investments in environmental protection. Yet growing evidence suggests that, even with complete information, the revealed value that people place on avoiding environmental hazards seems far below the value that would be justified by the physical harm done.

Our second finding is that informal collective action to improve environmental quality fails to address many environmental problems. The ideal for governance of the local commons is to coordinate action through institutions that grow to meet the scope of an externality (Ostrom, 1990). There are instances of local institutions that have grown in this way and a large body of positive research describing their functions. Yet, we find scant evidence that collective management results in efficient resource use, in the sense of equalizing the marginal costs and benefits of use across all parties who contribute to and draw on a natural resource. Most studies of local environmental management do not even attempt to estimate its efficiency, and those few that do suggest that local management regimes are far from fully efficient.

The ideal of local management fails because many environmental hazards, from air pollution and bad water quality to the disease environment, act on a scale that outstrips the span of informal coordination. Norms do not constrain a farmer from burning their field, or a plantation from burning a forest, when the main harm of pollution is felt in a neighboring state or a different country. Moreover, even for externalities that are local in scope, collective action is limited by failures of information and enforcement. Coasian bargaining fails to resolve externalities when pollution and damages are poorly measured and agreements are costly to enforce.

Our third finding is that government action to improve environmental quality works better than it looks. Formal environmental regulation in developing countries is incomplete, corrupt and inefficient—but also, in many cases, generates benefits far in excess of its costs. Incomplete information, about both pollution emissions and abatement costs, leads to agency and incentive problems in environmental regulation in all countries. These failures are particularly severe in developing countries, due to weak state capacity for monitoring and contract enforcement. As a result, governments retreat to coarse, even haphazard regulations, that can be implemented with little information, like banishing entire industries to the countryside or rationing access to water. Coarse regulations are inefficient, both because they manage proxies for environmental damage, rather than the damage itself, and because they neglect heterogeneity in the costs and benefits of abatement. Yet they can still have very high social returns, because of the large value of marginal improvements to environmental quality. Regulation is heavily constrained by failures of markets and governance, but that does not necessarily imply that a coarse regulation will not deliver social benefits greater than its costs.

We are skeptical that observed low levels of environmental quality represent a socially efficient equilibrium path of development. In many low- and middle-income countries, the private costs of improving quality appear low, but the social costs of compelling agents (people, firms) to make socially beneficial contributions to quality are high. Investments in state capacity for monitoring and enforcement, in this scenario, can have high returns, since these investments incentivize private actors to use technologies for abatement that already exist and may have low or moderate costs. A main direction for research is then to develop a more prescriptive, empirically informed environmental economics of the second-best. The regulations used and useful are mostly not efficient, but it is more difficult to argue what second-best (. . . or third-best, or ninth-best) form regulation ought to take. The political economy of environmental regulation places additional constraints on the kinds of regulations that can work in practice.

1.1 The content of the chapter

We start by introducing some stylized facts on environmental quality and development in Section 2. Thereafter, this chapter is organized into two main parts, on the individual (Sections 3 and 4) and collective action (Sections 5, 6, 7 and 8).

The organization of this chapter is economic, concerning the parties involved and their incentives and organization, rather than physical. There is no one section on "water" or "climate."

The same economic ideas apply to a variety of physical environmental problems. For example, externalities across jurisdictions from common use of a resource appear for the management of groundwater reservoirs as well as transboundary air pollution. Conversely, many environmental problems (poor air quality) recur to illustrate different economic principles, such as environmental harms to productivity, the extent of private adaptation to environmental hazards, and the role of information failures in compromising formal regulation.

1.1.1 The environment and the individual

Section 3 models the individual's relationship with the environment. People rely on the environment in many ways. They care about the amenity value of the environment (a smog-free view), its effect on health, and any loss of productivity and hence income from environmental harms. But people also like other consumption goods, which generate environmental externalities from their production. When making consumption decisions, individuals may internalize some of these externalities, but do not account for others, resulting in environmental quality below the socially efficient level. In response, a person on their own has only one recourse: to invest in adaptation that lowers her own exposure to ambient environmental hazards.

The empirical literature uses expenditures on private adaptation as a stand-in for people's values of avoided damages from environmental hazards. We use our model to scrutinize the assumptions needed for the willingness-to-pay for adaptation to reveal the value people place on environmental quality. These assumptions include that: (i) adaptation that changes experienced environmental quality (e.g., the air in my apartment) is just as good as changing environmental quality itself (e.g., the air outside); (ii) adaptation does not affect utility through channels other than experienced environmental quality; (iii) households know the relationships between adaptation, exposure to environmental quality and utility.

Section 4 lays out the empirical evidence on environmental harms corresponding to the mechanisms in the model of the individual.

1.1.2 The environment and collective action

Individual adaptation is both theoretically and empirically unable to reach efficient allocations of environmental quality or experienced harm. We next study how collective action can improve environmental quality, above the protection individuals can gain on their own.

Section 5 models how people or firms contribute to environmental quality and the scope for collective action or regulation to improve efficiency. The model illustrates the strengths and weaknesses of local collective action. We suppose that agents belonging to local groups each decide how much to contribute to a public good, environmental quality. At a local level, each agent observes, imperfectly, the actions of their neighbors and can decide whether or not to punish them, in order to move the group towards a locally efficient level of quality. The main advantages of local action are that neighbors know each other, hence may have better information, and can levy punishments directly in utility terms. Even when people observe norms and contribute to environmental quality, these punishments impose a cost: because compliance is not perfectly observed, punishments are sometimes imposed needlessly.

The state can also coordinate collective action by taxing actions that lower environmental quality. The state cares about all externalities, even those that span different local groups. However, the state's signal of individual actions is likely to be worse than that of group insiders, and it has a limited ability to levy taxes. This limitation on environmental taxation is akin to the limits on revenue raising in the literature on tax capacity. Both local and state action are imperfect, due to their own constraints, and will fail to implement the efficient level of quality. Whether local (informal) or state (formal) collective action is better at managing environmental quality will depend on the relative importance of information, the capacity to tax, and the span of externalities within versus across groups.

Sections 6 and 7 consider empirical evidence on these regimes of informal and formal environmental regulation. Section 8 describes how political economy affects the supply of environmental quality.

1.1.3 What we do not cover in the chapter

The chapter is focused on micro-empirical evidence on environmental harms and environmental regulation in development economics. We emphasize literature from the last decade, since the publication of an earlier review on the topic by Greenstone and Jack (2015). For lack of space, and the limits of our own expertise, we exclude several important domains.

We do not cover the macroeconomic literatures on economic growth and the environment or international trade (Copeland, 2013; Balboni and Shapiro, 2025; Bilal and Stock, 2025). We also do not explicitly consider the dynamics of natural resources (Dasgupta and Heal, 1979). We do describe evidence on the flows of environmental services from natural resource stocks, like groundwater or forests, and discuss some issues specific to regulating stocks, but we do not explicitly model their dynamics.

We complement several recent reviews of adjacent literature, including the effect of economic development on the environment (Jayachandran, 2022) and adaptation to climate change (Carleton et al., 2024). We incorporate climate change as one important environmental hazard among a range of others. We complement, in this volume, Dupas (n.d.) on the persistent importance of physical, "first" geography features for economic development.

2 Stylized facts on the environment and development

What is different about the human relationship to the environment in developing countries? We begin by presenting stylized facts on the empirical relationships between economic development and environmental quality and proxies for individual exposure to environmental hazards.

2.1 Environmental quality is worse in low-income countries

We assemble consistent data for countries around the world on two key indicators of environmental quality: particulate matter ($PM_{2.5}$), to represent air quality, and biochemical oxygen demand (BOD), to represent water quality.[1]

Figure 1 shows particulate matter ($PM_{2.5}$) air pollution levels around the world. Particulate matter is one of the most widely studied and regulated pollutants. The correlation of $PM_{2.5}$ levels with economic development leaps off the map. Poor countries in West Africa, North Africa and South Asia have particulate matter levels that are starkly higher than in the United States or Europe. Middle-income countries in Latin America and Asia lie in between.

[1] $PM_{2.5}$ refers to particulate matter in which the particles have a diameter of 2.5 micrometers or less. Particles this small penetrate deeply into the lungs and brain. $PM_{2.5}$ therefore causes respiratory problems and accelerates mortality. BOD is biochemical oxygen demand, which measures the oxygen required to break down organic matter in water. When BOD is high, it indicates high levels of bacteria and other pathogens that may be harmful to humans.

Figure 2 plots the relationship between environmental quality and GDP per capita across countries and over time. Each curve segment shows the time path of the environmental quality indicator in the data over roughly the last two decades, with a dot at the most recent observation. The curve segment for each country therefore shows the within-country evolution of environmental quality for each country as it grows richer (moves to the right along a segment). The pattern across segments shows the across-country heterogeneity by levels of per capita income. Both scales are in logarithms. The sample is restricted to show only countries with a population above 50 million and countries with a population above 200 million are highlighted in blue.

There are three main take-aways from the figure. First, the disparities in air and water quality by levels of development are astonishingly large. Relative to the United States, major countries in Africa (Tanzania, Ethiopia, Kenya) and Southeast Asia (Thailand, Vietnam, Myanmar) have air quality about three times worse. Major countries in South Asia (Bangladesh, Pakistan, India) and some in Africa (Egypt, Nigeria) have air quality about seven times worse. These figures are population-weighted averages, but still understate the extremes of air pollution in dense, developing megacities. For water quality, the disparities are still very large, but not quite as extreme. Major countries in Africa (Tanzania, Nigeria, Kenya, Ethiopia) have water quality three times worse. Major countries in South Asia and East Asia (Pakistan, India, China) have water quality about six times worse than in the United States.

Second, both across and within countries, there is evidence of an inverted ∪-shape relationship of air pollution to economic growth. This shape is known as the environmental Kuznets curve (EKC), after the Nobel laureate Simon Kuznets's characterization of the cross-country relationship between income per capita and inequality. A large literature in the 1980s and 90s debated mechanisms and the empirical relevance of the EKC (e.g., Arrow et al., 1995; Shafik and Bandyopadhyay, 1992). This literature concluded that the inverted ∪-shape relationship failed to hold in longitudinal data for many countries and pollutants (Harbaugh, Levinson and Wilson, 2002). In our data, the relationship appears alive and well. For countries with the highest air pollution (Bangladesh, Pakistan, Egypt, India and Nigeria), pollution has continued to increase with GDP, though they are arguably close to inflection points. For other countries, including China, Korea, Vietnam, and Brazil, economic growth is clearly associated with an initial increase followed by a decline in pollution.

Table 1. Elasticities of Ambient Pollution with Respect to Income

	Pre-country inflection (1)	(2)	*Post-country inflection* (3)	(4)
Panel A: Air pollution $PM_{2.5}$ ($log_{10}(\mu g/m^3)$)				
log(Real GDP per Capita)	-0.20***	0.28***	-0.21***	-0.30***
	(0.011)	(0.018)	(0.0077)	(0.017)
Country FEs		Yes		Yes
Mean. dep. var at peak	1.39	1.39	1.20	1.20
R^2	0.13	0.97	0.23	0.97
Countries	175	175	168	168
Years	24	24	24	24
Panel B: Water pollution BOD ($log_{10}(mg/L)$)				
log(Real GDP per Capita)	-0.25***	0.44***	-0.26***	-0.25***
	(0.023)	(0.038)	(0.030)	(0.045)
Country FEs		Yes		Yes
Mean. dep. var at peak	0.38	0.38	0.44	0.44
R^2	0.058	0.97	0.053	0.97
Countries	133	133	112	112
Years	21	21	21	21

Notes: This table reports the coefficients from regressions of logged environmental indicators on income. In Panel A, air pollution is proxied by $PM_{2.5}$, a measure of the mass of particles in the air smaller than 2.5 micrometers. In Panel B, water pollution is estimated using biological oxygen demand (BOD), a measure of water quality which shows the amount of oxygen taken up in the decomposition of organic waste. We use a sample of countries split into pre-inflection and post-inflection observations. There are 205 countries in the full sample of panel A and 166 countries for panel B. We assign pre- and post- inflection based on whether an observation is before or after the local maximum of each individual country. Columns (1) and (2) report the coefficients for the pre-inflection regressions. Columns (3) and(4) report the coefficients for the post-inflection regressions. Standard errors are reported in parentheses. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

The environmental Kuznets curve for water quality looks less pronounced. There is some curvature across countries, whereby water quality first worsens and then improves with income (though this relationship is a poor fit for large countries with naturally abundant water, such as Brazil, Colombia and Russia). Within many countries, water quality has improved relatively little with economic development (Figure 2). In a few places (Kenya, Nigeria, Bangladesh), it has grown worse. In others (China, Korea, Germany), it has improved slightly. Pollution is diluted when mixed with rivers, lakes and streams. Water pollution is a concentration measure, of a pollutant mass divided by the volume of water. It may be that huge heterogeneity in the natural endowments of water, in the denominator, makes any component of water-quality driven by growth and human pollution harder to detect.

Table 1 estimates the elasticities of air pollution (panel A) and water pollution (panel B) with respect to GDP per capita. To capture the non-monotonic relationship between pollution and income, we split the sample by whether an observation is before the peak pollution level (inflection point) for each country (columns 1 or 2) or after that point (columns 3 and 4). If a country has not reached a peak yet, all observations are pre-inflection, and if it has passed its peak, all observations are post-inflection. In estimates without country fixed effects (column 1), the elasticity of pollution with respect to log per capita income across countries is -0.20 for air pollution and -0.25 for water pollution. Within-country fixed effects estimates (columns 2 and 4) show positive elasticities of 0.28 and 0.44, respectively, pre-inflection, followed by negative elasticities of -0.30 and -0.25 post-inflection. That is, pollution initially increases somewhat steeply with per capita income and then declines just as steeply after its peak. In the regressions, fewer countries contribute to both the pre- and post-inflection samples for water pollution than for air pollution (as fewer countries have observations on both sides of the inflection point for water). Yet, with this sample construction, the EKC for water, represented by the two estimated elasticities, has about the same shape as for air.

The above comparisons are all across countries. Any cross-country view of environmental quality will be coarse, as there is enormous heterogeneity in pollution emissions within countries due to the agglomeration of economic activity and differences in geography. Looking within low- and middle-income countries, air pollution is generally increasing in income (Behrer and Heft-Neal, 2024). This relationship is strongest in countries where most air pollution is anthropogenic and derives from economic activity. In Africa, where a greater share of air pollution is not anthropogenic (e.g. dust storms), Gollin, Kirchberger and Lagakos (2021) find that air pollution in 10 km^2 grid cells is about the same in more- and less-densely populated areas.

2.2 Natural resource stocks are heavily drawn in certain countries

Air and water quality are important dimensions of the flow benefits from the environment. Economic development also draws on environmental stocks of natural resources, as raw inputs for production or incidentally, by transforming land use for other purposes. Growth accounting omits the value of natural resource stocks and therefore overstates economic growth that is heavily resource dependent (Arrow et al., 1995, 2012).

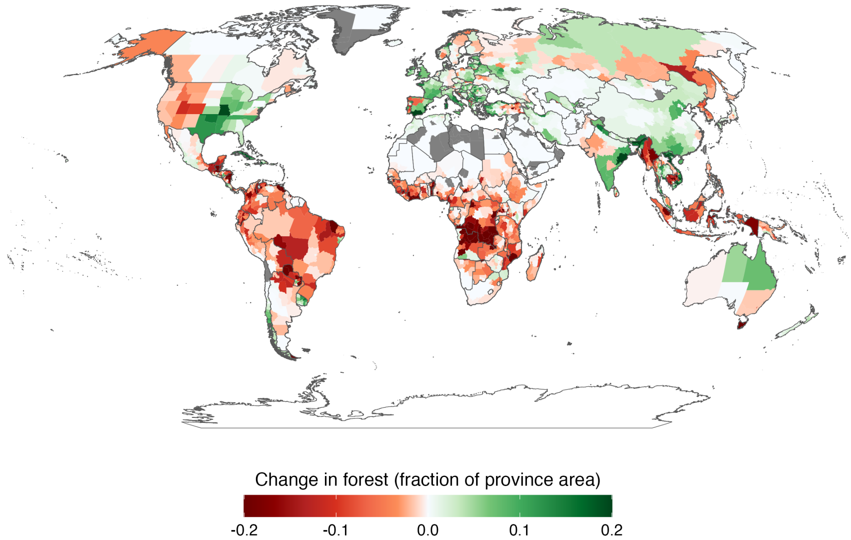
Figure 3 maps changes in forest cover from 1999 to 2019 (panel a) and groundwater (more broadly, terrestrial water) storage from 2002 to 2022 (panel b) around the world. Both of these natural resource changes capture a combination of human influence on the environment and natural regeneration; for example, groundwater stocks can rise because of unusually heavy rainfall, even if people are consuming a lot of groundwater.

With respect to forest cover, the relationship between income and net deforestation is complex. There is not an obvious trend with respect to per capita income, across the full range of the data, though many poor countries with high forest cover exhibit steady declines in forest with growth. These cases, like the Democratic Republic of the Congo (COD), Tanzania (TZA), Myanmar (MMR) and Indonesia (IDN), contribute a large portion of the gross decline in forest area in the world. However, there are also low- and middle-income countries that see increases in forest cover, including India (IND) and Thailand (THA), and rich countries that see declines, like South Korea (KOR). The complexity of the relationship of forest cover to income is due to multiple competing economic mechanisms through which growth affects land conservation and use (Foster and Rosenzweig, 2003).

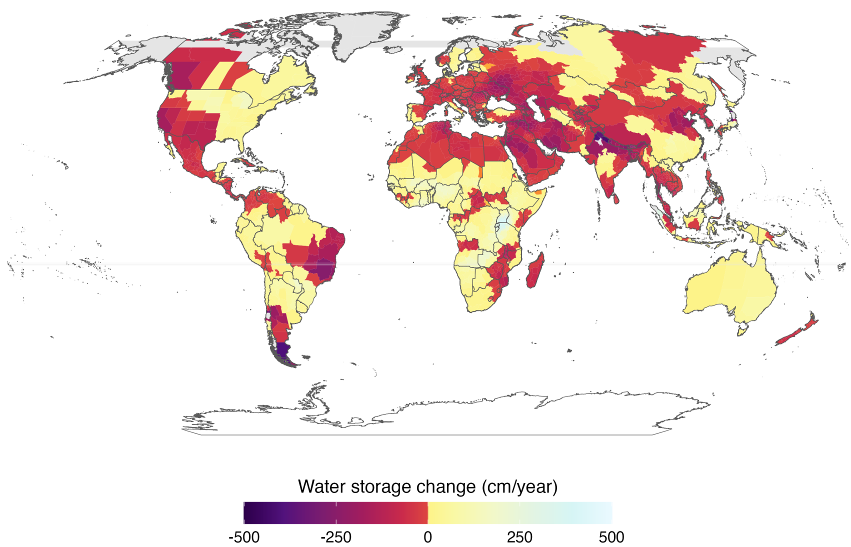
Similarly, with respect to groundwater storage, there is no simple story of growth drawing down groundwater stocks always and everywhere. Low-income countries see both the greatest gains and the greatest declines in groundwater storage (panel b). Many Central and East African countries see increases in groundwater storage over the last two decades (COD, ETH, TZA, KEN). By contrast, Middle Eastern (Iran, Turkey) and particularly South Asian (Pakistan, India, Bangladesh) countries have seen rapid declines in groundwater storage. The contrast, we hypothesize, is due to the interaction of water demand and the infrastructure for large-scale extraction. South Asian economies have linked agricultural growth to expanding groundwater use (Shah, 2010).

Figure 3. Natural resource stocks

(a) Forest cover changes



(b) Groundwater changes



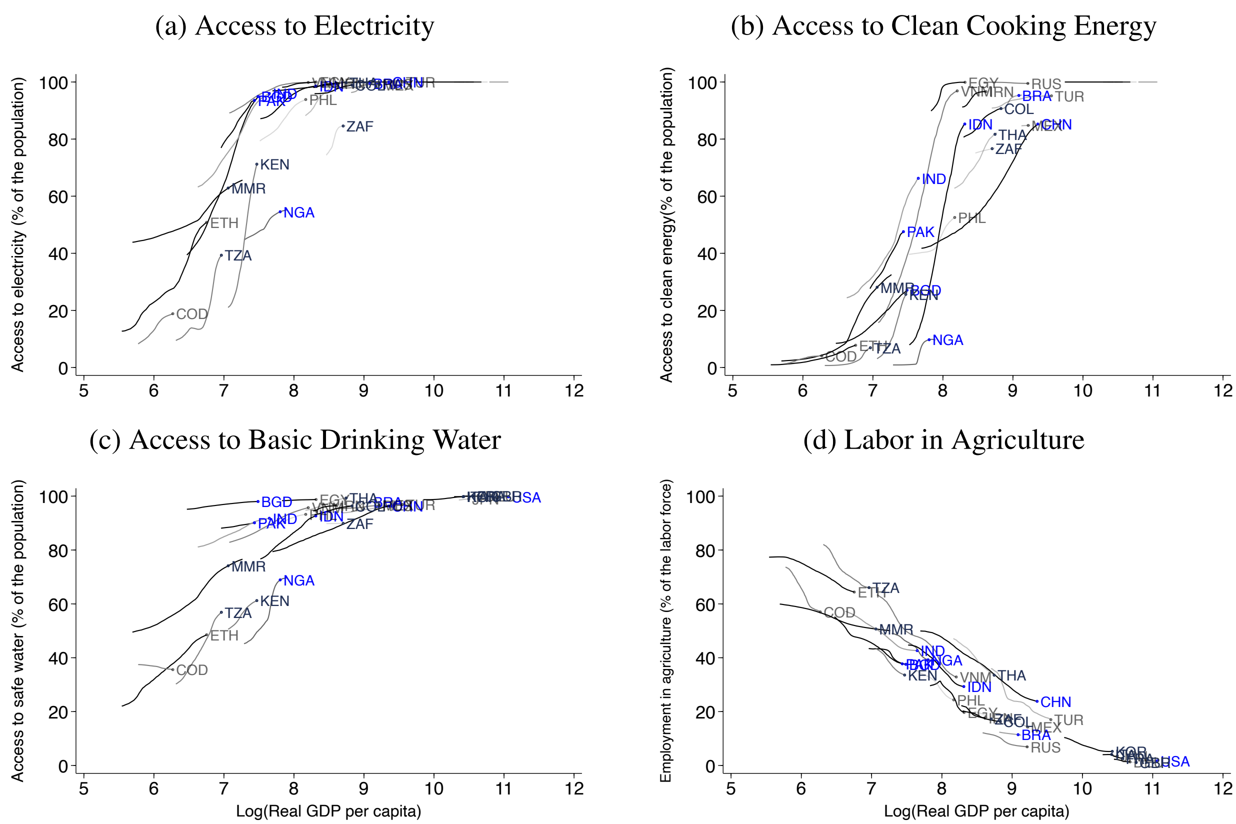
This figure shows the world map of forest cover and water storage changes at the province level. We plot the values at the country-province level using level 1 of the Global Adminstrative Areas (GADM) database. Panel 3a shows the long difference in changes in forest cover in each province as a fraction of province area. We use the Winkler et al. (2021) HILDA+ categorization of forest cover, isolate the forest pixels, calculate each pixel area and collapse across forest sub-categories. We then take the long difference in the forest fractions between 2019 and 1999. In Panel 3b, we calculate the cumulative changes in terrestrial water storage (TWS) from the GRACE dataset. The map shows the long difference between cumulative changes from 2002 to 2022 at the province level.

2.3 Exposure to the environment is greater in low-income countries

At a given level of environmental quality, people may be more or less exposed to environmental harms based on their jobs, how they live and their investments in self-protection. Figure 4 plots proxies for exposure to environmental harms using the same format as Figure 2. Panel a plots the share of households with access to electricity, panel b the share of households with access to clean energy for cooking (electricity or natural gas, as opposed to firewood or charcoal), panel c the share of households with access to basic drinking water, and panel d the share of employment in agriculture.

These access measures reflect both public investments (e.g., in the electricity grid) and private investments (e.g., purchasing an electricity connection). The consistent pattern across all exposure proxies is that people in poorer countries are much more exposed to environmental harms. For example, most countries where many households do not have access to electricity are in Africa, including the Democratic Republic of Congo, Ethiopia, and Tanzania (panel a). At a given level of air quality or temperature, households without access to electricity cannot run a fan, air purifier or air conditioner. They are therefore more exposed to any given ambient level of environmental quality, even as the level of environmental quality is worse, due to both high air pollution (Figure 2, panel a) and extreme temperatures (Figure 2, panel c). Panel b shows that use of modern energy sources for cooking, the single largest source of energy demand for poor households, is also low in Africa and South Asia. Using solid fuels for cooking exposes households to levels of indoor air pollution that can exceed the already high levels in outdoor air, exacerbating ambient exposure. A household without access to basic drinking water is more exposed to surface water pollution unless they take costly individual actions to reduce that exposure (panel c). Finally, someone working in an outdoor occupation is more exposed to temperature and air quality extremes than someone working in a climate-controlled office (panel d). The share of the population that works in agriculture offers a rough proxy for labor force exposure to temperature and pollution.

Figure 4. Exposure to environmental quality



The figure shows measures of exposure to environmental hazards. Panels (a) (b) and (c) show the proportion of individuals with access to electricity, clean energy and drinking water (World Bank, 2023*a*,*b*,*d*). Panel (d) shows the share of the population employed in agriculture (a proxy for outdoor occupations) (World Bank, 2023*c*).

2.4 Climate change will be most severe in low-income countries

The final salient environmental fact we highlight is that climate change will have the largest effects in countries that are already hot. Dupas (n.d.) notes in this volume that latitude has remarkable predictive power for income, with tropical countries having lower income per capita than non-tropical countries. There are few, small exceptions to this rule, which, as Dupas documents, has remained stable for decades.

In Figure 5, panel a, we plot the mean surface temperature of countries around the world. Most hot areas of the world, in Africa, the Middle East and South Asia, are low- or middle-income countries. Figure 5, panel b then plots the predicted change in cooling degree days (CDDs) by subnational region between the period 1960-1990 and the period 2035-2065 under the RCP 4.5 scenario. Cooling degree days are the most common non-linear measure of exposure to temperature extremes.[2] The RCP 4.5 scenario involves global emissions peaking around 2040 and declining thereafter and is more likely than not to result in global temperature rise between 2 °C and 3 °C by 2100. In panel b, we see that the increase in CDDs due to climate change is almost entirely concentrated in areas that are already hot, including tropical portions of South America, Africa, the Middle East and South Asia. Most rich countries, for example in Europe, see at most one-quarter of the rise in extreme temperature exposure as do these low- and middle-income areas.

The combination of higher initial temperatures, greater increases in temperature extremes and non-linear damages from climate change imply that LMICs will suffer much greater economic losses from climate change than will richer countries with more temperate climates (Burke, Hsiang and Miguel, 2015). In this chapter, we will consider the microeconomic mechanisms for these damages and individual-level responses to climate change alongside response to other environmental harms. Carleton et al. (2024) offer a review exclusively focused on climate adaptation.

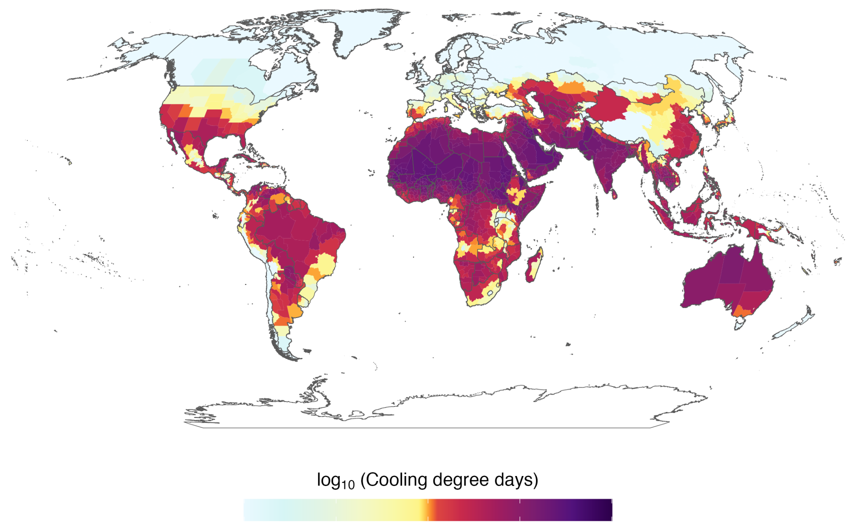
[2] The formula for cooling degree days in a year is

$$CDD_y = \sum_{d=1}^{365} \max\{t_d - 25, 0\}$$

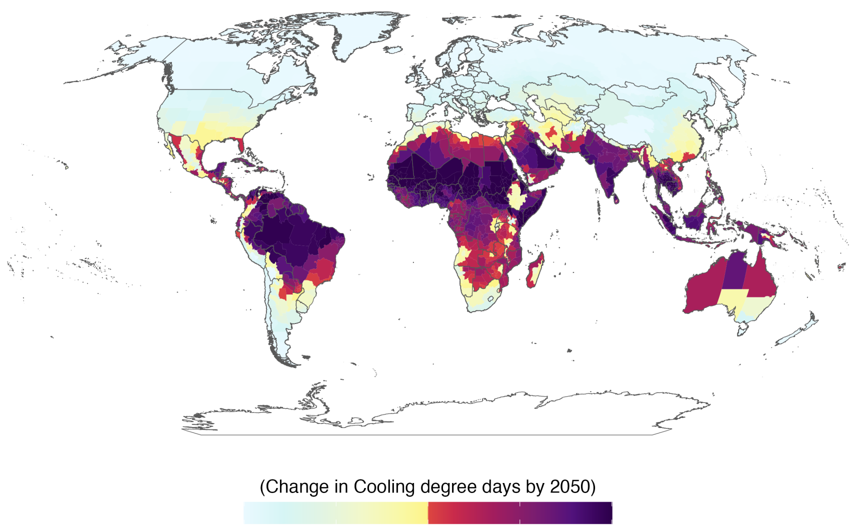
where t_d is the maximum temperature on day d. That is, a single day at 30 °C contributes 5 CDDs to the annual sum while a day at 20 °C contributes none.

Figure 5. Climate Change

(a) Cooling degree days



(b) Projected change in cooling degree days



This figure shows the world map of cooling degree days at GADM adminstrative level 1 in both panels. Panel (a) shows the map of the log of cooling degree days in 2018, using $25°C$ as the base temperature (Mistry, 2019). The maximum and minimum values on the map represent ≤ 0 and ≥ 4 log cooling degree day respectively. In panel (b), we show the projected change in cooling degree days using a data product of the RCP 4.5 scenario (Gassert, Cornejo and Nilson, 2021). The change here represents the difference between the 31-year average change in 2035-2065 and 1960-1990. We report the CDDs at a threshold temperature of $65°F$, the only base temperature available for this product.

These data demonstrate that environmental quality is much worse in low- and middle-income countries and that people in these countries are much more exposed to the environment. Natural resource depletion is heterogeneous across countries but in some prominent low-income cases, it is very rapid. These physical facts motivate the study of how the environment aids or hinders development as well as the feedback from economic development to environmental quality.

3 Model of the environment and individual adaptation

We model how environmental quality affects people and how, in turn, they adapt to environmental hazards. In this model, the environment enters utility directly and through effective labor supply. The production of goods for consumption degrades environmental quality. People can protect themselves against harm by consuming adaptation. The main results of the model are expressions that decompose the willingness-to-pay for environmental quality into component parts, which we use to guide the empirical review. There is no state or other means of collective action here. In Section 5, we model how regulation can change environmental quality.

3.1 Model set-up

3.1.1 Environment

Environmental quality $\hat{\mathbf{e}}$ has components e_k, indexed by $k \in \{1,\ldots,K\}$. These components generate environmental services that humans value (Assessment, 2001). For example, clean air and water generate health services. Biodiversity generates disease regulation and pollination services. Some e_k can represent natural resource stocks that produce a flow of services, such as groundwater extracted for use in agriculture. We do not explicitly consider the dynamics of these stocks (Dasgupta and Heal, 1979). This restriction is with loss because the consumption of flow environmental services from such stocks has an opportunity cost in terms of future use.

Environmental quality at a point in time is the sum of a baseline endowment of environmental quality and the contribution of human activity to the environment

$$\mathbf{e} = \mathbf{e}_0 + \Delta\mathbf{e}. \tag{1}$$

The baseline endowment $\mathbf{e}_0$ is given exogenously. We describe how human activity contributes $\Delta\mathbf{e}$ to environmental quality below, with the supply side of the model.

People i *experience* a level of environmental quality $\hat{e}_k$ that may differ from the *ambient* environmental quality e_k. For example, if I drive in an air conditioned car, I experience $\hat{e}_{k=climate} > e_{k=climate}$. Similarly, I may treat my drinking water or purify the air in my home. The relationship between experienced and ambient environmental quality is given by

$$\hat{e}_k = d_k(e_k, a_i) \tag{2}$$

for each element k. Here a_i is person i's consumption of adaptation, or just adaptation. We assume that experienced quality is weakly increasing in ambient quality $\partial d_k/\partial e_k \geq 0$ and in adaptation $\partial d_k/\partial a_i \geq 0$. We also expect that the cross partial $\partial d_k/(\partial e_k \partial a_i) \leq 0$, such that adaptation has a smaller effect on environmental quality when quality is already high.

3.1.2 Demand

People, or households, have utility over environmental quality $\hat{\mathbf{e}}$ and consumption goods $\mathbf{c}$. The consumption goods vector $\mathbf{c}_i \geq \mathbf{0}$ contains J elements indexed by $\{c_j\}_{j=1}^{J}$ with prices p_j. A person's decision problem is to choose a bundle of consumption goods that solves

$$\max_{\{c_{i,j}\}, a_i} \quad U(\mathbf{c}_i, \hat{\mathbf{e}}) \tag{3}$$

subject to the production of experienced environmental quality

$$\hat{\mathbf{e}} \;\; = \;\; d(\mathbf{e}, a_i), \tag{4}$$

and the budget constraint

$$w\ell_i(\hat{\mathbf{e}}) + \omega_i \geq p_a a_i + \sum_{j=1}^{J} p_j c_j. \tag{5}$$

We assume throughout that the utility function $U(\mathbf{c}_i, \hat{\mathbf{e}})$ is non-decreasing and concave in all arguments. People enjoy higher environmental quality and more consumption. Adaptation has a price in money p_a. The adaptation choice acts through expenditures rather than as a utility cost (for example, forgoing a trip to the park). In practice, adaptation costs plainly take both forms.

The environment therefore affects utility in two ways. First, people directly value environmental services. When choosing consumption, people may or may not expect that their consumption changes environmental quality.

Second, environmental quality enters labor supply and therefore earnings in the budget constraint. Labor supply $\ell_i(\hat{\mathbf{e}})$ depends on exposure. Those with indoor work are relatively insulated from ambient environmental quality, while workers in sectors such as agriculture or construction may become less productive when environmental quality decreases. We assume $\ell_i(\hat{\mathbf{e}})$ is increasing, strictly concave, and bounded between zero and $\bar{\ell}$.

3.1.3 Supply

Firms produce good j with a vector of inputs $\mathbf{x}$ using a sector-specific technology

$$Y_j = F_j\left(\mathbf{x}_j\right) \tag{6}$$

which is homogeneous of degree one in the set of factor inputs $x \in \mathbf{x}$. Firms purchase these intermediate inputs at prices $\mathbf{p}^x$ from perfectly elastic suppliers. The market for final goods is competitive in each sector j such that each industry can be thought of as operating as a representative firm. Taking prices as given, the representative firm in sector j chooses a level of inputs that solves

$$\pi_j = \max_{\mathbf{x}_j} \left\{ p_j F_j\left(\mathbf{x}_j\right) - \mathbf{p}^x \cdot \mathbf{x}_j \right\}. \tag{7}$$

These input choices, in equilibrium, lead to zero profits for each representative firm.

Producing one unit of good j induces a change $\Delta\mathbf{e}_j$ in environmental quality. Each element k captures the constant marginal effect that producing j has on environmental service k, such as coal-fired electricity affecting air quality. The aggregate environmental effects of production in all sectors are given by

$$\Delta\mathbf{e} = \sum_{j=1}^{J} \Delta\mathbf{e}_j Y_j \tag{8}$$

Since production changes environmental quality, people's consumption choices feed back to environmental quality through (1).

3.1.4 Equilibrium

We assume there is a unit mass of consumers $i \in [0,1]$ facing the problem (3).

Definition (Equilibrium of the environmental quality game)**.** *A partial equilibrium consists of endowments ω_i and consumption bundles $\{\boldsymbol{c}_i\}$ for all individuals $i \in [0,1]$, final goods prices $\{p_j\}_{j=1}^{J}$ and intermediate goods purchases $\boldsymbol{x}_j$ for each firm, and equilibrium environmental quality $\hat{\boldsymbol{e}}$, such that consumption bundles solve the decision problem in* (3) *subject to each individual's budget constraint, firms' factor demand solves* (7)*, and markets for consumption goods clear.*

The equilibrium is partial because we do not require that the labor market or the markets for firm inputs clear.

3.2 Model results

We first compare the first-best level of demand with the demand from private consumption choices. We then characterize willingness-to-pay for environmental quality.

3.2.1 Efficiency of household consumption choices

Definition (Socially-efficient consumption choices)**.** *Socially efficient consumption choices necessarily satisfy the system of first-order conditions given by*

$$\begin{aligned}
\underbrace{\lambda_i^* p_j}_{\text{Direct Cost}} = & \underbrace{\frac{\partial U(\boldsymbol{c}_i,\hat{\boldsymbol{e}})}{\partial c_{i,j}}}_{\text{Private benefit of consumption}} \\
& + \int_{\iota\in[0,1]} \underbrace{\sum_k \frac{\partial U(\boldsymbol{c}_i,\hat{\boldsymbol{e}})}{\partial \hat{e}_k}\frac{\partial d_k(e_k,a_i)}{\partial e_k}\Delta e_{jk}\,d\iota}_{\text{Social environmental utility}} \\
& \underbrace{+ w\int_{\iota\in[0,1]} \lambda_\iota^* \sum_k \frac{\partial \ell_\iota(\hat{\boldsymbol{e}})}{\partial \hat{e}_k}\frac{\partial d_k(e_k,a_i)}{\partial e_k}\Delta e_{jk}\,d\iota}_{\text{Social environmental productivity}}
\end{aligned} \tag{9}$$

where λ_i^* is the Lagrange multiplier attached to the planner's constraint on i's budget.

The planner sets the direct utility cost of the good equal to the marginal utility of consumption adjusted by two environmental terms. The first environmental term is social environmental utility. This is the aggregate social utility loss due to i's consumption of good j, which decreases environmental quality through production. The second term is social environmental productivity, or the loss that i's consumption of good j causes for the productivity, and therefore budgets, of all people together. Again, this is due to the effect of i's consumption choices on environmental quality through production.

For the purpose of considering private consumption choices, suppose that a person i expects their consumption will affect dimensions $k \in K_{int}$ of environmental quality but not $k \in K_{ext}$. For example, K_{int} may include air pollution in my home, if I cook with charcoal, and K_{ext} global climate change.

Definition (Privately-optimal consumption choices)**.** *Privately optimal consumption choices necessarily satisfy the system of first-order conditions given by*

$$\begin{aligned}
\underbrace{\lambda_i p_j}_{\textit{Direct cost}} \quad = \quad & \underbrace{\frac{\partial U(\boldsymbol{c}_i, \hat{\boldsymbol{e}})}{\partial c_{i,j}}}_{\textit{Private benefit of consumption}} \\
& + \underbrace{\sum_{k \in K_{int}} \frac{\partial U(\boldsymbol{c}_i, \hat{\boldsymbol{e}})}{\partial \hat{e}_k} \frac{\partial d_k(e_k, a_i)}{\partial e_k} \Delta e_{jk}}_{\textit{Own environmental utility}} \\
& + \underbrace{w\lambda_i \sum_{k \in K_{int}} \frac{\partial \ell_\imath(\hat{\boldsymbol{e}})}{\partial \hat{e}_k} \frac{\partial d_k(e_k, a_i)}{\partial e_k} \Delta e_{jk}}_{\textit{Own environmental productivity}}
\end{aligned} \tag{10}$$

where λ_i is the Lagrange multiplier on i's budget.

There are two differences between i's consumption problem and the planner's consideration of i's problem. First, the planner considers the environmental costs of i's consumption for all other people. That consideration will tend to make social environmental utility and social environmental productivity much larger (more negative) than own environmental utility and productivity, which implies lower consumption of $c_{i,j}$ than i would choose on their own, and correspondingly higher environmental quality (in the leading case where the Δe_{jk} are negative). Second, i may also assume that their consumption does not affect some dimensions $k \in K_{ext}$ of environmental quality. For dimensions of environmental quality that depend on many sources of emissions, like ambient air quality, this assumption will be nearly right, in that one person's contribution to overall quality will be small.

3.2.2 Adaptation choice and willingness-to-pay for environmental quality

A main purpose of modeling adaptation is to understand how this choice reflects people's valuations of the environment. An important empirical literature measures the willingness-to-pay for environmental quality using revealed preferences for adaptation.

Here, we discuss the assumptions needed for revealed preference estimates to approximate the marginal value of environmental quality. The marginal utility of a change in environmental quality, measured in money units, measures a person's willingness-to-pay for environmental quality. This WTP for quality is equivalent, at the margin, to the monetary value she places on avoided damages. The marginal WTP for environmental service e_k is

$$\mathrm{WTP}(e_k) = \underbrace{\frac{1}{\lambda_i} \frac{\partial U(\mathbf{c}_i, \hat{\mathbf{e}})}{\partial \hat{e}_{i,k}} \frac{\partial d_k(e_k, a_i)}{\partial e_k}}_{\text{Marginal utility of } e_k} + \underbrace{w \frac{\partial \ell_i(\hat{\mathbf{e}})}{\partial \hat{e}_{i,k}} \frac{\partial d_k(e_k, a_i)}{\partial e_k}}_{\text{Marginal income due to } e_k} \tag{11}$$

where λ_i is the Lagrange multiplier on her budget constraint (5).

We cannot estimate (11) because it is not possible to observe utility, or changes in marginal utility, directly. Empirical studies typically use the observed choices of adaptation expenditures to reveal (11). People choose their privately optimal level of adaptation, to solve

$$\underbrace{p_a}_{\text{Price}} = \underbrace{\frac{1}{\lambda_i} \sum_{k \in K_{int}} \frac{\partial U(\mathbf{c}, \hat{\mathbf{e}})}{\partial \hat{e}_{i,k}} \frac{\partial d_k(e_k, a_i)}{\partial a_i}}_{\text{Marginal utility of adaptation}} + \underbrace{w \sum_{k \in K_{int}} \frac{\partial \ell_i(\hat{\mathbf{e}})}{\partial \hat{e}_{i,k}} \frac{\partial d_k(e_k, a_i)}{\partial a_i}}_{\text{Marginal income from adaptation}}. \tag{12}$$

Demand for adaptation depends on the effectiveness of a_i in improving $\hat{e}_k$, which differs widely for different dimensions of environmental quality. A sufficient level of treatment can turn sewage into potable water. It may be prohibitively costly, however, to protect oneself from poor ambient air quality outside. If adaptation is relatively ineffective, such that $\partial d_k / \partial a_i$ is small, then the marginal utility of $\hat{e}_k$ will be large, implying that people are stuck with consuming a low level of $\hat{e}_k$, closely tied to ambient quality.

The equation (12) is widely used as the basis for empirical analysis to estimate the effect of the environment on utility. We can observe the tight parallels between the marginal WTP for environmental quality (11) and the optimal choice of adaptation expenditures (12). Both expressions depend on the marginal utility and the marginal income from improving experienced environmental quality. The left-hand side of (12) can be directly observed in the data. The marginal income from adaptation is also, in principle, estimable with exogenous variation in adaptation (for example, offering discounted water filters or air purifiers).

However, the differences between these expressions also point to a number of factors that complicate the use of adaptation as a proxy for the WTP for environmental quality:

- *Adaptation does not change e_k itself.* The goal is to measure WTP for a change in ambient environmental quality, whereas the WTP for adaptation acts on $\hat{e}_k$ indirectly. Translating this relationship requires understanding the $d(e_k, a_i)$ function to judge the extent to which adaptation approximates a change in environmental quality. (For example, is purifying the air in your apartment the same as having clean air for a whole city? If you spend 12 hours a day at home, is it half as valuable?)

- *Adaptation is local (i.e., concerned with small changes).* Because each person privately takes environmental quality e_k as given when deciding a_i, the value of adaptation is strictly local. We rule out the possibility of coordination (on which see Section 5). People may place a high value on a clean neighborhood but little value on, say, not throwing their trash in the gutter if others are already doing so.

- *Multi-dimensional adaptation.* Adaptation may change multiple measures of environmental quality at once. WTP is therefore measured for a bundle of such changes. Moreover, a_i is assumed not to enter utility directly. However, many adaptive actions, like moving to a new neighborhood, affect e_k but also enter utility directly.

- *Implicit full information assumption.* Households are assumed to choose a_i in full knowledge of $\partial U / \partial \hat{e}_k$ and $\partial d_k / \partial a_i$. But households may know neither the benefits of environmental quality for utility nor the effect of an action on environmental quality. For many environmental domains, the damages that determine $\partial U / \partial \hat{e}_k$ accrue over a lifetime and are realized far in the future.

- *Implicit complete markets assumption.* We assume that households have access to a market for a and that their purchases of a_i reflect their true WTP for environmental quality. However, purchases of a_i often take the form of *investments* in protection that yield some future stream of returns. Households may be credit constrained and unable to purchase the level of a_i they would wish, based on their own lifetime income. In that case, households may solve (12) with some constrained $\lambda_i' > \lambda_i$. This results in a low revealed willingness-to-pay for adaptation, despite high marginal utility from experienced environmental quality.

In broad terms, how well adaptation expenditures (ability-to-pay) reveal marginal benefits from environmental quality depends on both the technology for adaptation and the absence of other market failures (of information, credit, and the like) that may impinge on efficient investments.

Beyond these practical criticisms, the above discussion assumes that ability-to-pay based on lifetime income is an appropriate proxy for utilitarian social welfare. Society may not conceive of welfare in this way. In a capabilities approach, it may be seen as unjust that a person's health and well-being are at risk through external environmental harms. Governments may place a high per se value on environmental protection for people who cannot protect themselves.

3.3 Discussion

While we do not model regulation, the model of individual action here has implications for public choice over regulation as well.

First, in this model the willingness-to-pay for environmental quality will increase in income.[3] As people grow richer, their marginal utility from private goods consumption declines, and they place relatively higher marginal value on environmental services. This observation is consistent with the WTP for environmental protection (adaptation) increasing in income in micro-economic

[3] Totally differentiating (11) in wealth ω_i gives that WTP(e_k) is

$$\frac{d\mathrm{WTP}(e_k)}{d\omega_i} = -\frac{1}{\lambda_i}\left[\underbrace{\frac{\partial \lambda_i}{\partial \omega_i}}_{<0 \text{ by concavity}} \frac{1}{\lambda_i}\left(\frac{\partial U(\mathbf{c}_i,\hat{\mathbf{e}})}{\partial e_k}\right)^{-1} + \left(\frac{\partial U(\mathbf{c}_i,\hat{\mathbf{e}})}{\partial e_k}\right)^{-2}\sum_{j=1}^{J}\frac{\partial c_{i,j}}{\partial \omega_i}\left(\underbrace{\frac{\partial^2 U(\mathbf{c}_i,\hat{\mathbf{e}})}{\partial c_{i,j}\partial e_k}}_{\leq 0 \text{ by substitutability}} + \underbrace{\Delta \mathbf{e}_j \cdot \nabla^2_{\mathbf{e}} U(\mathbf{c}_i,\hat{\mathbf{e}})}_{<0 \text{ by concavity}}\right)\right] > 0. \tag{13}$$

The marginal utility of wealth λ_i is decreasing in c_j because utility is concave in all arguments. The inequality (13) then holds if consumption and environmental goods are weak substitutes.

studies (e.g., Ito and Zhang, 2020; Berry, Fischer and Guiteras, 2020). It is also consistent with the downward-sloping portion of the environmental Kuznets curve, wherein people at high levels of income demand, and regulators provide, improvements in environmental quality. However, the aggregate EKC does not really discipline WTP for environmental quality, because observed equilibrium pollution also depends on the supply of environmental quality. The supply of environmental quality depends on industrial composition and the capacity of the state to regulate, both of which also vary with income.

Second, inadequate public regulation will drive demand for adaptation. In a laissez faire equilibrium where people choose consumption privately, the levels of environmental quality e_k will be lower than what the planner would choose. When public provision of e_k is low, the marginal value of $\hat{e}_k$ will be high and so people will have a high willingness-to-pay for (effective) adaptation. This finding assumes that utility is concave in experienced environmental quality. In our set-up, marginal improvements in environmental quality will have the greatest effect on utility at low levels of ambient environmental quality, just as the marginal utility of consumption decreases with consumption. In practice, it is not clear if the marginal utility of $\hat{e}_k$ is decreasing in environmental quality; some frontier research on air pollution suggests the opposite.[4] In general, environmental damages are heterogeneous across people not only by income and environmental quality but on many other dimensions (Hsiang, Oliva and Walker, 2019).

Third, conversely, private choices of adaptation will shape the appropriate social choice of regulation. For certain dimensions of environmental quality e_k, such as the quality of drinking water, it may be that $\partial d_k/\partial a_i$ is large and people can protect themselves at a reasonable cost. If so, the value of further improvements in ambient environmental quality, measured by (11), will be low. The state may refrain from collective action where private protection works well enough.

[4] Both Miller, Molitor and Zou (2024) and Heft-Neal et al. (2023) use wildfire events in the United States as a source of variation in health. These studies find evidence for concave "concentration-response" curves. This terminology, distinct from the more standard "dose-response" curve, acknowledges that many factors drive a wedge between ambient quality (concentration) and individual exposure (dose). Concave damages from air pollution would suggest that the marginal benefits of improving environmental quality are *increasing* in environmental quality.

4 Evidence: Environmental damages and individual adaptation

How does environmental quality affect health, productivity and well-being? How do people value these impacts, as in equation (11)? How much should a planner be willing to pay to improve environmental quality, as in equation (9)?

Two main approaches are used to answer these questions. The first, epidemiological approach, estimates the direct effects of environmental quality on measures of health or productivity. For example, hospital visits, asthma cases or mortality. Economists have increased the credibility of this approach by relying on causal inference methods to reduce the bias from omitted variables that affect both environmental quality and health (Currie et al., 2013). The main limitation of this approach is that it captures an incomplete measure of the costs of environmental harms, because direct damages to health omit the costs people incur to adapt to poor environmental quality. To be useful for welfare or cost-benefit analysis, the direct effects of environmental quality must be converted into monetary units.

The second, economic approach, relies on revealed preference based on people's own choices of environmental quality e_k or of adaptation a_i to infer a valuation for the environment (Mendelsohn, 2019). This approach has the advantage of being theoretically complete, as it can encompass both direct and indirect benefits of environmental quality. Revealed preference based on expenditures are measured directly in money units and based on time use are easily converted to money units. The economic approach, like the epidemiological approach, obtains credibility from causal inference methods. However, in addition, it requires that people can make meaningful choices over environmental quality; in reality, they often cannot. Applying the economic approach is hard because of the practical limitations discussed in Section 3.

The epidemiological and economic approaches can, and do, yield wildly different estimates for the harms of poor environmental quality in developing countries. The first approach yields large, causal effects of environmental quality on health, mortality and productivity (Section 4.1). The second approach, where it has been applied, yields positive, precise, but quite small estimates of the demand for environmental quality (Section 4.2). In a few, powerful settings, we can measure both the direct effects of environmental quality and the revealed valuation of environmental quality at the same time. From these studies, it seems that people do not value the environment as much as the damage estimates suggest they should. The economic approach to environmental valuation appears to yield low valuations because it fails to surmount the many constraints on choice, including credit, information and other market failures, that are widespread in low-income countries. It also may be that the costs of adaptation assumed by researchers omits important learning costs or other factors that go beyond market prices.

4.1 Direct estimates of damages from poor environmental quality

In Section 3, health is not explicitly modeled, but instead contributes to the utility from experienced environmental quality, $\partial U(\mathbf{c}_i, \hat{\mathbf{e}})/\partial \hat{e}_k > 0$. Health also enters the individual problem through effective labor supply, $\partial \ell_\iota(\hat{\mathbf{e}})/\partial \hat{e}_k$. The direct approach measures damages through these arguments to the individual's utility and budget constraint.

We note at the start the two main limitations of this epidemiological approach. First, it omits the costs of adaptation. People adapt to changes in environmental quality through a_i to mitigate harms to utility, including to health and productivity. Estimates of the direct effect of environmental quality changes cannot hold constant adaptation. Therefore, these estimates are net of adaptation and represent a lower bound, which excludes costly private adaptation, on total damages (Carleton et al., 2022). The resulting bias from the omission of adaptation depends on the setting and the time horizon of people's responses.[5] Ironically, the more effective is adaptation, the more people will employ it to mitigate poor environmental quality, and the more we may wrongly conclude that an environmental insult imposes only small costs.

The second limitation of the epidemiological approach for economic purposes is that it measures damages in physical units. To compare these damages to the costs of improving environmental quality, or to the benefits of other policies, it is necessary to monetize them—to measure damages in money units. The typical approach to monetize damages to health or mortality is to use a value of statistical life (VSL), which itself may be inferred from choices people make over more-or-less risky alternatives (León and Miguel, 2017). Therefore, even "direct" estimates of

[5] A few papers measure direct effects of environmental quality on health spending. For example, Barwick et al. (2024*a*) use payment network data in China to analyze the relationship between healthcare spending and pollution shocks. Measuring direct market spending on health offers a second, distinct lower bound on the cost of pollution on health and therefore complements measurements of effects on health.

damages rely on revealed preference to be monetized. This aspect of environmental valuation is controversial because revealed values for health and life will depend to a large extent on people's income (Hammitt, Liu and Liu, 2022). In addition, reliable VSL estimates from low income settings remain few and far between (Killeen, 2025).

4.1.1 Health damages

Exposure to pollution, extreme temperatures, and other environmental hazards makes people sick and shortens their lives (Landrigan et al., 2018). Myriad studies of single, distinct environmental hazards, such as particulate matter air pollution, surface water pollution, extreme heat or changes in the disease environment, each find large impacts on mortality and health. (See Brewer, Dench and Taylor (2023) for a review of the empirical evidence on the relationship between pollution and health and Lemoine, Hausman and Shrader (2025) for a review of climate damages, including health.)

Table 2 highlights selected evidence from LMICs on the magnitude of environmental damages. Burgess and Greenstone (2017) document that just a single additional day per year above 95° F, relative to a reference temperature, increases all-cause mortality in rural India by 0.74%. These effects are concentrated in rural areas, where livelihoods are dependent on growing conditions. Extreme heat kills people directly, and it also undermines sources of income, killing them indirectly when crops fail. Infants are particularly vulnerable to heat. Across 53 low and middle income countries, a single additional day with a wet bulb temperature above 95° F increases infant mortality by 0.74 deaths in 1000 (Geruso and Spears, 2018). Air pollution also kills both adults and infants. In China, long run exposure to total suspended particulate (TSP) levels reduces life expectancy by a full three years, for a 100 $\mu g/m^3$ increase in pollution (Chen et al., 2013). Birth cohort size falls by 12% for a one standard deviation increase in upwind agricultural fires in Brazil (Rangel and Vogl, 2019).

Households that lack access to piped and treated water are also exposed to poor water quality. Increasing water pollution by a single point on a seven point quality scale is linked to a 22% higher risk of digestive cancers among adults in China (Ebenstein, 2012). In cases where environmental quality has improved, health improves alongside it. For example, water quality improvement in India by 0.24 log biochemical oxygen demand reduced infant mortality by 19.5% (Do, Joshi and

Stolper, 2018). Table 2 documents other cases that we discuss in greater detail below. While this is a selected set of studies, chosen to highlight the range of environmental hazards and populations covered by the literature, the magnitudes are not outliers. The overwhelming message is that poor environmental quality has profound effects on morbidity and mortality in LMICs.

Table 2. Selected evidence on health damages

Harm	Δe	Damage	Population	Method	Reference
Temperature	$\uparrow$ 1 day >95F	$\uparrow$ 0.74% mortality	All ages in India	TWFE	Burgess and Greenstone (2017)
Temperature	$\uparrow$ 1 day >85F (wet bulb)	$\uparrow$ 0.74 deaths per 1000	Infants in 53 countries	TWFE	Geruso and Spears (2018)
Air pollution	$\uparrow$ 100 $\mu g/m^3$ TSP	$\downarrow$ 3 years life expectancy	Adults in China	RD	Chen et al. (2013)
Air pollution	$\uparrow$ 1SD in agricultural fires	$\downarrow$ 12% birth cohort size	Infants in Brazil	TWFE	Rangel and Vogl (2019)
Water pollution	$\uparrow$ pollution index	$\uparrow$ 22% digestive cancer	Adults in China	2SLS	Ebenstein (2012)
Water pollution	$\downarrow$ 0.24 log BOD	$\downarrow$ 19.5% mortality risk	Infants in India	DiD	Do, Joshi and Stolper (2018)
Forest loss	$\downarrow$ 1 SD forest cover	$\uparrow$ 9.3% mortality rate	Infants in Nigeria	FE	Berazneva and Byker (2024)
Species loss	Vulture extinction	$\uparrow$ 4.7% mortality	All ages in India	DiD	Frank and Sudarshan (2024)

Notes: Damages from select environmental harms. Changes in environmental quality have not been standardized beyond what is reported in the individual publications. Methods are as follows: TWFE is two-way fixed effects, RD is regression discontinuity, 2SLS is two-way least squares, DiD is difference in difference, FE is fixed effects.

The magnitudes in Table 2 are high relative to comparable findings in high income countries, where the evidence base is much larger. What can account for this difference? First, in low-income countries, pollution concentrations are often much higher, which could lead to higher or lower marginal damages, depending on the curvature of the experienced dose-response curve (Arceo, Hanna and Oliva, 2016; Hsiang, Oliva and Walker, 2019; Miller, Molitor and Zou, 2024). Second, baseline levels of health are lower in low-income countries. The effects of exposure to poor environmental quality may then be worse, as implied by models of health as a capital stock, in which mortality is represented as crossing a threshold level of health from above (Grossman, 1972; Deryugina and Reif, 2023). Alternatively, it may be that environmental hazards and non-environmental hazards (e.g., infectious disease, road accidents) are competing risks, which would imply that environmental hazards are less important as determinants of mortality. Third, because adaptation (a_i) is latent in estimates of the "direct" relationship between ambient pollution concentrations and health, a higher willingness-to-pay for adaptation at high levels of income (equation (12)) will bias downward estimates of damages from high income settings. A naïve application of estimates from a rich setting, where adaptation is affordable, to a poor one, where it is not, may lead to the wrong conclusion that environmental hazards are not harmful. For all these reasons, pollution impacts on health measured in high income countries may not generalize to poorer ones.[6]

Another difference between high and low income settings is the quality and availability of data. The challenges of measuring environmental quality and health outcomes in developing countries has spurred innovation in measurement and methods. Jayachandran (2009) is an early and creative example of measuring the health impacts of pollution in a low-income country, specifically the effect of particulate matter air pollution on infant mortality in Indonesia. The creativity is on demand, to fill data gaps. To overcome a lack of vital statistics data on mortality, Jayachandran (2009) uses the size of birth cohorts from census data as the principal outcome. To overcome a lack of pollution monitoring data, the paper turns to satellite measures of particulate concentrations. The paper finds that prenatal and neonatal exposure to smoke from large wildfires in 1997 decreased the size of birth cohorts by 1.2%, roughly a 20% increase in the baseline under-three mortality rate. The decrease in cohort size is estimated to be twice as large in districts in the bottom quartile

[6] Colmer et al. (2021) provide some evidence that levels of income matter more for estimates of the health damages of particulate matter air pollution than does the level of pollution.

of the income distribution as the top quartile, and also higher for households that cook with solid fuel, a proxy for baseline pollution exposure.

Rapid improvements in the quality of satellite data have been transformative for environmental research in otherwise data poor settings. As one example, the satellite data used by Jayachandran (2009), from the Earth Probe Total Ozone Mapping Spectrometer (TOMS), were on a 175 km grid, while contemporary satellite proxies for air pollution have 10 km resolution (van Donkelaar et al., 2024). Good satellite proxies for environmental quality have exploded. Papers use satellites to measure air pollution, land use change, heat, precipitation, floods and other natural disasters (Heft-Neal et al., 2020; Jain, 2020; Balboni, Burgess and Olken, 2025; Jack et al., 2025; Patel, 2025). A main limitation of remotely-sensed measures is that they are not as finely resolved or accurate as ground-level measures. They also do not measure many dimensions of environmental quality e_k. With these caveats, the advantage of wide, uniform spatial coverage is enormous in countries that may otherwise not have reliable pollution monitoring.

The literature on environmental damages in developing countries has also been a source of innovation for finding new, important pathways through which the environment supports human well-being. Frank and Sudarshan (2024) hypothesize that human health depends on the health of natural ecosystems. In particular, they study a keystone species—the vulture—that provides humans with an environmental service, free sanitation and waste disposal, by consuming livestock carcasses. Frank and Sudarshan (2024) show that after a livestock painkiller toxic to vultures became widely used in India, vulture populations declined, and human mortality in areas where vultures used to live increased. The effects are shockingly large: the authors estimate that the decline of vultures increased the death rate, from *all* causes, by 4.7%.

What seem like "natural" disasters for ecosystems are often attributable to human policies. Toxic painkillers spread in India after a drug patent expired (Frank and Sudarshan, 2024). Frank et al. (2025) describe another example of a novel and important ecosystem service provided by a different bird: sparrows. China, in 1958, abruptly launched a campaign to kill off sparrows. The trouble is, sparrows eat insects, and insects eat crops. As a result, the sparrow-eradication campaign reduced rice and wheat yields enough to induce localized famine and increase all-cause mortality. The relationship between natural predators and pests is easily disturbed by economic activity, as well as by policy. For example, growing evidence points to a link between deforestation and increased malaria transmission in the tropics (Garg, 2019). In Nigeria, a 1 standard deviation decline in forest cover is associated with a 9.3% increase in the neonatal infant mortality rate, and a correspondingly high increase in malaria cases (Berazneva and Byker, 2024).

Vultures? Sparrows? Are these cases curiosities? Hardly—they are just a couple of the many environmental services that matter for human life. These instances appear novel because of the difficulty of isolating causal empirical links mediated by ecosystems. The large effects of ecosystem services on human well-being these studies document suggest that our standard measures of environmental quality, like air and water pollution, are woefully incomplete.

A nice methodological feature of the Frank and Sudarshan (2024) study is that it relies on relatively long-run variation, over many years, in environmental quality, since the decline in the vulture population was a permanent shock. Long-run studies provide more complete estimates of environmental damages than short-run studies due to the cumulative nature of many environmental harms, whether in the ecosystem or within the human body. Estimating long-run exposure effects is empirically challenging, however, since it requires persistent variation in environmental quality that is unrelated to other determinants of human health.

Where studies have been able to isolate long-run variation in exposure, the results are—like in Frank and Sudarshan (2024)—shockingly large. An important example is provided by Chen et al. (2013). This paper studies a Chinese policy that subsidized coal heating and thereby increased air pollution in northern China relative to the rest of the country. Together with restrictions on migration, this policy generates exogenous variation in long-run exposure to particulate matter air pollution (the same variation is employed by Ebenstein et al., 2017; Ito and Zhang, 2020; Xue, Zhang and Zhao, 2021). They estimate that elevated particulate air pollution level north of the Huai river reduces life expectancy by 5.5 years, relative to south of the river. While this estimate is larger than other estimates of the impact of particulate matter on mortality in the literature, the levels and duration of exposure in this population are also exceptionally high.[7]

More commonly, researchers study short-run environmental shocks, over the course of days, weeks or months, using panel data and two-way fixed effects. These different empirical designs have complementary strengths and weaknesses. Short-run studies might miss most of the health

[7] Other studies estimate that per $\mu g/m^3$ reductions in particulate matter increase life expectancy by 0.04 to 0.10 years (0.04 in Correia et al. (2013), 0.06 in Pope, Ezzati and Dockery (2009), 0.06 in Apte et al. (2018), 0.10 in Ebenstein et al. (2017)).

damages from pollution. On the other hand, the empirical designs of short-run studies often rely on high-frequency variation in pollution exposure that is more plausibly exogenous with respect to omitted, unobserved characteristics of the population.

Another solution to concerns about the endogeneity of exposure to environmental hazards has been to focus on the health outcomes of infants. Infants cannot choose their exposure based on unobserved health histories (though, of course, their health may be determined by their parents' choices). For example, Garg et al. (2018) combine remotely-sensed water quality and census data to link infant mortality to surface water pollution in Indonesia. Many other papers have quantified the impact of particulate matter (Heft-Neal et al., 2018; Rangel and Vogl, 2019; Adhvaryu et al., 2024), poor water quality (Do, Joshi and Stolper, 2018; Hill and Ma, 2022; Fan and He, 2023), extreme heat (Geruso and Spears, 2018; Blom, Ortiz-Bobea and Hoddinott, 2022) and other environmental hazards on infant health and mortality.

The current gap in life expectancy between poor and rich countries is around 12.8 years (WHO, 2025). How much of that can be explained by differences in environmental quality? A limitation of the epidemiological approach to quantifying environmental damages is that each study setting is unique—the level of environmental quality, specific hazard, population, outcome measure—which makes it difficult to integrate across studies to assess the overall effect of the environment on differences in life quality or expectancy across countries or populations (Landrigan et al., 2018). The levels of poor environmental quality documented in Section 2 tend to load onto the same places. For example, even after controlling for income, the correlation between our main measures of air and water pollution has a coefficient of 0.34. If long-run exposure to one source of harm increases vulnerability to others, these correlations may imply higher damages, but also the potential for mis-attribution, when examining environmental hazards in a piecemeal fashion.

The environment may also affect mental health or perceived well-being in addition to physical health. While the evidence is still nascent, a small literature documents mental health and happiness benefits from a cleaner environment. Measured through surveys (Zhang et al., 2022; Chen, Oliva and Zhang, 2024), sentiment expressed on social media (Zheng et al., 2019), and extreme outcomes such as suicide (Carleton, 2017; Zhang et al., 2024), these papers find evidence that poor environmental quality worsens mental health. It is not clear if these estimates should be thought of as mediated by physical health or a distinct mechanism through which the environment enters utility.

Together, four factors—the geographic bias toward studies of high-income countries; the fact that new environmental health services are still being discovered; the short-term nature of environmental shocks in the literature; and the scrutiny of singular environmental threats in isolation—lead us to believe that the magnitude of environmental impacts on health is even larger than currently understood, and may explain a significant part of the life expectancy gap. Research that makes progress on these four factors, including integration of environmental quality into models of health capital and mortality, will help discipline this belief.

4.1.2 Human capital damages

Environmental quality can also affect human capital accumulation, which in turn shapes long run utility through earnings, health and quality of life. In the short-term, poor environmental quality reduces human capital measured through school attendance, school performance and educational attainment. On a daily basis, environmental quality affects school attendance and learning (Garg, Jagnani and Taraz, 2020; Chen, Guo and Huang, 2018; Zivin et al., 2020; Bedi et al., 2021; Carneiro, Cole and Strobl, 2021; Lai et al., 2022). Even short-term shocks can have durable effects. For example, Lai et al. (2022) find that pollution due to upwind agricultural fires on the day of a high stakes exam in China impacts both test scores and the eventual likelihood of access to a top university.

Over the course of early life, the cumulative effects of environmental harms erode human capital formation (Bharadwaj et al., 2017; Chen, 2025). Environmental shocks are also a major driver of fluctuations in income in the rural economy. For example, suggestive evidence in Garg, Jagnani and Taraz (2020) points to an income mechanism: extreme heat lowers agricultural income for rural households in India, which decreases school attendance and worsens child health, culminating in lower test scores. Shah and Steinberg (2017), studying rainfall shocks in agriculture, document that there is also an opportunity-cost channel, through which *positive* environmental shocks to productivity decrease schooling for children who are old enough to work on their family farms. Environmental effects that lower human capital decrease labor productivity later in life. We study direct effects of the environment on contemporaneous productivity in the next subsection.

4.1.3 Labor productivity

Up to this point, the evidence reviewed suggests that a clean environment makes people healthier and raises human capital. In addition to measuring effects on labor productivity ($\partial \ell_i / \partial e_k$ in the model), the epidemiological approach has been applied to a variety of other productivity-related outcomes (see Lai et al. (2023) for a review of the literature). Aggregate environmental shocks have large effects on output. For example, Burke, Hsiang and Miguel (2015) build on earlier related work by Dell, Jones and Olken (2012) to examine the aggregate relationship between temperature anomalies and economic production at the country by year level. They document a non-linear relationship with sharp declines at high temperatures, with both agricultural and non-agricultural sectors contributing to the effect. We break down the evidence on the mechanisms behind these economy-wide effects, starting with labor productivity.

If pollution makes workers sick, they will spend less time on the job. Hanna and Oliva (2015) were among the first to show effects of pollution on hours worked in an LMIC context. They find that a 20% reduction in SO_2 concentrations increased hours worked by 3.5%. Aragón, Miranda and Oliva (2017) find that it is not only workers' own health, but also that of their dependents, that determines the effect of pollution on labor supply. Specifically, labor supply responses to pollution shocks are concentrated among workers with vulnerable dependents. At least some of the labor supply effect likely comes from avoidance behavior, if workers choose to reduce hours to avoid exposure. Hoffmann and Rud (2024) provide evidence that this form of adaptation is increasing in income, consistent with the model. This implies that lower income workers, because of a higher marginal value of income, are less willing to adjust labor supply to avoid pollution. In their setting, income is a more important source of heterogeneity in responses to pollution than are job attributes such as flexibility or self-employment.

Once people are at work, labor productivity suffers if pollution or other environmental hazards increase effort costs or impair judgment (Adhvaryu, Kala and Nyshadham, 2020; Somanathan et al., 2021; Wang, Lin and Qiu, 2022; Adhvaryu, Kala and Nyshadham, 2022; Chang et al., 2016). The effects of heat and air pollution (the two best-studied environmental hazards) on labor productivity have been shown across a surprisingly wide range of settings, not just in physically demanding jobs but also in a range of tasks that require focus or coordination. For example, hotter working conditions lower labor productivity in Indian manufacturing firms (Adhvaryu, Kala and Nyshadham, 2020; Somanathan et al., 2021). Garment workers, whose work mainly involves fine motor skills, produce less when air pollution worsens (Adhvaryu, Kala and Nyshadham, 2022). Wang, Lin and Qiu (2022) find that ozone pollution reduces productivity for couriers, whose work blends cognitive and non-cognitive tasks. Programmers working in pairs produce less when working in a hotter room, though productivity does not decline for those working alone (Garg, Jagnani and Lyons, 2025). Chang et al. (2019) estimate declines in productivity on polluted days among call center workers in China, a setting that involves little physical exertion at all. Rode et al. (2024) estimate that heat decreases labor supply, with effects driven by workers in industries relatively more exposed to temperature variation.

A number of the above studies zoom in on tasks where productivity can be observed at the worker level, in order to tie environmental shocks to a well defined measure of output. The risk of such extreme focus is that it may miss actions that firms or industries take to mitigate the aggregate effects of shocks to individual workers. For example, in the simplified exposition in our model, when labor supply declines because of poor environmental quality, firms can simply hire more workers; as such, firm productivity may not depend on $\hat{\mathbf{e}}$. Do environmental shocks to workers, then, pass-through to productivity at the firm level?

A growing literature documents that firm productivity declines along with the productivity of workers. For example, Fu, Viard and Zhang (2021) combine estimates of the pollution elasticity of output (positive) with the output elasticity of pollution (negative) in a general equilibrium model that accommodates feedbacks. In China during their study period, the overall effect of pollution on output is negative. In their sample of firms, labor is the most important input, suggesting that most of the effect on productivity is driven by effects on labor. In a sample of firms in industrial towns in China, He, Liu and Salvo (2019) find insignificant effects of pollution shocks on contemporaneous daily output, but that cumulative pollution exposure over the prior month reduces output by 1% for each 10 $\mu g/m^3$ increase in ambient concentration.

Environmental quality can impact productivity through costs or the productivity of other inputs, not just labor. For example, some forms of capital may perform less well in extreme temperatures, or require regular cleaning under high levels of pollution. Zhang et al. (2018) estimate the effect of temperature shocks on TFP of Chinese firms and show that both labor and capital intensive firms are sensitive to extreme temperatures, which they take as evidence that labor is not the only channel through which firm productivity is impacted. An alternative way to measure the impact of environmental shocks on firms is through indicators of financial performance or profitability, such as loan defaults, which increase with temperature for both agricultural and non-agricultural enterprises in Mexico (Aguilar-Gomez et al., 2024).

4.1.4 Agricultural productivity

Productivity depends on the environment most in agriculture, where many people in low-income countries work (Figure 4). Many agricultural inputs, like soil, energy and water, are drawn directly from nature. Productivity varies widely both cross-sectionally based on environmental conditions and from season to season with the weather.

A rapidly growing literature estimates the costs of climate change to agricultural productivity and rural livelihoods.[8] Damages have already been substantial: Ortiz-Bobea et al. (2021) estimate that climate change since the 1960s has erased seven years of productivity growth, with the biggest losses in Africa, where productivity levels are the lowest in the world. Climate change hurts agricultural production through distinct mechanisms, including: hotter temperatures (Aragón, Oteiza and Rud, 2021; Auffhammer and Carleton, 2018), floods (Patel, 2025), saline intrusion from sea level rise (Patel, 2024; Haque, 2025), and cyclones (Hsiang and Jina, 2014). Because some of these mechanisms durably alter the environment for cropping, even transitory climate shocks can have persistent effects on productivity, including in agriculture (Patel, 2025; Hsiang and Jina, 2014).

Taking a global view, Hultgren et al. (2025) summarize the magnitude of agricultural productivity damages from higher temperatures, accounting for adaptation. They estimate that a 1 °C increase in global mean surface temperature decreases food production by 120 kCal per person per day, which is 4.4% of recommended consumption. They show that yield declines are larger in magnitude in richer, more productive places where current growing conditional are favorable. That does not mean, however, that the welfare losses are also greater in those settings. For several reasons, farmers in developing countries are more exposed to declining agricultural productivity due to climate change. First, incomes are more dependent on agriculture, with fewer opportunities for sectoral reallocation if productivity in the agriculture sector declines. Second, the innovations

[8] See Ortiz-Bobea (2021) for a comprehensive review of methods used to study climate damages in agriculture.

necessary to sustain yields in a changed climate have lagged behind in poorer countries. Moscona and Sastry (2025) show that most innovation in agricultural technologies occurs in rich countries and diffuses weakly to poor countries because of agronomic differences. Third, trade can buffer the impact of climate shocks in agriculture if trading partners face uncorrelated shocks (Costinot, Donaldson and Smith, 2016). Yet Zappala (2024*b*) and Dingel and Meng (2025) show that poorer countries have less diverse trading networks and therefore higher residual exposure to shocks. Finally, policy intervention could protect farmers and consumers from transient weather shocks, by delivering weather insurance payments or altering the terms of trade in favor of smallholders. Hsiao, Moscona and Sastry (2024) show that current tariff policy responses to extreme weather act to stabilize prices, which protects consumers but disadvantages food producers.

When agricultural households lack access to financial instruments and diversified income sources, productivity losses due to bad weather in a single year can have devastating consequences on outcomes ranging from child malnutrition to suicide. For example, Baker and Anttila-Hughes (2020) use data on nearly 200,000 children in Sub-Saharan Africa to show that a 1 °C increase in annual temperature is associated with a 0.08 standard deviation decrease in child weight for height. These effects can be attributed largely to agricultural productivity losses. Farmers, unable to provide for their families when crops fail, resort to desperate measures. Carleton (2017) finds that extreme temperatures can explain 6.8% of farmer suicides in India in recent decades. These studies highlight that at least some of the health impacts described in Section 4.1.1 may be traced back to agricultural income losses (see also Burgess and Greenstone (2017)).

Agricultural productivity depends on other resource endowments, not just the climate. Soil quality, groundwater, and ecosystems all provide important environmental services. Blakeslee, Fishman and Srinivasan (2020) study what happens when farmers in Karnataka, India lose access to an important natural resource: groundwater. Groundwater reduces dependence on rainfall and increases production by enabling dry-season cropping and complementing other productive inputs (Gollin, Hansen and Wingender, 2021). Blakeslee, Fishman and Srinivasan (2020) note that one unlucky farmer may have their well run dry while similar, nearby farmers happened to tap a larger aquifer. The paper finds that this large, essentially permanent shock of a dry well reduces on-farm income by one-quarter, because farmers pull back on dry season agriculture. Though farmers move into employment on other farms or in other sectors, debt rises and food expenditures decline.[9] The overall effect on income is driven by less-developed areas farther from alternative employment opportunities. In a similar setting, Sekhri (2014) shows that inaccessible groundwater not only lowers agricultural yields and income, but also increases intra-village conflict. Agricultural productivity is vulnerable to other environmental hazards too, including water pollution (Cui, Lai and Lin, 2025; Hagerty and Tiwari, 2025).

4.2 Demand for environmental quality

The economic, as opposed to the epidemiological, approach to valuing environmental quality uses revealed preference: to infer a value for the environment from people's own choices. Though there is no market for environmental quality itself, the willingness-to-pay for environmental quality (equation (11)) can be recovered by estimating how environmental quality changes adaptation expenditures a_i (equation (12)). This isolates the private value that individuals get from environmental quality; adaptation is a private good and so, absent other frictions, adaptation spending should be privately optimal.

There are several difficulties in applying this approach in practice, as detailed in Section 3. First, for many environmental services there are no markets for even close substitutes (candidate adaptation expenditures a_i). For example, a water filter will clean up someone's drinking water, but a private water filter will not allow them to swim safely in a polluted river. A related problem is that, when there are substitutes, they are often consumption bundles that comprise both environmental quality and different levels of other public amenities. For example, the hedonic approach to environmental valuation attempts to infer the value of environmental quality, or other public goods, from housing prices (Roback, 1982; Gao, Song and Timmins, 2021).[10] Areas with high environmental quality may be desirable in other respects, in which case the market may assign value to a_i for reasons that are correlated with but distinct from environmental quality.

The second difficulty is that willingness-to-pay for adaptation a_i may depart from the value of the environmental service e_k. Perhaps people do not know the impact of the environment on their

[9]Sectoral reallocation has similarly been found to mitigate damages from extreme temperatures (Colmer, 2021).

[10]Hedonic wage studies use a similar approach to estimate valuations of occupational mortality risk (Evans and Taylor, 2020). Where land or labor markets are incomplete, these methods may be infeasible or unreliable.

future health. Or, they know, but cannot afford a durable good, such as a clean cooking stove, that would reduce their own exposure. In general, market failures in the market for a_i, due to informational problems, insecure property rights, credit constraints and the like, will separate the willingness-to-pay for environmental quality implied by a_i consumption from the true benefit of environmental quality for households. In these cases, revealed preference methods may be worse than epidemiological methods for measuring the benefits of environmental quality.[11]

We summarize in Table 3 selected estimates of the willingness-to-pay for adaptation (protection from environmental harm). The table reports the valuation people place on a given reduction in exposure to an environmental harm (column 1), and the magnitude of the associated damages (column 2). By measuring both valuations and damages in the same setting, these studies allow estimates of household (or firm) willingness-to-pay for protection from damages (column 3). We report WTP estimates from five studies on the health and productivity benefits of air and water quality. These studies tend to find very low WTP for protection from environmental harms. We return to discuss the methods and findings of each study as we proceed through this Section 4.2.

4.2.1 Adaptation by individuals to poor environmental quality

Private adaptation (consumption of a_i) is any costly action that improves experienced environmental quality or reduces the damages from a poor ambient environment.[12] The simplest cases are investments that improve experienced environmental quality relative to ambient environmental quality: an air purifier pulls fine particles out of the indoor air; a water filter removes bacteria; an air conditioner moderates the temperature and humidity. Adaptation can also take the form of behavior change rather than technology. For example, staying home on a very hot day, or even migrating to a less polluted city, lower exposure. In other cases, adaptation may be the purchase of a good that substitutes for the deficiency of an environmental service or natural resource. For example, fertilizer can compensate for a lack of soil nutrients, and bottled water provides an alternative drinking water source when natural sources are contaminated.

When adaptation takes the form of consuming a private good, it is straightforward to estimate

[11] While, in principle, stated preference measures could be used to circumvent the missing markets problem that plagues revealed preference methods in LMICs, this methodology has been largely discredited as a reliable means of environmental valuation (Hausman, 2012; Kling, Phaneuf and Zhao, 2012). Without a real budget constraint and real-stakes choices, there is nothing to impose discipline or consistency on stated preferences for the environment.

[12] Carleton et al. (2024) provide an in-depth review of adaptation to climate change.

Table 3. Willingness-to-pay for environmental protection and energy savings

	Valuation	Avoided Damages	WTP per Avoided Damage
	(1)	(2)	(3 = 1 /2)
Ito & Zhang (2020)	$1.34	0.224 life years	$5.98
Units	per PM10 reduction per year	per PM10 reduction per year	per life year
Kremer et al. (2011)	$2.96	0.125 DALYs	$23.68
Units	per spring protection	per spring protection	per DALY
Burlig, Jina & Sudarshan (2025)	$20	0.282 DALYs	$71
Units	per clean water provision per year	per clean water provision per year	per DALY
Berkouwer & Dean (2022)	$6	$118.50 fuel savings	$0.05
Units	per clean stove per year	per clean stove per year	per $ savings
Garg, Jagnani & Lozano-Garcia (2025)	$45	$926.28 profit	$0.049
Units	per PM10 reduction per year	per PM10 reduction per year	per $ profit

Notes: This table spotlights the current literature on willingness to pay for environmental damages. Columns (1) to (5) highlight research conducted in different settings and on different measures of environmental pollution. Ito and Zhang (2020) examine households near China's Huai River policy boundary, estimating willingness-to-pay for cleaner air by linking air purifier purchases to pollution exposure. We calculate life years per $\mu g/Nm^3$ using Ebenstein et al. (2017) x household size of 3.5 (as used by the authors). Kremer et al. (2011) evaluate the health and economic benefits of improved rural water quality in Kenya, highlighting how property rights institutions shape clean-water access and valuation. We use the reported cost per DALY and avoided damages in the paper, and back out the valuation. Burlig, Jina, and Sudarshan (2025) conduct a large-scale field experiment in rural India showing that clean water delivery improves health and elicits high revealed willingness-to-pay. We use the authors' reported cost per DALY and avoided damages, and back out the valuation. Berkouwer and Dean (2022) study energy-efficient cookstove adoption among low-income Kenyan households, finding that credit constraints drive under-adoption despite large private returns. We use the per year fuel savings and WTP from using clean stove for the attention treatment group. Garg, Jagnani, and Lozano-Gracia (2025) document high potential returns but limited uptake of air purifiers among Bangladeshi firms, pointing to behavioral and institutional barriers in pollution abatement. We use the authors' monthly reported gains from (BDT 11000) and WTP for (BDT 437.50) air purifiers from the best outcome treatment arm (T9 - low risk learning) along with the author's implied exchange rate of BDT 116.67 per dollar.

the demand for adaptation. One approach involves direct demand elicitation. Berry, Fischer and Guiteras (2020) use a Becker-DeGroot-Marschack (BDM) mechanism to elicit demand for a water filter in Ghana. The authors find that higher willingness-to-pay for the water filter predicts higher filter use and lower prevalence of child diarrhea after one year. This approach to measuring willingness to pay produces precise estimates of the value of adaptation household-by-household. The literature using similar experimental designs in different domains has therefore continued to grow (Yishay et al., 2017; Chowdhury et al., 2025; Berry, Fischer and Guiteras, 2020; Ahuja, Kremer and Zwane, 2010; Brown, Jeuland and Turrini, 2017; Baylis et al., 2023).

The studies described above often create or subsidize a market for adaptation only for the purpose of the study. These bespoke markets raise concerns about experimenter-induced demand and resale (since prices are often subsidized to below the market price, demand may appear to be high if subjects mean to resell the good). The main alternative approach relies directly on secondary data from existing markets. Ito and Zhang (2020) recover WTP for clean air by measuring how the market share of air purifiers that remove particulate matter varies with the level of pollution in urban China. The empirical design uses variation in prices from distance to suppliers, rather than a randomized experiment, to estimate demand. The authors use this variation to estimate WTP for air filters in a discrete-choice demand model. They then convert WTP for air filters into WTP for clean air based on engineering estimates of the efficacy of the filters. A particularly nice feature of the study is that the authors can estimate demand for air purifiers that remove harmful fine particulate matter (so-called HEPA filters) relative to demand for less-effective filters that may have aesthetic benefits, but do not improve health. This contrast allows the authors to separate the demand for a_i from other confounding aspects of the good with unusual precision. The headline finding of the paper is that households are willing-to-pay \$1.34 annually to remove 1 μg/m^3 of PM_{10} (Table 3, column 2).

Is this a lot, or a little? Ito and Zhang (2020) estimate a lifetime valuation of \$455 to extend life by an additional year, which is equal to a per capita annual valuation of \$6 per life-year, in a sample where income is around \$600 per household member.[13]

[13] We calculate the annual individual-level value of statistical life year (VSLY) in Table 3 by dividing the paper's estimated WTP of \$1.34 per unit of PM_{10} by the life-years saved by the same change in pollution from Ebenstein et al. (2017) (following Ito and Zhang (2020)) and dividing by the number of individuals in a household. This assumes that the household willingness to pay for an air filter is a function of household size.

This valuation seems extremely low, perhaps because air purifiers only reduce air pollution inside, and people spend time in places other than their own apartments. Another data point comes from Kremer et al. (2011), who conduct one of the first randomized controlled trials (RCTs) applied to environmental quality in an LMIC setting. The authors work with an NGO to improve drinking water quality at randomly selected springs. This allows them to estimate two outcomes of interest: first, how access to clean water affects child health outcomes, and second, how much people are willing to pay (measured in time) for improved water quality, as revealed by their decision to switch from a closer but dirtier spring to a more distant, cleaner one. Using variation in time spent obtaining clean water, and scaling this by the wage, they find that cleaner water reduces diarrheal disease in children, but that households have very low willingness to pay for improved water quality and therefore for better health, equivalent to a valuation of $24 per life-year (Table 3, column 3). This, again, seems very low, even for a poor Kenyan household. Of course, such an estimate relies on a number of assumptions to translate a revealed willingness to expend time into a monetary willingness to pay (see Section 3).

The benefits of environmental quality may be undervalued because they are both unknown and far in the future. There is a small but high-quality base of evidence from low-income countries that investments in adaptation may be inefficiently low, for reasons of both information and credit constraints. For example, Barwick et al. (2024*b*) analyze the effect of changes to China's air pollution monitoring and disclosure policies. They measure how improved disclosure increased the purchase of air purifiers and reduced outdoor recreation, using comprehensive credit and debit card spending data. The paper's estimates of large changes in behavior from improved disclosure suggest that people's adaptation to pollution prior to disclosure were not efficient. Of course, once information is shown to be imperfect, there is no reason to expect that adaptation is fully efficient after the policy either. Several experiments seek to demonstrate the existence of an information gap by attempting to close it (Jalan and Somanathan, 2008; Baylis et al., 2023).[14]

It can be hard to interpret the results of informational interventions when we do not know how much they moved beliefs. Understanding how people form beliefs about environmental quality has

[14] Information frictions are not a uniquely LMIC phenomenon. Tarduno and Walker (2025) show that individuals in the United States overestimate both their exposure to ambient pollution and its impact on life expectancy. Providing information about effects on life expectancy lowers willingness to pay for an air purifier; information about exposure has no impact. On average, valuations are low ($8 per $\mu g/m^3$ $PM_{2.5}$) even in this relatively wealthy sample—though ambient air quality is notably better than in the settings described in this chapter.

therefore become an active area of ongoing work (Ahmad et al., 2025; Zappala, 2024*a*; Kala, 2019; Patel, 2024). For example, Burlig et al. (2024) elicit beliefs about the timing of monsoon rainfall in a study of farmer adaptation in India. They consider the farmer's problem of when to plant, which depends on the uncertain arrival of monsoon rainfall (Kala, 2019). Burlig et al. (2024) give farmers information from an improved, accurate forecast of monsoon onset and elicit farmers' beliefs about when it will rain. They show that the improved forecasts cause farmers to change their beliefs and, in turn, their agricultural investments. These effects are heterogeneous based on whether farmers learned that the monsoon was going to arrive sooner or later than they had initially expected. Conveying accurate and actionable information about a regular, discrete event like monsoon onset maybe substantially easier than for extreme events such as 100-year floods or heat waves.

If households are unaware that they have incomplete information about environmental quality, they may underinvest in learning. Barnwal et al. (2017) show that only 31% of households are willing to pay INR 50 for information about the contamination of their wells by arsenic, though one-third of households change their source of water if they find out that their own well is contaminated. These two results appear contradictory—if households choose to act and change their water source when receiving information, should not they value the information itself more highly? At the same time, in many cases, if a household does nothing when they learn of an environmental hazard, it may be because they do not understand the harm, but it may also be because alternatives are worse. Buchmann et al. (2019) also study drinking water in Bangladesh. In response to arsenic contamination of water, a large-scale public health campaign urged people to switch from arsenic-contaminated groundwater to surface water. Surface water contamination with bacteria proved more harmful to infant health than the initial, slow-acting arsenic poisoning, causing an increase in infant mortality. The general lessons are that the informational burden for adaptation is high and that the interpretation of an action depends on the choice set. Optimal adaptation requires that households know their own exposure, the health impacts of that exposure, and also the costs and benefits of alternatives, which may carry distinct and unknown risks.

Another potentially important friction for private investment in adaptation is credit or liquidity constraints. Berkouwer and Dean (2022) show that household adoption of fuel-conserving cookstoves is extremely low, despite an estimated annual return approaching 300%, and measurable improvements in indoor air quality (Berkouwer and Dean, 2023). The stove has more salient benefits than, say, an air purifier, because households can directly observe their reduced fuel expenditure. Yet valuation for the stove per unit of fuel savings is a mere \$0.05 (Table 3, column 3). A loan doubles household willingness-to-pay, but does not fully close the gap between the return on investment (fuel savings) and upfront willingness to pay. Relaxing credit constraints for a single adaptive technology may increase adoption of that technology, but what about all the other adaptive actions households were too constrained to take? Lane (2024) shows that guaranteed access to credit conditional on a climate shock allows households—farmers, in his case—to invest in adaptation that is both less privately costly and more effective than their adaptation choices without credit access. High upfront costs have also been shown to constrain willingness-to-pay for electricity, the gateway to clean energy services for many households (Lee, Miguel and Wolfram, 2020). While not necessarily attributable to credit constraints, Burlig, Jina and Sudarshan (2025) find that WTP for clean water is significantly lower than an equivalent willingness to accept measure. Their WTP estimate implies a valuation per DALY of \$71 per year (Table 3, column 3), in a sample where per capita annual income is \$420. They argue that WTA delivers a higher valuation because of a lack of substitutes, something that may be true for a large number of environmental goods and services.

Evidence that willingness to pay for adaptation is increasing in income (equation 12) is largely correlational (e.g., Ito and Zhang, 2020; Berry, Fischer and Guiteras, 2020). Without exogenous variation in income, these results are hard to interpret: income may be correlated with local exposure (via occupations or housing quality) and with baseline health status (affecting returns to self protection). A recent set of papers on climate adaptation leverage income shocks to study impacts on adaptation (Premand and Stoeffler, 2022; Macours, Premand and Vakis, 2012) and find that higher incomes are associated with lower damages from extreme weather; some also measure changes in technology or other choices that may underlie the effect, including migration (Macours, Premand and Vakis, 2012). Balboni et al. (2025) leverage a well-studied ultra-poor graduation program that gave productive assets, typically cows, to very poor women in Bangladesh. Access to detailed survey data allow the authors to document how the effect of weather shocks on consumption varies with access to the asset. Their findings imply that 4/5ths of the average consumption benefits of the program come from mitigating the impact of negative weather shocks; in the treatment group, negative weather shocks have no impact on consumption. The benefits of many anti-poverty programs may lie in increased resilience to negative environmental shocks. To our knowledge, similar analysis have not extended to other forms of environmental quality, where adoption of air purifiers, water filters and other technologies can improve people's own experienced environmental quality even in the face of low ambient quality.

Our inchoate sense from recent research is that the twin market failures of a lack of information and credit constraints may still not be enough to explain low adoption. Chowdhury et al. (2025) make this point clearly in the context of air purifier adoption in Bangladesh. Selected households in their study are given access to a free indoor air purifier, subsidized electricity, and information about exposure reductions from an in-home air quality monitor. In spite of this, utilization of the air purifier remained low throughout the study period, which cannot be explained by either a lack of information about pollution exposure, the effectiveness of adaptation, or credit barriers.

4.2.2 Migration as adaptation

Air purifiers can clean up your room, but not your park or your commute. For that, you may have to move. Moves, to a new neighborhood, city or occupation, can reveal a more comprehensive WTP for environmental quality. The main difficulty with using moves to value environmental quality is that they also inevitably change other things people value. A recent literature documents the importance of migration as a strategy for avoiding environmental damages (see Oliva (2024) for a review). Freeman et al. (2019) apply a classic sorting model from environmental economics to migration choices within China, using exogenous variation in air pollution across cities to address the endogeneity of environmental quality. Their results imply a roughly \$20 per household willingness to pay for a one unit decrease in $PM_{2.5}$. Multiplied by a very large population, total willingness to pay is over \$8 billion. Others confirm the importance of migration as an adaptation strategy, even in China where mobility is constrained. Chen, Oliva and Zhang (2022) use thermal inversions to instrument for particulate matter in Chinese cities and find large outmigration responses to increases in pollution levels. Barwick et al. (2022) instead look at short run migration in response to improvements in China's high speed rail network, and find that individuals relocate to cleaner destinations to avoid pollution.[15] Khanna et al. (2025) highlight that these decisions

[15] Sectoral reallocation and rural to urban migration can also affect environmental quality at the origin or destination, as shown by Garg, Jagnani and Pullabhotla (2024).

may have aggregate productivity effects if high skilled workers relocate away from polluted cities, where they are also most productive. This equilibrium effect has spillovers for lower skilled non-migrants, who continue to breathe dirty air and also face a decline in wages due to the departure of (complementary) high skilled workers.

Migration is a high fixed cost adaptation strategy; take up will depend on credit and liquidity constraints, as well as income. Cattaneo and Peri (2016) show that temperature shocks increase migration, both from rural to urban areas and internationally, in middle income countries (consistent with evidence from Mexico (Jessoe, Manning and Taylor, 2018)). However, in poor countries, higher temperatures reduce the probability of migrating. They interpret this as the result of binding liquidity constraints that tighten when temperature reduces agricultural productivity. A similar phenomenon has been documented in India (Liu, Shamdasani and Taraz, 2023). A contraction in liquidity or in demand for non-agricultural labor can result in less mobility (adaptation), both out of agriculture and from rural to urban areas. Nath (2025) studies how constraints on migration and trade mediate the response to temperature shocks in general equilibrium. Since trade in agricultural goods is subject to frictions, if climate change causes lower agricultural productivity, people may—perversely—have to devote more resources to agriculture to maintain their incomes. Aragón, Oteiza and Rud (2021) provide micro-evidence of this effect: Peruvian farmers respond to high temperatures by using more inputs, including land and child labor, to offset income losses. Nath (2025) finds that such perverse responses are a quantitatively plausible consequence of climate change in the presence of barriers to agricultural trade.

4.2.3 Adaptation by firms

Evidence from the epidemiological approach suggests that firms bear some of the cost of poor environmental quality (Section 4.1.3). An extension of the supply side of the model described in Section 3.1.3 would either set $\ell_i(E)$ as an input to production, or allow the productivity of other inputs to vary with environmental quality. For example, in the model in Somanathan et al. (2021), both total factor productivity and the output elasticities of labor and capital vary with temperature. In their paper, installation of cooling on factory floors in India significantly reduces the negative effect of temperature on labor supply and productivity. The authors calculate that the energy costs of cooling are high relative to the output losses; in spite of this, the firms in their sample expanded the use of cooling, primarily to cover labor-intensive, high return tasks. This provides some evidence that firms are also adapting to avoid environmental harms.

Are firms adapting optimally? Garg, Jagnani and Lozano-Garcia (2025) give air purifiers to Bangladeshi textile firms, paired with pollution monitors to measure their efficacy, and then offer to sell the purifiers back to the same firms. This setting is perhaps the best case for private adaptation, in two respects. First, the benefit of air quality to the firm—higher profits—is immediately observed and salient, whereas the health benefits to workers may accrue years in the future. Second, the authors estimate that air purification pays for itself in the form of higher firm profits within 3 months of use during the season of peak production, suggesting that credit constraints are unlikely to present a meaningful barrier. Nonetheless, despite the experimenters more-or-less bludgeoning the treatment firms with information and actual experience in use, their willingness-to-pay for purifiers remains only about one-fifth of the retail price. One way of understanding the low magnitude of this WTP is that firms are only willing to pay around \$0.05 for each \$1.00 of profit that they estimate air purifiers bring the firm (Table 3, column 3).

The results in Garg, Jagnani and Lozano-Garcia (2025) show that firms have low WTP for even contemporary increases in their own profit. The profit impacts mean that firms capture at least some of the benefits of private adaptation. At the same time, workers do capture some of the health benefits of workplace amenities such as environmental quality. If so, firms may underinvest in such amenities. To what extent firms or workers capture the benefits of workplace amenities depends on the structure of the labor market (Felix, 2021; Sharma, 2023), which jointly determines wages and workplace amenities.

Bassi et al. (2021) show that small scale manufacturing firms face a steep tradeoff between revenue and clean air: the places with more customer demand and more potential revenue are also high traffic and therefore high pollution. For employers, they document a large "pollution profit premium" but find that little of this is passed through to workers. This appears to stem from a combination of low worker bargaining power and incomplete information. In a standard hedonic wage model, workers balance wages against other job amenities, including pollution exposure. However, if workers are uniformed about exposure, they will not demand compensating wages. At the same time, if they have little bargaining power, any demands they make may go unmet. Findings in this nascent literature have important implications for the incidence of environmental harms in low and middle income settings. The structure of the labor market and the distribution of information between employers and employees is likely to shape who bears the costs of on-the-job exposure.

In the Bassi et al. (2021) sample, employer investments in protecting their workers are associated with managerial ability rather than pollution exposure. This echoes the findings by Adhvaryu, Kala and Nyshadham (2022), who show that attentive managers offset most of the effects of pollution on productivity by reallocating more sensitive workers to tasks that are less affected. In their setting, managers have limited scope to reduce worker exposure beyond reallocation across tasks. While this mitigates losses in the garment sector in India, it is unclear how much of the benefit accrues to workers. Many other potential channels affect the extent to which firms internalize the benefits of adapting to poor environmental quality on the part of their workers. We view this as an area ripe for further work to understand where firms have incentives to invest in worker protection versus where policy intervention may be necessary.[16]

The productivity of inputs other than labor may also depend on environmental quality (see Section 4.1.3 and Grover and Kahn (2024); Goicoechea and Lang (2025) for recent reviews of firm adaptation to climate change). Modifying air and water quality during the production process is widespread; for example, electronics firms rely on temperature control and air filters; pharmaceutical plants employ industrial scale water filtration systems. In addition, weather shocks can disrupt production and interrupt supply chain logistics. Recent evidence highlights strategies that firms take to lessen the impacts of climate risk, including diversifying supplier networks to reduce exposure to climate shocks (Castro-Vincenzi et al., 2025) and citing plants in less risky locations (Castro-Vincenzi, 2022). Balboni, Boehm and Waseem (2024) use microdata on firm to firm transactions and supply routes to uncover responses to floods in Pakistan. Affected firms respond by moving to less exposed locations, adjusting supplier relationships to reduce risk exposure via vertical supply linkages. An important feature of their empirical strategy is that it allows them to measure firm decisions that are forward-looking, consistent with ex ante adaptation (i.e., actions undertaken to reduce future environmental harms). In doing so, they highlight the importance of firm beliefs and recover dynamics consistent with learning about exposure to climate change. Just

[16]Increasingly, governments are issuing directives and other guidance for extreme heat. For example, India's Heat Action Plans direct employers to adjust working hours to cooler parts of the day, offer shade and water, and provide more frequent breaks.

as consumers may fail to efficiently adapt to environmental threats because of incomplete information, emerging evidence suggests the same is true of firms.

4.2.4 Adaptation is constrained and inefficiently low

Because people and firms retain the benefits of adaptation for themselves, we might expect that the level of adaptation chosen would be efficient. The empirical literature reviewed above finds otherwise. The benefits of environmental quality are high but the degree of adaptation seen is low. Of course, poor households spend less on everything, including environmental quality. Yet recent work provides sharper evidence that adaptation is not only low but inefficiently low. We catalog reasons why private adaptation fails for many environmental harms.

First, individual investment in adaptation may simply cost more than public adaptation. There are massive economies of scale in the provision of environmental quality.[17] Second, private adaptation is also incomplete. An air purifier at home does not clean the air outside, or at work. For many environmental services and resources, like groundwater, users may not have any close private substitutes available. Third, incomplete information about environmental quality and its effect on health compromises willingness-to-pay for environmental quality. Households have low values for air quality and water quality in study after study, despite equally compelling evidence that these harms have large effects on health. Fourth, failures in other markets, including the market for credit, limit the scope for adaptation. Failures in markets other than credit may similarly distort private adaptation decisions. For example, land tenure imperfections may hinder property sales making it difficult for people to migrate in response to environmental shocks.

We find the evidence particularly strong that market failures in information and credit constrain adaptation and suppress ability-to-pay for adaptation below the true marginal value of environmental quality. Yet, while these failures are present, our sense is that, quantitatively, they do not fully explain the gap between epidemiological estimates of environmental damages and economic, revealed-preference estimates of the willingness-to-pay for environmental quality.

We notice a consistent thread in empirical studies of climate adaptation of adaptation leading to immiseration. By immiseration, we mean that climate change lowers the return to rural economic

[17] For example, municipal scale water treatment costs less than achieving equivalent water quality through individual treatment. It is easier to abate pollution at the source than to use energy to pull it out of the air in someone's home. And so forth.

production (staying in place, growing crops), but that people—particularly those who cannot afford to relocate—respond by doing the same activities as before, but more intensively and at lower productivity. We interpret these responses as constrained-optimal because, for example, migration requires a large fixed cost. If the constraints were lifted, however, these results suggest that the sign of the optimal response (moving away, farming less) would altogether change.

For all of these reasons, private action has failed to provide meaningful protection from poor environmental quality in low- and middle-income countries. In the following sections, therefore, we turn to consider the scope for collective action and regulation to reach efficient levels of environmental quality.

5 Model of environmental regulation

The model in Section 3 characterized the demand for environmental quality and the first-best level of quality. It does not discuss how to *achieve* any given level of environmental quality through social coordination or regulation. Here, we provide a complementary model that characterizes how contributions to environmental quality depend on collective action and formal regulation.

We think of this model as describing the supply side of environmental quality. The model here will serve as the point of departure for our discussion of the efficiency of different approaches to environmental regulation in practice. The set-up of the model encompasses both formal and informal regulations. Our model therefore overlaps both with models of abatement, used to characterize the cost effectiveness of environmental regulation (Kotchen, 2024), and models of the cooperative provision of public goods (Fehr and Schmidt, 1999).

5.1 Set-up

There are $N \geq 2$ citizens, indexed by i. Each citizen belongs to one of $G \geq 1$ groups, indexed by g. A single government is common to all citizens and groups.

The game has two stages. In the first stage, citizens choose a contribution to environmental quality. In the second stage, the community sanctions people who fail to contribute to environmental quality and the government subsidizes contributions (or fines pollution).

5.1.1 Actions

Each citizen i chooses a contribution $e_{gi} \geq 0$ to environmental quality. The overall level of environmental quality for group g is

$$e_g = \sum_{i \in g} e_{gi}. \tag{14}$$

The contribution e_{gi} is any action to improve environmental quality or services. We think of e_{gi}, without loss, as being denominated in units of environmental quality (i.e., the size of an action is measured by its effect on ambient quality). Contributions impose utility cost

$$h_i(e_{gi}) = \frac{1}{2}\phi_i e_{gi}^2 \tag{15}$$

denominated in units of money. While we describe the agents contributing to environmental quality as citizens, they could also be firms. Under the citizen interpretation, we might think of a person as contributing e_{gi} liters to local groundwater supply (by forgoing extraction) or planting trees storing e_{gi} tons of carbon. For a firm, a contribution might be pollution abatement that reduces riverine water pollution by e_{gi} mg per liter.

Absent any regulation, a citizen's utility is

$$u_{gi}(e_{gi}) \quad = \quad -h_i(e_{gi}) + f_g\left(\{e_{g'}\}_{g'=1}^{G}\right). \tag{16}$$

People incur disutility from exerting effort and gain f_g from the environmental quality of all groups. We assume that f_g is strictly increasing and concave in own environmental quality e_g. The environmental quality of other groups g' may also benefit group g, due, for example, to transboundary air or water pollution (Heo, Ito and Kotamarthi, 2025; Do, Joshi and Stolper, 2018; Lipscomb and Mobarak, 2017; He, Wang and Zhang, 2020). If so, we likewise assume f_g is strictly increasing and concave in these additional arguments.

In our model e_{gi} is the contribution of i to environmental quality. This set-up has a natural interpretation when e_{gi} is an environmental good. If e_{gi} were an environmental bad, like pollution, we could just as well define e_{gi} as emissions that harm the environment, instead of raising quality.

In this case, $h(e_{gi})$ would be re-defined as a positive, decreasing and convex function of emissions and $f_g(\cdot)$ an increasing and concave function of abatement, where abatement is given by $abate_{gi} = \overline{e}_{gi} - e_{gi}$. The government might then use Pigouvian taxes $\tau_g < 0$ on emissions to reduce pollution. We will sometimes switch to this opposite-signed case when discussing empirical research for settings where e_{gi} is more naturally an environmental harm.

5.1.2 Timing and information

In the first stage of the game, citizens choose e_{gi} based on their expectations of the government and group sanctions that will be imposed in stage two.

At the beginning of the second stage, citizens all observe a common signal of each person's contribution to the public good. Citizens observe an informal signal $\tilde{e}_{gi}$. For each agent in group g, with probability π_g their true contribution becomes known to all others in their group, $\tilde{e}_{gi} = e_{gi}$. With probability $(1-\pi_g)$, their action remains hidden and $\tilde{e}_{gi} = 0$. The parameter π_g therefore governs the quality of the signal. Higher π_g yields better information within a group, for example due to a closer-knit community or closer monitoring of the public good. The government observes a different signal $\hat{e}_{gi}$, governed by probability π, with an analogous structure to the within-group signal. The probability π reflects the government's investment in monitoring, agency problems in gathering information about pollution and other like factors.

While signals of each person's contribution are imperfect, all players can observe the aggregate level of environmental quality e_g. For example, they may all know that a source of water is not potable, but not see whose sewage has contaminated it.

After the signals are realized, both the citizens and the government can take actions on the basis of what they have learned. Citizens can punish other players in their group based on the signals they observe $\{\tilde{e}_{gi}\}_{i=1}^{N}$ and environmental quality e_g.

The government has two policy instruments. First, it can make transfer payments t_i to each person. Second, it can set subsidies (or taxes) of τ_g per unit of each citizen's observed contribution to environmental quality in group g. We assume the government can announce these policies up-front and commit to carry them out. At the end of the second stage, the government pays out taxes and transfers based on the signals $\{\hat{e}_{gi}\}_{i=1}^{N}$ it observes and environmental quality.

5.1.3 Payoffs

There are two kinds of sanctions in the second period that affect citizens' payoffs: informal sanctions from own-group members and formal sanctions imposed by the government.

Citizens can impose informal sanctions on others in their own group. After observing $\tilde{e}_{gi}$ and e_g, group g collectively decides whether to punish person i. Punishment is a social penalty which causes a utility loss of $P_g > 0$ for the person punished. The group norm is to impose punishment if a person's contribution to environmental quality falls below a certain level, $\underline{e}_{gi}$, which may differ for each agent in the group. We do not model any coordination or collective action problems during the punishment phase, but assume that communities can commit to their norms in advance. In a dynamic game of multiple stages, these problems would correspond to constraints on the incentive compatibility of punishments after a violation of norms is observed. We may think of such constraints as limiting the size of P_g that can be imposed by the group.

The second set of sanctions is set by the government. The government operates under two constraints. First, following Besley and Persson (2009), we adopt an operational definition of state capacity as the government's ability to tax. The state capacity constraint is

$$\left|\tau_g \hat{e}_{gi}\right| \leq \kappa \tag{17}$$

for state capacity $\kappa \in [0, \infty)$. The parameter κ limits the amount of subsidies or taxes that the planner may impose. We think of κ as arising from several more fundamental limits. It may be that the government is not able to enforce tax collection. For example, in a case where the government is taxing a public bad, like pollution, there may be limited liability in the government's ability to collect. Or, there may be political limits on the ability to tax, because citizens do not have confidence in the accuracy of signals $\hat{e}_{gi}$ and so find large taxes on the basis of those signals unjust.

The second constraint on government policy is the budget constraint

$$\sum_{i=1}^{N} (t_i + \tau_g \hat{e}_{gi}) = 0. \tag{18}$$

The sum of government transfers and Pigouvian subsidies or taxes is zero.

Utility is the citizen's benefit from environmental quality after exerting effort and receiving informal punishments, transfers and subsidies

$$
\begin{aligned}
u_{gi}(e_{gi}) &= -h_i(e_{gi}) + f_g\left(\{e_g\}_{g=1}^G\right) \\
&\quad -P_g\,\mathbb{I}\left\{i \text{ is punished}\right\} + t_i + \tau_g \hat{e}_{gi}.
\end{aligned} \tag{19}
$$

Utilitarian social welfare is the sum of $u_{gi}(e_{gi})$ (19) across all people i and groups g.

5.2 Environmental quality under informal and formal regulation

Regulation shapes people's contributions and therefore environmental quality in equilibrium.

Definition (Equilibrium of the environmental quality game)**.** *A Nash equilibrium for the regulation game is a set of citizens' contributions $\{e_{gi}\}_{i=1}^N$, social norms $(P_g, \{\underline{e}_{gi}\}_{i\in g})$, and government tax and transfer policies $(\{\tau_g\}_{g=1}^G, \{t_i\}_{i=1}^N)$ across all groups such that (i) contributions to environmental quality are best responses for people taking government policy and group norms as given and (ii) the government state capacity and budget constraints are satisfied.*

In the first-best allocation, the marginal benefit of environmental quality for *all* equals the marginal private cost of effort for each agent, conditional on the contributions of all other agents (Samuelson, 1954).

Definition (First-best environmental quality)**.** *The first-best (FB) allocation is a level of environmental quality $\{e^*_{gi}\}_{i=1}^N$ such that*

$$
\sum_{j=1}^N \frac{\partial f_{g(j)}\left(\{e_g\}_{g=1}^G\right)}{\partial e_{gi}}\Bigg|_{\{e^*_{gj}\}_{j=1}^N} = \phi_i e^*_{gi} \tag{FB}
$$

for all agents.

A regulation that achieves the first-best allocation is *fully efficient*. A regulation is *cost effective* if it equalizes $\phi_i e_{gi}$ for all agents i, though it may not yield the first-best contributions $\{e^*_{gi}\}_{i=1}^N$ (Kotchen, 2024). The cost effective allocation for any given level of environmental quality is unique. The fully efficient allocation is the unique cost effective allocation that achieves the optimal level of environmental quality.

A regulation is *positive net benefit* if it results in higher utilitarian social welfare than the status quo. A regulation can have positive net benefits without being cost effective. Conversely, a regulation can be cost effective without having positive net benefits. Many regulations may be positive net benefit but not cost effective or fully efficient. It is especially likely that regulations will be positive net benefit but not cost effective if the level of the $\{e_g\}$ are low, such that marginal improvements to the $\{e_g\}$ have high returns $f_g'(\cdot)$ and can therefore cover the added costs of inefficient regulation.

We now describe what levels of environmental quality can be sustained with different types of environmental regulation, both informal and formal.

5.2.1 Informal regulation alone

Consider first a regime where there is no government and people observe only group norms. The group announces norms $(\underline{e}_{gi}, P_g)$. Agents view the probability of being punished as

$$\Pr(i \text{ is punished}|e_{gi}) = \underbrace{(1-\pi_g)}_{\text{Action hidden}} + \underbrace{\pi_g \mathbb{I}\{e_{gi} < \underline{e}_{gi}\}}_{\text{Action observed}}. \tag{20}$$

Agents see a sharp inflection point in punishment based on whether they adhere to the norm $\underline{e}_{gi}$ or not. If they do not adhere to the norm, they might as well contribute nothing. Therefore a person contributes at the norm when

$$\pi_g P_g \geq \frac{1}{2}\phi_i \underline{e}_{gi}^2 \tag{IC1}$$

with $e_{gi} = 0$ otherwise. In this expression, information π_g and punishment P_g are complements. An increase in π_g, through better monitoring, for example, implies that effort can be sustained at a lower level of punishment.

Definition (Informal best)**.** *The informal-best (IB) environmental quality is an allocation $\{e^{*IB}_{g'i}\}_{i\in g'}$ for group g' such that*

$$\sum_{i\in g'} \frac{\partial f_{g'}\left(e_{g'}|\{e_g\}_{g\in G\setminus g'}\right)}{\partial e_{gi}}\Bigg|_{e_{gi}=e^{*IB}_{g'i}} = \phi_i e^{*IB}_{g'i} \tag{IB}$$

for all agents $i \in g'$.

In the informal-best allocation, each group follows a set of norms such that the marginal benefits of contribution for all members in a group equals their marginal cost of effort, taking as given the levels of quality provided by all other groups.

Lemma 1 (Spillovers across groups)**.** *If there are spillovers from contributions across groups*

$$\frac{\partial f_g(\{e_g\})}{\partial e_{g' \neq g}} > 0$$

for at least one group, the informal best allocation (IB) *will not coincide with the first-best allocation* (FB).

Proof. Suppose the allocations did coincide. Then for any group g'

$$\begin{aligned}
\phi_i e_{gi}^* &= \sum_{i=1}^{N} \frac{\partial f_g'\left(\{e_g\}_{g=1}^G\right)}{\partial e_{gi}}\Bigg|_{\{e_{gi}\}_{i=1}^N = \{e_{gi}^*\}_{i=1}^N} \\
&= \sum_{i \in g'} \frac{\partial f_g'\left(\{e_g\}_{g=1}^G\right)}{\partial e_{gi}}\Bigg|_{\{e_{gi}\}_{i=1}^N = \{e_{gi}^*\}_{i=1}^N} + \sum_{i \notin g'} \frac{\partial f_g'\left(\{e_g\}_{g=1}^G\right)}{\partial e_{gi}}\Bigg|_{\{e_{gi}\}_{i=1}^N = \{e_{gi}^*\}_{i=1}^N} \\
&= \phi_i e_{gi}^* + \sum_{i \notin g'} \frac{\partial f_g'\left(\{e_g\}_{g=1}^G\right)}{\partial e_{gi}}\Bigg|_{\{e_{gi}\}_{i=1}^N = \{e_{gi}^*\}_{i=1}^N} \\
0 &= \sum_{i \notin g'} \frac{\partial f_g'\left(\{e_g\}_{g=1}^G\right)}{\partial e_{gi}}\Bigg|_{\{e_{gi}\}_{i=1}^N = \{e_{gi}^*\}_{i=1}^N} .
\end{aligned}$$

The last line is a contradiction, under Lemma 1, because with spillovers the contribution of people outside of group g' to environmental quality within g' is strictly positive. □

Corollary 1 (Limits of informal regulation)**.** *In the absence of spillovers, allocation* (IB) *will coincide with* (FB) *while reducing aggregate welfare when* $\pi_g < 1$.

Proof. Without spillovers, (FB) and (IB) define the same profile of contributions $\{e_{gi}^*\}$. With informal regulation, the punishments required to induce private abatement to the level (IB) is given by (IC1). Unless $\pi_g = 1$, inducing (IB) will always lead to some spurious punishment $(1-\pi_g)P_g$, which lowers aggregate welfare. □

Proposition 1 (Limits of informal regulation)**.** *The informal best allocation may not raise welfare relative to laissez faire.*

Proof. Consider the private abatement provision decisions in (IC1). There is always a sufficiently large punishment P_g to make the expected losses from deviating from social norms less costly than expending a given level of effort. However, even the smallest level of punishments which satisfies (IC1) across all groups may impose aggregate welfare costs which offset the gains from higher environmental quality. □

Corollary 2 (Limits on punishment)**.** *If the set of feasible social norms limits the maximum socially-acceptable punishment $\overline{P}_g$, a group may be unable to implement the informal-best* (IB)*.*

Proof. This follows from the incentive constraints (IC1) and (IC1'); the right hand side may be larger than P_g fixing τ_g and $\underline{e}_{gi}$. □

There are therefore three limitations on informal regulation in our model. First, since groups care only about their own members' costs, when there are spillovers they do not set norms ambitious enough to reach the first-best environmental quality. Second, informal regulation is a costly technology because signals are noisy. Inducing a high level of effort may require large punishments when people do not contribute; these punishments will be imposed in equilibrium with some probability because signals are imperfect. Since punishment is costly, groups, even without spillovers, may not choose norms to implement the first-best level of environmental quality.[18] Third, while P_g is set outside of our model, it is possible that this punishment is not great enough to sustain informal-best contributions.

5.2.2 Informal and formal regulation together

We now consider a regime where groups may impose sanctions as before and the government also sets transfers and subsidies. Each person has payoffs as in equation (16). People have to choose their contributions prior to knowing the signals received by their group and the government. When the government also regulates pollution, the punishments needed to sustain a level of social norms must satisfy

$$\pi_g P_g \geq \frac{1}{2}\phi_i \underline{e}_{gi}^2 - \tau_g \pi \underline{e}_{gi}. \tag{IC1'}$$

[18] In this way the trade-off in the model is similar to that in agency models with risk-averse agents (Bolton and Dewatripont, 2005). The principal may give weaker incentives to the agent to reduce the risk they bear. Here, people are risk neutral, yet the group may give weaker incentives to its members to avoid imposing costly punishments.

Stronger formal regulation, in the form of either larger subsidies τ_g for contributions or greater monitoring π, lessen the level of punishment P_g needed to sustain contributions for a given social norm $\underline{e}_{gi}$. Or, for a given level of punishments, a more ambitious norm can be chosen. In this way, formal regulation relaxes the limits of informal regulation. A higher state capacity κ allows the government to raise τ_g and, indirectly, groups to choose lower levels of P_g, more ambitious $\underline{e}_{gi}$, or some combination of both.

The advantages of formal regulation depend on the ability to tax and any differences in signal quality vis a vis informal regulation.

Lemma 2 (Pigouvian taxation)**.** *Suppose the state capacity constraint κ does not bind. Then formal regulation alone can achieve the first-best* (FB)*.*

Proof. Suppose there are no group norms. Then agents abate pollution up to the point

$$\phi_i e_{gi} = \tau_g \pi. \tag{IC2}$$

The left-hand side of the above (IC2) is the right-hand side of the definition of the first-best allocation (FB). The left-hand side of the first-best definition varies at the group level. The government can therefore choose τ_g group-by-group to match the left-hand side of (IC2), for any π, to give all agents socially efficient incentives for effort. □

In this case, the government is allowed to raise τ_g without bound. A deficiency in monitoring can be made up for by raising subsidies until the expected value of contributing at the efficient level is restored (as, in the Becker (1968) model of crime, poor monitoring can be offset by ever-higher punishments). In practice, finite κ may make this solution impossible, as the government does not raise enough revenue to finance subsidies that support the first-best. When κ is binding, this will leave open the scope for informal norms to improve efficiency—even though these norms have ancillary costs via mistaken punishment. The central government may choose to focus its limited capacity on externalities that generate spillovers across groups and are therefore not well-regulated by norms.

Can informal regulation bridge the gap to efficient formal regulation? Perhaps not. Suppose that the social norm is simply: punish if the contribution of any person is less than $\{\underline{e}_{gi}\}$, but that the socially efficient level of contribution is greater than this norm, $e^*_{gi} > \underline{e}_{gi}$. We may expect that informal regulation would weaken the state capacity constraint κ, just as formal taxation lowers the level of punishment required to implement a given social norm $\{\underline{e}_{gi}\}$. However, the incentive constraint (IC2), which dictates the contribution to environmental quality *at the margin*, is unchanged in the presence of informal regulation. The government still has to raise enough funds to finance a subsidy τ_g dictated by π and the first-best allocation itself (FB). As long as the government cannot observe each group's norm, it cannot, for example, pay subsidies only for the additional abatement effort that agents have undertaken, beyond what they would contribute on their own due to norms.

5.3 Discussion

This model of regulation integrates classical ways of thinking about externalities. The limiting case of informal regulation with perfect information, $\pi_g = 1$, follows Coase (1960) in allowing for coordination on an efficient outcome. In our model, this outcome is reached by social norms that punish agents in utility terms, rather than being mediated bilaterally through monetary transfers. The general case of informal regulation with imperfect information follows from the tradition of Ostrom (1990), who describes collective action problems over the environment or common resources as games in which contributions must be sustained by equilibrium play, and institutions established by the players, rather than a central "Leviathan." Finally, the case of formal regulation is Pigouvian (Pigou, Aslanbeigui and Oakes, 1920), in which the Leviathan is able to impose taxes to correct externalities.

These several cases illuminate what is distinct about environmental regulation in developing countries. The relative poverty of citizens and lower state capacity of governments lower the feasible degree of formal regulation (through transfers and subsidies). State capacity may also weaken monitoring. With weak monitoring, reaching the first-best allocation requres *greater* levels of subsidies, which the fiscal constraint will not allow. A pincers movement of low monitoring capacity and fiscal capacity together cuts off the efficacy of regulation.

The low efficacy of constrained formal regulation may lead to a social choice to stick with laissez faire. In the vacuum left by formal regulation, informal regulation can set norms around environmental quality and resource use. Such norms, though, generally incur a utility loss through imperfect monitoring generating mistaken punishments. Moreover, norms are only effective at a local scale, and are not ambitious enough when externalities spillover across groups, far beyond the bounds of social coordination and punishment. For both of these reasons, informal regulation through norms will result in underprovision of environmental quality, especially for large-scale environmental problems. Ostrom acknowledged this failure of collective action in her later work (Dietz, Ostrom and Stern, 2003).

6 Evidence: collective action and informal regulation

Natural resources and environmental quality are often managed at a local scale, either by groups of people interacting without government or through local institutions formed of group members. Collective action over the environment and common pool resources have become a paradigm of economic theory (Ostrom, 1990; Ostrom, Gardner and Walker, 1994). Our model of informal regulation is a simple example of such a public goods game.

We take Ostrom's definition of informal regulation as regulation by neither the market nor the state. We divide our discussion of informal regulation into two segments. First, under collective action, we consider situations where the users of a resource themselves choose how much to extract and whether and how to sanction fellow users, but have not delegated authority to a mediating institution. Under the head of informal regulation, we consider similar situations, but where the group has delegated their authority to a leader or institution. The line between these cases is not always so bright, but we find the distinction useful.[19]

Despite an avalanche of prior research, our view is that the question of whether local governance of the commons has been successful remains open.[20] There is a vast theoretical and lab experimental literature examining sufficient conditions for cooperation. Ostrom and others have

[19] Some institutions exist more or less solely to monitor and enforce norms that developed among users; i.e., as a kind of equilibrium selection device. Bardhan (1993) draws the line at a similar position, between "traditional cooperative institutions" and "the new self-governing associations, based on shared reciprocity and defined rights, common lobbying interest, and legal-rationalistic norms (like regular auditing of accounts or checks and balances on arbitrary use of power)."

[20] Casey (n.d.) (this volume) discusses decentralization and state capacity, and covers related themes. A larger literature in development economics studies the conditions under which communities maintain public goods, including the informational advantage they hold over a central government. This work tends to focus on delegation of control and resources to the community rather than analyzing the endogenous institutions that arise to manage local public goods.

provided many rich examples of longstanding institutions to address local commons problems around the world. Yet, we see gaps between the positive, qualitative findings of this agenda and the need for normative analysis of efficiency. Observing some degree of cooperation or restraints on use is not enough for an institution to be deemed successful. Almost no research on cooperative institutions attempts to measure efficiency (FB). The goal of analysis should be to push towards quantifying whether institutions approximate first-best efficiency or, if they are constrained away from efficiency, quantifying the constraints and directions for second-best optimality.

6.1 Collective action

6.1.1 Theoretical and lab experimental background

Externalities in resource use (environmental quality) may lead to over-exploitation of a resource. The main thesis of Ostrom (1990) is that institutions that are neither the state nor the market have successfully governed certain common resources over long periods. One way to achieve high efficiency in resource use is for a group of users who repeatedly interact to follow norms, like $\underline{e}_{gi}$, for how much each party should use or contribute.

The informal-best allocation (5.2.1) in our model is an example of an allocation, enforced by punishments for the violation of norms, that can improve on laissez faire. In our two-period version of the game, monitoring with probability π_g observes the true contribution, and is used to levy punishments P_g. In a repeated game these parameters are endogenously determined by the specification of information and actions. The structure of monitoring and communication will determine whether norm violations $e_{gi} < \underline{e}_{gi}$ are detected. The structure of outside options, the availability of social or economic sanctions, and the patience of the players will determine what punishments P_g can be credibly imposed and what outcomes these punishments can sustain in equilibrium.

One difficulty in applying the lessons of repeated games to resource problems is that the main prediction tends towards "anything can happen." Famously, the folk theorem of repeated games states that, with sufficiently patient players, any individually rational outcome can be sustained in equilibrium. Seabright (1993) and Baland and Platteau (1996) discuss at length the application of repeated games to common resource problems. Dutta and Sundaram (1993) study the Markovperfect equilibria of a common resource game and find that, even within this restricted strategy space, there is a wide range of equilibria, including equilibria that do not generate over-exploitation of the resource. Sethi (1996) and Sethi and Somanathan (1996) study the equilibria of repeated common resource games, where the static stage game generates over-exploitation of a resource in equilibrium. They find that there are a multiplicity of stable norms of cooperation that could evolve.

A large literature on lab experiments varies the set-up of a game to study changes in cooperation and, perhaps, discipline the panoply of theoretical outcomes. Experiments have considered, for example, how communication among users (Hackett, Schlager and Walker, 1994; Ostrom, Gardner and Walker, 1994), the rules for allocation or punishment (Walker et al., 2000; Casari and Plott, 2003), or inequality (Cardenas, 2003) shift cooperation. Lab-in-the-field studies measure correlations between user or leader strategies in games of cooperation and their real-world cooperative behavior (Fehr and Leibbrandt, 2011; Kosfeld and Rustagi, 2015).[21]

6.1.2 Empirical evidence

Empirical research on common resources is needed because of the wide range of theoretical outcomes and the lack of realism and stakes in the lab. Bardhan (2000) wrote a quarter-century ago, of research on common resources, that "Much of the existing empirical literature on these issues is social-anthropological, without a great deal of quantification. Among other things, this makes isolating and deciphering the effect of a particular factor rather difficult." We find that this situation has improved, but only recently and partially.

Studying the determinants of cooperation in the real world is difficult. The proper unit of analysis is a group or resource. Yet different groups form endogenously in response to resource characteristics and the returns from coordination. Wade (1982*a*) writes that a concern for the village welfare arises not because of a moral sense of the community, but from "a tightly individualistic assessment of mutual interest." The sample of institutions that exist to study is thus selected on

[21] For example, Kosfeld and Rustagi (2015) ask forest-group leaders from Ethiopia to participate in a lab-in-the-field experiment in which they can choose whether to punish members of their group after observing their play in a cooperation game. They then correlate leaders' tendencies to punish with the real-world conservation of the forest in their purview, finding that tree growth is highest in forests under leaders who punish those who contribute less to environmental quality. These findings cannot be taken as causal. There are only four such leaders in the sample and reverse causation or omitted variables may lead to healthy forests having leaders of a certain type.

their fit for the environmental problem at hand.

Bardhan (2000) offers a careful descriptive analysis of cooperation among irrigation tank user groups in Tamil Nadu, India that illustrates the difficulty. He regresses a proxy for cooperation (system maintenance) on group characteristics and finds that maintenance is higher: (i) in areas with lower inequality of landholding; (ii) when a system employs a guard; (iii) when a user group works jointly with the Public Works Department; and (iv) when the irrigation infrastructure can be used for a longer part of the year. Bardhan (2000) acknowledges, indeed illuminates, a web of endogeneity between these outcomes. For example, groups that use guards have been around longer and groups that are more likely to work with the Public Works Department are in water scarce areas, where scarcity itself may affect cooperation.

One way to probe the efficiency of cooperation is to see how cooperation responds to external shocks. Haseeb (2020) studies canal irrigation in Pakistan. Irrigation canals are a classical commons (Wade, 1982*a*; Ostrom, 1994). The high fixed costs of water infrastructure necessitate cooperation to build a canal but, once it has been built, farmers have an incentive to overdraw. A Pareto efficient allocation would allocate all farmers water to equalize their marginal returns. If farmers high up on the canal use too much water, their marginal returns will be lower than for farmers at the tail-end of the canal, for whom water is scarce.

Haseeb (2020) considers how canal users respond to water shortages. Both social norms and, to a lesser extent, Irrigation Department rules control water use. This situation parallels our model case in which both formal and informal sanctions apply simultaneously. The paper finds, first, that in response to low weekly rainfall, farmers break norms: incidents of water theft from canals increase. However, the pattern is reversed for longer-term shocks. When the groundwater quality in an area permanently declines, increasing the relative value of canal water, cooperation, measured by the availability of water for users at the tail-end of the canal, instead *increases*, particularly on canals where farmers at the head and tail are more likely to be from the same caste. Haseeb (2020) argues that long-term scarcity increases the need to organize. One way to interpret this result would be that the effective P_g of exclusion from the canal becomes more severe when groundwater is not available as a substitute, which improves the range of cooperative outcomes that can be sustained.

The efficiency of allocation cannot necessarily be increased by moving from cooperation or quotas to markets, when other market failures stop markets from working well. Espin-Sanchez and Donna (2025) study the misallocation of water between rich and poor farmers. They assume that the two groups have similar production functions in agriculture. The paper gives evidence that poor farmers are liquidity constrained and so cannot buy as much water as would be efficient. To relieve somewhat this inefficiency, and any social strain that it might bring, the justice system adapted to be lenient with poor farmers who stole water (Donna and Espín-Sánchez, 2021).

Social structure has an important mediating role in how communities respond to environmental shocks. In an idealized model, agents respond to shocks by shifting their production choices along an efficient frontier. Such a response may not be possible if it requires coordination. Haque (2025) studies the case of farmer responses to rising soil salinity in Bangladesh. The technically optimal response to higher salinity, which reduces rice yields sharply, is to switch from cropping rice to aquaculture (i.e., farming shrimp). Making this switch, however, requires coordination, because the minimum efficient scale for aquaculture is far larger than for rice, so many farmers have to switch together and merge their parcels. Haque (2025) finds that land consolidation is more likely to occur in areas with less land fragmentation and more religious diversity. He argues that religious diversity, here meaning a balance of Hindu and Muslim residents, contributes to land consolidation by solving a contracting problem over the returns to consolidated parcels. It is likely that any potential coalition of farmers will include adherents of both religions, since plots are interspersed. Yet a farmer of the minority may fear that, after consolidation, he will not be paid his share of the return. The paper argues that farmers can better commit to informal contracts over consolidation in diverse communities, where elections are contested and power is balanced between groups.

6.2 Informal regulation

As the scale of a resource grows, so does the need for mediating institutions to govern it. Users form institutions to embody rules-in-use through monitoring and enforcement and to reduce the transaction costs of collective action. There are two main questions about these institutions. First, the positive question of how informal institutions change resource use. Second, the ultimate, normative question of whether informal or local management is preferred to state management or laissez faire.

A body of evidence suggests that local control of common resources reduces resource use.

Somanathan, Prabhakar and Mehta (2009) find that village council management maintains forests as well as does state management, but at one-seventh of the cost. This study uses an early version of a border regression discontinuity design, by restricting the sample to pairs of polygons on either side of the border between a state-run forest and council-run forest. Edmonds (2002) studies the effect of local control on forest use in the Arun valley of Nepal. The paper estimates regressions showing that areas placed under the control of local forest user groups extract fewer resources from the forest than areas that remain under the control of the national government.

If contributions to environmental quality are too low, under laissez faire, then reductions in resource use (increased contributions, in the framework of our model) can be seen as moving in the direction of efficiency. But such directional statements do not show that local management is efficient.[22] Efficiency is a more stringent standard, under which it must hold both that (i) marginal costs of contributions are equal across all users and (ii) the common marginal cost of contributions equals the marginal benefit of environmental quality for all users together (5.2). The analogy, for resource use, is that the marginal benefits of use must be equal across all users and equal to the marginal cost for all. To characterize efficiency therefore requires measuring the entire distribution of the marginal costs of extraction and/or marginal returns to resource use.

The equality of resource use can proxy for allocative efficiency, between users, if all users have the same production function. (Of course, even under this strong assumption, it may be that total use is too high or too low to be fully efficient.) Ostrom and Gardner (1993) study institutions for managing irrigation canal water in Nepal. On canals, equal water use is efficient if all farmers have the same marginal return to water and there are no losses in water transport or opportunity costs of water. Ostrom and Gardner (1993) find that the gap between water availability for farmers at the top and farmers at the bottom (i.e., the tail-enders) of canals is smaller for farmer-run than for government-run irrigation systems, "presumably because farmer-managed systems are more likely to reach bargaining solutions about their own operational rules that more effectively take tail-ender interests into account." This conclusion, however, requires many unsubstantiated ceteris paribus assumptions, in addition to those about returns to water.

Garcia and Belmar (2025) more closely approximate the ideal of comparing marginal returns

[22] As also acknowledged by the authors. Edmonds (2002) writes "Similarly, nothing in this paper suggests that the level of resource extraction associated with government-initiated community forestry is 'optimal' in any sense."

across users, in their study of the efficiency of water use for 12 water basins in Chile. Chile has full, tradeable rights to water, yet it can be difficult to judge compliance with rights, since actual water availability fluctuates. The authors hypothesize that Water Boards, local organizations established by users to enforce water rights and resolve conflicts, should increase the efficiency of surface water use in agriculture. The paper tests for efficiency by regressing the value of agricultural yields on rainfall shocks in different locations. The idea is that if surface water is allocated efficiently, then rainfall shocks (i.e., marginal doses of additional water) should have equal effects on yields in all areas. Garcia and Belmar (2025) find, by contrast, that marginal water increases yields by 42% per cubic meter per ha-month at the mouth of a river but has no effect (an imprecise null) roughly 200 km upstream. This pattern is consistent with over-extraction by upstream users. The paper shows that this pattern of differential returns along the river is observed only for water basins that lack a Water Board.

Whether informal regulation is more efficient than group collective action is ambiguous, in general. Informal institutions may be delegated the capacity to monitor and punish and execute these rules more reliably than users could manage on their own. A concern with informal regulation, and with formal regulation as well, is that the existence of an authority may crowd out enforcement through norms. Once some user becomes the "leader," or some quasi-state is involved, perhaps resource use becomes their problem, rather than a shared responsibility.

Community monitoring of common pool resources has received disproportionate attention in the empirical literature. Community monitoring can be viewed as one instance of a larger push for community-driven development, not only for the environment but in other domains also. As community monitoring increases π_g expected sanctions for non-compliance should also increase, possibly raising compliance with group norms (IC1). Kahsay and Bulte (2021) run a randomized experiment on the monitoring of forest use in Ethiopia. Forest User Groups are groups of members whom the government has given exclusive right over forest blocks of several hundred hectares. The experimental design compares arms in which forest group leaders are assigned to be monitored either by government officials or by their own users. They find that top-down monitoring raises the consumption of forest group members by 0.2σ while facilitating internal monitoring by group members has no significant effect on consumption. The authors speculate that top-down monitoring is more likely to replace group leaders and may therefore deter self-interested leaders from selling off access to the forest. They argue that user monitoring does not work because monitoring is itself a public good that may be under-provided.

A series of loosely coordinated experiments on community forest and water resource monitoring found support for a relationship between monitoring and quality of the resource (Ferraro and Agrawal, 2021; Slough et al., 2021). Increased monitoring in one location can displace resource use to other less monitored locations (Eisenbarth, Graham and Rigterink, 2021). These spillovers across groups imply inefficiency of informal-best regulation (5.2.1) in our model. Improvements in monitoring technology, for example through satellite data, crowd-in monitoring effort (Bernedo Del Carpio, Alpizar and Ferraro, 2021; Slough, Kopas and Urpelainen, 2021), but do not necessarily reduce resource use (Christensen, Hartman and Samii, 2021). This suite of experiments relies on external interventions to vary community monitoring exogenously. They are therefore, at best, indirect tests of the core Ostrom hypothesis that institutions adapt to manage common resources on their own.

A major advantage held by resource users or citizens in environmental monitoring is that they may have better information, or stronger incentives to attend to environmental problems, than a formal authority. Buntaine, Zhang and Hunnicutt (2021) study citizen (NGO) monitoring of waterways in China. They find that such monitoring reduces pollution when information is shared with government authorities, but that disseminating this information to the broader public has no effect. Buntaine et al. (2024) run an experiment in which citizen volunteers, recruited through NGOs, file complaints against firms in China for violations of pollution standards. The paper finds that firm violations of air and water pollution standards decline from 0.9% of days in the control group to 0.3% of days in a treatment group where these complaints are publicly amplified over social media. The treatment effect on violations is one-third as large when complaints are made to the regulator in private. An interesting aspect of the setting is that the citizen complaints are based on pollution measures gathered and publicly posted by the regulator. The treatment is therefore not giving the regulator new information on pollution, but rather focusing the regulator's attention on a violation it already knew about.

A leader is a coordination device that may select an equilibrium with higher or lower contributions from group members. Jack and Recalde (2015) study the role of leadership with an experiment in which community members pool their funds to buy (environmental) books for a local school, to be used by all. The paper finds that when a leader (community president) makes a public contribution before members make their own decisions it roughly doubles contributions by members. This higher level of contribution is only observed when leaders move first; allowing a randomly selected community member to make an initial public contribution has no effect on their peers' contributions. Lab experiments have probed the mechanisms by which leadership may improve cooperation.[23]

This collection of results suggests that: (i) monitoring (π_g) and enforcement (P_g, τ_g) are complementary; (ii) citizen enforcement (P_g) against polluters or norm violators struggles on a peer-to-peer level; (iii) citizen monitoring (π_g) can be an effective complement to formal enforcement (τ_g). Information alone is not enough to change user or firm behavior, unless there are informal (group leader) or more formal (water board, regulator complaints) channels through which this information can spur enforcement.

We see the main direction of future research as being quantification of the efficiency of collective or informal management. Many past studies, both qualitative and quantitative, have had a narrow positive goal: to test the null of no cooperation. The popular reading of Ostrom (1990), Ostrom (1994) and subsequent work has retained one core finding, that we can reject this null for many common resources, despite the absence of the state. Yet, the rejection of pure laissez faire does not imply efficiency. Our reading is that there is scant empirical evidence that directly measures efficiency, and perhaps none that plausibly shows collective action or informal regulation to be fully efficient. We should not confuse the existence of a cooperative or informal institution, or the long tenure of such an institution, with a claim about its efficiency.

7 Evidence: Formal regulation

This section presents evidence on the efficacy of formal environmental regulation in developing countries. The overwhelming theme is that low state capacity, particularly for monitoring ($\pi \to 0$), weakens regulation and indeed changes the very *form* that regulation takes on. When contributions

[23] In a laboratory study with subjects in the Netherlands, Engl, Riedl and Weber (2021) have subjects play two public goods games in parallel. In one game, there may or may not be a central authority who punishes subjects when $e_{gi} < \underline{e}_{gi}$. They find that the existence of this leader in one game spills over to improve cooperation in the second, parallel game without a leader. Abatayo and Lynham (2016) find that, conditional on the level of norm $\underline{e}_{gi}$ chosen, varying whether that norm was selected by group users or imposed exogenously does not affect cooperation.

to environmental quality are badly observed, then the taxes or subsidies needed to correct externalities on the basis of these observations must be large. Such large taxes and subsidies, however, often violate the private incentives of the agents who must enforce or disburse them. As a result, governments retreat to coarse regulations that are blatantly inefficient but easier to enforce. These coarse regulations have mixed efficacy in reducing pollution and likely have high costs. However, they may have social benefits greater than their costs if the returns from improving environmental quality are high enough.

7.1 Formal command-and-control instruments

We call a regulation "command-and-control" if a government directly chooses the action or contribution to environmental quality of every agent. These regulations take a range of forms, from bans to rations, quotas and standards. In each form a regulation may be coarse, imposed at the same level $\underline{e}_{gi} = \underline{e}$ for all agents, or tailored, for each agent, to the extent that the regulator's monitoring and enforcement capacity will allow.

7.1.1 Bans and rations

The coarsest way to reduce pollution is to shut down some economic activity contributing to that pollution altogether. India famously took this approach, to combat air pollution staining the Taj Mahal, by ordering factories in a roughly 10,000 km^2 "Taj Trapezium" zone around the tomb to close (or switch fuels) (Mehta, 1986). Another court case ordered thousands of factories to relocate out of the polluted capital city of Delhi to new industrial zones on the outskirts (Gechter and Kala, 2025). China's Two Control Zones policy set tighter rules for 175 prefectures exceeding ambient air quality standards; in those places small power plants were shut down and larger plants mandated to install abatement equipment (Tanaka, 2015).

We have scattered evidence on the efficacy of such sweeping bans. China's Two Control Zones policy targeted emissions from the power sector, comprised at that time almost exclusively of coal plants, a major source of sulfur dioxide (SO_2) and particulate matter (PM) emissions. This policy succeeded in reducing SO_2 emissions (He, Huo and Zhang, 2002). Tanaka (2015) uses a difference-in-difference design to estimate that infant mortality declined 20% in TCZ areas relative to areas not targeted by the policy. India's policies appear to have been less successful. Greenstone and Hanna (2014) study 16 "Action Plans" imposed by India's Supreme Court, largely in the period from 2003 to 2006. A Supreme Court Action Plan (SCAP) is a city-level hodge-podge of measures including industrial relocations and closures but also technology standards for transportation (for example, the adoption of Compressed Natural Gas in public transportation). They find no effect of SCAPs, in general, on ambient levels of PM, SO_2 or NO_2. They report some evidence that the ambient pollution growth rates (as opposed to levels) decline after a more narrowly targeted policy, requiring installation of catalytic converters in new cars in 49 major cities. Gechter and Kala (2025) estimate that banning some 20,000 factories from New Delhi slightly reduced ambient fine particulate matter ($PM_{2.5}$) concentrations in areas that had denser initial concentrations of firms, but that these reductions fade out by four years after the start of the ban.

Why the starkly different results? One interpretation is that they follow from the differences in policy design: not all bans are created equal. China's TCZ was national in scope and targeted at the power sector, the single largest source of SO_2 emissions and a major contributor to PM. The power sector causes large transboundary spillovers in air quality due to the distance that stack emissions travel (as in our Lemma (1)). India's SCAPs and industrial bans were local in scope, at the level of a single city or at best a small region, and weakly targeted, as they addressed only an arbitrary subset of emissions sources. Both policies are coarse, partial instruments but China's combination of bans and standards was broader, better targeted and more stringent. Our model anticipates exactly this difference, because local groups will choose to set regulations $\underline{e}_k$ on abatement of transboundary pollution that are weaker than is socially efficient. In India, more stringent, national-level regulations on power sector emissions were proposed in 2015 but have languished for a decade, without being enacted, over concerns about abatement capital costs (India Ministry of Environment Forest and Climate Change, 2015; Bhattacharji, 2025). Guttikunda and Mohan (2014) argues that India has also lagged in introducing more stringent national fuel-quality standards, though such standards would likely pass a benefit-cost test.

A weakness of bans, in practice, has been evasion or substitution to other polluting activities. A ban may be targeted in regulating an activity that does contribute to pollution, yet still ineffective in bringing down pollution, if it induces substitution to other polluting activity. Davis (2008) uses a regression discontinuity in time to study the introduction of driving restrictions in Mexico City, under which most private vehicles could not drive on day per week, on the basis of their license plate number. This kind of rotating ban has the strong appeal of simplicity of enforcement, as the license plate already exists and is visible to all. Davis (2008) finds that the policy does not reduce ambient air pollution. A likely reason is that people may have substituted to driving other, non-banned cars on the days when they could not drive their own. Consistent with this, Davis (2008) finds an increase in new vehicle registrations after the policy comes into force. Despite this early negative finding, other desperate polities have adopted similar policies at times of air pollution crises, with mixed results. [24]

A ban or quota can be effective in reducing pollution if both (i) the activity banned is tightly linked to pollution emissions and (ii) agents cannot easily substitute to other activities that replace the banned activity and also pollute. The TCZ satisfies these two criteria. One policy in transport that satisfies these criteria is a ban (or large registration tax) on old cars (Barahona, Gallego and Montero, 2020). Tail pipe air emissions from old cars are orders of magnitude worse than from new cars. If a ban is uniform across a market, then the only avenue of substitution is towards new cars, or public transport, both of which are cleaner than the banned alternative.

Even nominally successful bans and rations, those which do reduce pollution, can be very costly. To achieve short-term reductions in air pollution, Santiago, Chile instituted driving bans for 80% of vehicles and shut down factories responsible for 50% of stationary point-source emissions in the city (Mullins and Bharadwaj, 2015). In the Pigouvian benchmark, the effort of each agent towards abatement is heterogeneous based on their cost and the contribution of their effort to environmental quality (FB). Bans, rations and quotas do not respect such heterogeneity—your odd-numbered car cannot drive, regardless of whether you are a nurse traveling to work at a hospital or a teenager shopping for a new pair of pants. Moreover, when such policies impose a fixed contribution to environmental quality, they obscure their economic costs. The policy itself tamps down, or makes illegal, the heterogeneity in actions that typically reveal people's values for different choices.

Ryan and Sudarshan (2022) study a policy of rationing groundwater in the Indian state of

[24] Mexico City's restrictions on driving on Saturday did not reduce pollution (Davis, 2017). In New Delhi, a license-plate-based ban that alternated between odd- and even-numbered plates appears to have reduced air pollution by 16% in January of 2016, but not in April the same year (Greenstone et al., 2018) (Chowdhury et al. (2017), using satellite data, find no significant effect of the policy, even in the winter months). Viard and Fu (2015) find that similar driving restrictions did reduce ambient air pollution in Beijing.

Rajasthan. Groundwater is vital to agricultural production as one of the main parts of the Green Revolution input bundle, which has lifted yields and living standards around the world (Gollin, Hansen and Wingender, 2021). There are externalities across groundwater users, however, since one farmer's contribution to environmental quality (the opposite of my groundwater use) affects his neighbor's access to water, as in Lemma 1 and as supported by empirical evidence (Jacoby, 2017). India manages this scarce resource by rationing agricultural use of groundwater via restrictions on electricity supply to agriculture, for example to 6 or 9 hours per day.

Ryan and Sudarshan (2022) find that groundwater rationing achieves its goals, in a way, but at a high economic cost. They use data on agricultural production to estimate the contribution of groundwater to farm profits. With this production function, they find that the level of the groundwater ration is roughly efficient, in that the marginal benefit of increasing the ration (higher farm profits) and the marginal cost of increasing the ration (greater power and water use) are about equal. This result, however, is that the ration is about efficient among all uniform rations, *not* that rationing itself is an efficient policy. In fact, because rationing restricts farmers with heterogeneous productivity to similar levels of water use, it sharply reduces agricultural output. The paper estimates that rationing reduces social surplus by 12% of household annual income, relative to a Pigouvian benchmark (FB).

We finally note that bans, despite their simplicity, are commonly flouted. Examples where bans do not deter the banned activity include bans against crop residue burning, deforestation, or the use of fire to clear forest specifically (Jack et al., 2025; Balboni, Burgess and Olken, 2025; Souza-Rodrigues, 2019). In many of these cases, bans are more-or-less openly defied, so it does not appear that a lack of information is the main constraint on enforcement. More likely, bans are not enforced because regulators are reluctant to impose economic costs on those who would deforest, pollute and the like. The regulatory capacity for enforcement may also be underdeveloped. We consider the political economy of regulation in Section 8.

7.1.2 Standards

A standard is a rule that dictates either that agents must contribute a certain $\underline{e}_{gi}$ to environmental quality, or, alternatively, must produce or consume with a technology that proxies for a certain expected level of contribution. In the first case, the standard applies directly to the externality in question. An example of this type is an emissions standard that says particulate matter emissions coming out of a factory's stack must have a concentration of less than 150 mg/Nm^3. In the second case, technology standards proxy for the underlying externality. Examples of the second type are a technology standard that says all power plants must install a flue gas desulfurization machine or an efficiency standard that says all room air conditioners must get at least 10 BTU per hour for each watt of power input.

There are trade-offs, in setting standards, between the quality of the standard as a proxy for e_{gi} and the cost of monitoring. Directly observing e_{gi} with a sufficiently high π may be very costly. If so, then, with a low π, providing incentives for quality may require large formal subsidies τ_g (or penalties, if we interpret e_{gi} as emissions rather than environmental quality), possibly violating the state capacity constraint κ. Regimes are constrained in this trade-off by the cost of monitoring.

Duflo et al. (2018) study the trade-offs in the command-and-control regulatory regime for industrial pollution in Gujarat, India. Gujarat is an industrial powerhouse within India; partly as a result, many of its cities violate National Ambient Air Quality Standards and certain rivers are critically polluted. The paper observes detailed data on the environmental regulator's inspections of a sample of polluting factories, the technology adoption of these factories and their levels of air and water pollution emissions. The authors collaborated with the regulator to run an experiment increasing the rate of inspection for a treatment group of factories over the course of two years.

The results reveal a regime that is sharply constrained by information. The regulator visits polluting factories infrequently, about once in a year or two. At those visits, it collects pollution readings, on the basis of which the regulator can impose penalties. Duflo et al. (2018) estimate, using a model in which firms can install costly abatement equipment to avoid sanctions, that these penalties are very costly—when imposed. However, because the prospect of being visited by the regulator is remote, and the likelihood that the regulator will measure a sample with a high pollution reading is low, the effective π in this regime is very low. We may expect that increasing inspections for a random treatment group of firms would help by raising the probability of a detected violation. However, the authors find marginal reductions in pollution from the experiment, only for firms that were already near the (binary) regulatory standard. The reason is that the regulator appeared already to be inspecting the plants with the highest pollution potential (likelihood of a high reading) before the experiment started, consistent with the regulator having some private information about what plants are most likely to be high polluters. Therefore, despite low rates of inspection at baseline, adding randomly assigned treatment inspections, which mainly picked up plants with low or moderate pollution, had modest environmental returns.

What is the way out, in a low information environment? There are two main avenues: regulate based on a proxy, or try to improve information. Whether proxy regulation works depends on whether the link between that proxy and the contribution to environmental quality is inviolate. Cropper et al. (2019) conduct a benefit-cost analysis showing that, hypothetically, installing flue gas desulfurization machines at Indian coal-fired power plants would have high benefit-cost ratios, due to avoided mortality, for plants that are in densely populated areas of the country. A risk to such an analysis is whether the plants would actually operate this equipment efficiently ex post. In the Duflo et al. (2018) setting, with a sample of smaller Indian factories, there is already a rigorous mandate in place for the installation of air pollution control devices—the trouble is, they are seldom run. In other cases technological standards are very strong proxies for environmental outcomes. One good example of this type is fuel standards that regulate the content of gasoline with the goal of reducing tail pipe emissions in transportation. Because they require monitoring only the few refineries that produce gasoline, fuel standards are easier to enforce, and stringent fuel standards can greatly improve ambient air quality (Li, Lu and Wang, 2020).

The second avenue for escape from a low-information regime is to use technology to try to improve monitoring. With higher π, a smaller τ_g, which is within the capacity of the state, can be set, without compromising on expected subsidies (or penalties) and therefore the efficacy of regulation. A wave of recent research has shown improvements in environmental enforcement as a result of better monitoring. Yang et al. (2024) compare, with differences-in-differences, $PM_{2.5}$ concentrations for areas near ambient air pollution monitors to areas further away. They find that pollution declines 3.2 percent near new monitors, probably due to more stringent regulation reducing industrial activity. Axbard and Deng (2024) find that enforcement activity picks up against firms that have an ambient pollution monitor installed nearby, reducing aerosol optical depth (a proxy for PM) by around 4% for each additional monitor. Assunção, Gandour and Rocha (2023) use variation in satellite monitoring of deforestation to estimate that additional enforcement activity reduces deforestation with an elasticity around -0.5. Saavedra (2025) trains a machine-learning algorithm on satellite images to detect illegal mining in Colombia. He finds, in a randomized experiment, that disclosing likely mining sites to the municipal government decreased illegal mining by 5%.

High monitoring costs boost the relative merits of standards based on proxies for pollution instead of pollution itself. The main difficulty in regulatory design is to ensure that proxies are reliable even after they become the object of regulation. Some proxies, like fuel content, do remain reliable, and therefore offer channels for low-cost, upstream regulation. Other proxies, like machine installation or license-plate numbers, have been relatively weak. Gains from monitoring improve the efficacy of any sort of standard and may crowd-in regulatory effort (π complements τ_g).

All of the above estimates of the benefits from improved monitoring are within-regime. These studies find meaningful, but modest, reductions in pollution from better monitoring—on the order of 3 or 4%, as compared to the $3\times$ or greater differences in air pollution between poor and rich countries (Figure 2a). In the medium-term, a greater benefit from step-changes in monitoring technology is to use better monitoring to establish regimes that are more flexible and efficient than command-and-control. For example, instead of using remote sensing to enforce existing, coarse regulations, use it to establish a new market. We turn to consider market-based regulations next.

7.2 Formal market-based instruments

We call an instrument market-based if it sets an incentive for agents to contribute e_{gi} but does not directly set their choice of e_{gi} or the technology they must use to achieve any e_{gi}. Market-based instruments can be fully efficient in theory if the state capacity constraint κ does not bind (Lemma 2). Owing, arguably, to the general weakness of monitoring, market-based instruments are less commonly-used for major environmental regulations in developing countries than in the United States and Europe, for example (Blackman, Li and Liu, 2018). Nonetheless, there are cases where market-based instruments have been used at apparently low cost and with good environmental results.

7.2.1 Pigouvian subsidies

In our model, e_{gi} is a positive contribution to environmental quality and so Pigouvian subsidies ($\tau_g > 0$) are a natural starting point. Pigouvian subsidies are commonly used in Payments for

Ecosystem Services (PES) programs, or cash transfers conditioned on environmental actions or outcomes in developing countries.[25] Land use generates externalities. Planting trees or avoiding deforestation, for example, can store carbon dioxide, clean the air and decrease local temperatures, among other benefits. Conversely, burning crop refuse after the harvest pollutes cities downwind. The core research questions in this domain concern the elasticity of the supply of conservation (or abatement) with respect to payments and the effects of contract design and informational market failures on effective supply.

Jayachandran et al. (2017) run and study a randomized-control trial of a forest PES program in Uganda. The treatment paid farmers in 60 villages USD 28 per ha per year if they complied with a contract not to deforest their privately-owned land. An NGO devoted to habitat conservation conducted in-person spot-checks on land to verify compliance while the research team used high-resolution satellite imagery to track deforestation rates across treatment and control villages. The study finds that the PES caused a decrease in forest loss, from 9.1% over 1.5 years in the control group to 4.2% in the treatment group. Treatment villages therefore had 5.6 ha more forest at endline than control villages. At a relatively low 3% discount rate, the authors estimate that the program cost about $1 to delay the emissions of a ton of carbon from 2 to 4 years.

The results of this study provide a benchmark or ideal case for PES in several respects. First, compliance is monitored by agents whose incentives are aligned with the goal of the program, rather than private companies seeking to maximize payments. Second, the authors do not find adverse selection in participation. In land-use PES, a major concern is that landowners with low-value alternative uses of the land opt-in to the program and conserve, but that these landowners would have conserved in any case. In the Uganda study, the experiment estimates that payments do have a causal effect on conservation. The decrease in deforestation rates (46%) is not statistically significantly different from the enrollment rate in the program (32%), which is consistent with the counterfactual deforestation of enrolled farmers being about the same as the average in the control group. Third, the authors search for, but do not find, significant spillovers of conservation to deforestation in nearby areas.

All of these strengths of the Ugandan program have been found to be violated in other settings.

[25] Other subsidies on contributions to environmental quality in low and middle income countries are common. These include subsidies for cleaner fuels and for energy efficient appliances (e.g., Davis, Fuchs and Gertler, 2014; Fowlie and Meeks, 2021; Barnwal, 2024; Abubakari et al., 2024).

The Wall Street Journal and the Guardian have run a series of exposes on outright fraud caused by agency problems in the international market for land-use offsets (Greenfield, 2023; Cox, 2024; Smagalla, 2024; Kaminski, 2025). Retrospective studies using synthetic control designs have generally found that forest conservation PES programs reduce forest loss, but to a lesser extent than claimed (West et al., 2020; Guizar-Coutiño et al., 2022). And work on deforestation has also identified spillovers whereby conservation may accelerate forest loss in areas nearby (Alix-Garcia, Shapiro and Sims, 2012). Probst et al. (2024) conduct a meta-analysis of 14 studies on 2,346 carbon abatement projects. They estimate that "less than 16% of the carbon credits issued to the investigated projects constitute real emission reductions."

The details of program design and implementation plainly matter a great deal for the efficacy of PES programs. Jack et al. (2025) provide an example from a PES for not burning crop residue after the rice harvest in Punjab, India. Punjab is an agriculturally intensive state and many farmers burn the stalk of the rice plant after harvesting the grain, to clear their fields for the next planting season. The pollution from this annual mass burning wafts over some of the most densely populated regions on earth. The authors design an experiment to offer farmers a base incentive of INR 800 (about USD 12, at the time) per acre if they did not burn their crop residue. The incentive could be paid either ex post, on confirmation of not burning, or up front, to imbue trust and ease credit constraints. The striking finding is that the traditional PES has no significant impact on burning, while the up-front payments reduce burning by 7.7 pp on a base of 9.1 pp, at a cost of about USD 40 per acre averted. It is possible that the large difference in response across arms is due to farmer concerns about trust; the contracts were signed and payments disbursed by researchers, rather than the government or a local NGO. In this case, we may expect the "up front" PES compliance rates to be more representative of long-term results as trust in payments develops.[26] Nian (2023) study an alternative to PES, in the form of biomass power plants that raise the opportunity cost of polluting by giving crop residue a positive economic value. They find that building such plants reduces air pollution from crop burning nearby.

In parallel with the experimental literature on PES, a related strand of research has used structural econometric models to study the supply curve of environmental quality from land use changes

[26] Oliva et al. (2020) provide complementary evidence from a different setting that the returns to ex post payments are greater than the returns to up-front payments. This is in part due to the option value from take up; in many PES programs, compliance is rewarded but non-compliance is not penalized.

at scale. A leading case is the cost of avoiding deforestation in the Amazon, the earth's largest tropical rainforest, which provides myriad ecosystem services through biodiversity, induced precipitation, air quality and carbon storage. In this domain, a market-based instrument could be either a Pigouvian subsidy for carbon storage or a Pigouvian tax for the carbon emissions from deforestation. Souza-Rodrigues (2019) estimates a static, discrete-choice model of land use using transportation costs to vary the relative returns to agriculture, which requires access to markets, and forest cover, which does not. Using data from the Brazilian Agricultural Census of 2006, a key finding is that even a trivial carbon tax, of USD 1 per tCO_2, if perfectly applied and enforced, would basically halt deforestation in the Amazon, because the returns to agricultural use of the land are so low. Araujo, Costa and Sant'Anna (2025) study the same setting using a dynamic model with costs of switching between land uses, so that land use choices are not necessarily permanent. They fit the model using high-resolution satellite imagery on land use from 2008 to 2017 and hypothetical potential yields, as opposed to the agricultural census. Even with these major changes in method, the core finding remains qualitatively similar: a small carbon tax, of USD 10 per tCO_2, would forestall 95% of deforestation. The authors study deforestation in the portion of the Amazon where agriculture is legal. The result that this agriculture has very low value suggests that an extension of conservation land or banning deforestation outright would be close to efficient, as well as obviating the need for possibly immense transfer payments to inframarginal landowners.

The research on PES shows a tension between low private costs of conservation and yet great difficulty in using market-based instruments at scale. Evidence from both small-scale experiments and structural econometric analyses in a variety of domains have found that PES programs could contribute to environmental quality at strikingly low costs. However, the real-world programs that have tried to achieve such benefits at scale have been beset by agency problems that undercut their environmental goals and cost-effectiveness. Many of the parties in PES markets, from suppliers of conservation to market intermediaries, have incentives to maximize the sale of conservation, rather than its integrity. These problems are not unique to PES programs but rather a general problem of subsidy design under incomplete information.

7.2.2 Pigouvian taxation

Pigouvian taxation can be fully efficient, achieving the first-best allocation (FB). For this reason, economists advocate Pigouvian taxation for a range of environmental problems, including, prominently, taxing carbon dioxide emissions to mitigate global climate change (Nordhaus, 1993, 2007; Metcalf and Stock, 2023). Despite the efficiency case for Pigouvian taxation, this instrument has not been widely adopted in developing countries (Blackman, Li and Liu, 2018). We discuss a few prominent counterexamples and then speculate as to *why* adoption is low.

One prominent counterexample is the pollution levy system in China (Jin and Lin, 2014). China's Environment Protection Law of 1979 instituted a levy system for the water pollutants Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD) and Total Suspended Solids (TSS) and the air pollutants Sulfur Dioxide (SO_2) and Total Suspended Particulates (TSPs). The marginal charge for each pollutant depended on both the volume and concentration of discharge and followed a step function, rising discontinuously for non-compliant plants above a target concentration, even as the *level* of the charge could fall for non-compliant plants. The levy is applied to plant *reports* of pollution, as verified by in-person inspections (Lin, 2013). This regime, therefore, is a kind of hybrid between a proper Pigouvian tax and the command-and-control system of inspections in India (Duflo et al., 2018). Jin and Lin (2014) note that pollution levies varied widely by region. They use a province-year panel to estimate fixed effects models for the relationship between pollution intensity per unit of GDP and the pollution levy rate. The regressions show that both lower quantity targets and higher levies are associated with lower SO_2 intensity. A broad concern with this empirical strategy is that the measurement of intensity is highly aggregated and that variation in levy rates across provinces may be endogenous to trends in pollution. The pollution levy system was revised in 2003. A major policy question is to what extent this reform and later reforms to the system of market-based instruments, as opposed to the coarser instruments of bans and rations, contributed to the declines in water and air pollution China achieved after the mid-2000s.

A second prominent but under-studied example of a Pigouvian tax in a developing economy is India's coal cess. India introduced a coal cess (tax) on July 1st, 2010 on all coal production and imports, at an initial rate of INR 50 per ton of coal, which has been gradually raised to INR 400 per ton (Kamboj, 2020). This higher rate is still only about USD 2 per tCO_2.[27] At this low level, it may be difficult to estimate any aggregate effect on coal usage. Still, coal makes up roughly three-quarters of Indian electricity generation, in addition to other uses, so this tax has one of the broadest bases of any carbon tax in the world. With the tax administration already in place, the Indian government is free to adjust the price level at any point in the future, depending on its revenue needs and desired emissions targets.

These respective examples point to three reasons why Pigouvian taxation may not be widely used. First, it is difficult to impose a tax reliably without accurate, high-frequency monitoring (see the discussion of monitoring in the standards part of Section 7.1). The China pollution levies were initially based on self-reports, as is most pollution monitoring in India. Only after China invested heavily in monitoring in the mid-2000s and beyond did pollution intensity begin to steeply decline. Second, though we do not have evidence to this specific point, it may be difficult politically to impose a tax on energy staples like coal, when consumers are highly sensitive to energy prices. Indeed, in many developing countries, end-use consumption of energy is heavily subsidized, either directly or through a tolerance for theft (Burgess et al., 2020). When policy already depresses retail prices below private cost, it is not clear that upstream Pigouvian taxes, which mean to add the social costs of energy to wholesale prices, would change final demand. Standards and bans, while less efficient, may be more visible means of taking action that have the political advantage of obfuscating their own *higher* costs, relative to Pigouvian taxation. Third and relatedly, people may not have enough money to pay Pigouvian taxes. The externalities from some economic activities may outweigh the capacity of people causing those externalities to pay.

7.2.3 Trading in rights

A Pigouvian tax on emissions is equivalent to a cap-and-trade system in which the cap is set at the total emissions resulting from the tax. Ex ante, however, environmental regulators typically will not have complete information about abatement costs ϕ_i and therefore the mapping from tax levels to emissions. The rationale for using market-based instruments in the first place is to achieve

[27] The conversion depends on the assumed carbon content of coal, for example at 2025 exchange:

$$\frac{INR\ 400}{1\text{ ton coal}}\frac{1\text{ ton coal}}{0.65\text{ ton carbon}}\frac{12\text{ ton carbon}}{44\text{ ton CO}_2}\frac{1\text{ USD}}{85\text{ INR}}=\frac{1.97\text{ USD}}{1\text{ ton CO}_2}.$$

efficiency in spite of information being incomplete or dispersed. In this common scenario, the marginal benefits and costs of any given regime may be uncertain. A regulator can increase expected welfare, in this scenario, by using a quantity-based instrument (cap-and-trade) instead of a price-based instrument when the slope of marginal damages is high relative to the slope of marginal costs (Weitzman, 1974).[28]

A market for an externality or a natural resource will be fully efficient when there are not other market failures, for example of information or credit, that interfere with market allocation. Espin-Sanchez and Donna (2025) study the dissolution of a seven-century-old water market, in southern Spain, in favor of a system of water quotas assigned pro rata to arable land. Most economists would presume this change was for the worse. Donna and Espín-Sánchez (2021) find the opposite: quotas improved the efficiency of water allocation. They argue that production is relatively homogeneous between rich and poor farmers but that poor farmers are illiquid, as they do not have the money to buy water during the dry season, when prices shoot up. As a consequence of this credit market failure the market allocation of water is not efficient.

Whether a market is better than a quota or standard will depend on the parties to the market and what other constraints they face. The liquidity constraints present for farmers are less likely to impinge on market efficiency among large industrial firms. Greenstone et al. (2025) partner with a state environmental regulator in India to roll-out and study a new emissions market for particulate matter, covering industrial point sources in a large city. The context for this randomized experiment overlaps with the prior experiments of Duflo et al. (2018), discussed above, and Duflo et al. (2013*a*), discussed below: the regulator has limited information about plant emissions and severe sanctions are therefore not sufficient to induce high compliance. At baseline, only two-thirds of firms in the Greenstone et al. (2022) experiment are compliant with the binary standard for particulate matter emissions concentration.

The paper uses the randomized experiment to compare the emissions and compliance costs of plants in the market to plants that remain in the command-and-control status quo. All plants in both systems were required to install Continuous Emissions Monitoring Systems (CEMS) to report pollution continuously prior to the experiment. The two regimes differ in several respects:

[28] The reason is that when the slope of marginal damages is high uncertainty may result in relatively large damages for small changes in the quantity emitted; thus it is best to guard against such changes by fixing quantities ex ante and allowing the market price to adjust.

plants in the market have load standards that can be traded, whereas plants in the status quo have concentration standards that are fixed at the plant level. In addition, the penalties $-\tau_g$ in the market are literal charges for each emissions permit, whereas in the status quo penalties, when levied, take the form of equipment installation, posting performance bonds, or even plant closure. We can think of the market as a regime, therefore, with a higher π but a smaller and much more predictable $-\tau_g$ per unit of pollution.

The analysis finds that the particulate matter market is remarkably cost-effective at reducing pollution. The authors estimate that pollution emissions (PM load) decline by 20 to 30% in the treatment plants relative to control plants that remain in the status quo. Compliance, in the treatment, with the market-based rule that firms must hold enough permits to cover their emissions, is nearly perfect. It is not possible directly to compare the cost of abatement for treatment and control plants, because the best measure of the cost of abatement, permit bid prices, is only observed for the treatment plants. The authors therefore use these bids in the treatment plan to recover the distribution of marginal abatement costs (MACs) in the population of plants. Using these MAC curves to evaluate total costs under both the treatment and control distributions of emissions, the authors find that the market reduced compliance costs by 11%.

If markets can lower pollution *and* cost, why are they not used everywhere? We think of three main reasons. First, other market failures, like credit constraints (Donna and Espín-Sánchez, 2021) or limited liability, may make markets less efficient than command-and-control instruments. Second, even if other market failures do not obviate the efficiency gains of markets, policy-makers may be concerned with how markets redistribute (for example, auctioning the right to drive in the city center may not be popular). Environmental policy-makers cannot assume they can control or enact lump-sum transfers to make users whole. Third, markets rely on monitoring that takes large fixed costs to set up. The particulate matter market described above was set up after years of investment in monitoring (Sudarshan, 2023). In the absence of these investments, markets may not reduce emissions or compliance costs.[29] Governments should turn a keen eye to domains where

[29] Montero, Sanchez and Katz (2002) study a market for particulate matter air pollution introduced in Santiago, Chile in response to stubbornly bad air quality. This market largely did not work, because it regulated boiler capacity, a proxy for air pollution, rather than pollution itself. While larger boilers produce more air pollution, the trouble is that most abatement for air pollution happens at the end-of-pipe, by installing and operating machines that remove emissions after combustion in a boiler or another industrial process. By setting up a market for boiler capacity "upstream," therefore, Santiago removed the possibility of low-cost abatement. This design choice was presumably necessitated by the absence of low-cost monitoring at the time.

externalities are generated by a few, large actors whose scale justifies the fixed costs of monitoring.

7.2.4 Additionality and leakage

Common complaints against market-based instruments are that they are not "additional" or promote "leakage." These issues, however, are not unique to market-based instruments. They arise because a regulation has incomplete coverage, not because it is implemented using market-based instruments. If a Pigouvian tax had complete coverage it would be fully efficient, even though offset markets are not (van Benthem and Kerr, 2013).

"Additionality" is jargon for whether a policy changes someone's decision. If a policy pays a landholder to conserve their forest, but they were planning to do so anyway, then that landholder's conservation is not *additional* to the PES policy (in economic terms, the landholder is inframarginal to the subsidy). This problem applies not only to environmental programs but to virtually all public taxes or subsidies that aim to change behavior, from subsidies for retirement savings or education to taxes on unhealthy consumption. In the PES domain, a transfer to a non-additional landholder does not change efficiency but does raise the taxes needed to finance τ_g and may therefore violate the state capacity constraint κ and impose some deadweight loss of taxation.

The additionality of emissions reductions from offset programs is a lively domain of research. Low additionality may be responsible for low realized savings in land-use PES programs, discussed in Section 7.2.1 above. Aspelund and Russo (2025) find that only one-quarter of landholders receiving conservation subsidies in the US Conservation Reserve Program change their conservation decision because of the subsidy. A particularly important domain for estimating additionality is the international market for carbon offsets. Most low-income countries do not regulate carbon domestically or do so only leniently; however, they do supply offsets to international carbon markets.

Calel et al. (2025) provide estimates of additionality in the context of Indian wind farms. Wind power plants may be privately profitable on their own. After an approval process, they may also be eligible to get carbon credits. Calel et al. (2025) compare the observable characteristics of wind projects that were approved for carbon credits under the Clean Development Mechanism (CDM), a carbon offset program of the United Nations, to those of other projects that did not apply to the CDM. They find that CDM projects do not systematically look less profitable than non-CDM projects, as the sites of CDM projects are just as windy and as close to the electric grid. For half of CDM projects, the authors can find another project that appears to be strictly less profitable, on observable characteristics, and yet was built without carbon credits. This evidence suggests that many wind projects are inframarginal to the subsidy provided by the CDM.

The presence of non-additional projects does not necessarily imply that offsets are useless. Given the very low costs of abatement in developing economies, some degree of transfer to inframarginal participants may be acceptable, to realize abatement from others. There is no general answer to the question of how much abatement or conservation must be additional, as it depends on the context, program design and the costs of abatement through other policy means.

Chen, Ryan and Xu (2025) study carbon offsets sold by manufacturing firms in China under the Clean Development Mechanism (CDM). The goal of this program was to improve efficiency by allowing regulated firms with high costs of abatement (e.g., in Germany) to buy abatement from unregulated firms with low costs of abatement (e.g., in China). The authors match UN records of firm participation in the CDM to firm-year panel data on manufacturing firms in China. They find, contra the intention of the program, that emissions at firms that sell carbon offsets steeply *increase* after they register an offset project. The authors use a model of firm application and production choices to rationalize this finding. The key idea is that the offset market here is not strictly paying for reductions in emissions but rather for the installation of more efficient capital. In the model, this generates two reasons why emissions rise. First, firms that are growing quickly select into selling offsets, because their greater future demand justifies the investment in efficient capital needed to sell offsets. Second, offsets cause some part of emissions growth, because firms that do install efficient capital as a result of the program increase their scale of operations and emissions in response. Therefore, ironically, higher "additionality" of firms in this context increases emissions, because it increases the adoption of efficient capital and firm growth. The authors conclude that the CDM, in the Chinese manufacturing sector under study, reduced compliance costs for firms under the EU ETS but sharply lowered global social surplus due to the external costs of higher emissions.

"Leakage" is jargon for substitution between producers in a market equilibrium. If some economic activity is regulated, raising its cost, then that activity may shift to other, non-regulated firms, sectors or areas, which then produce more of the externality and offset part of the gain of the initial regulation. The most common mechanism for leakage is through output markets common to both regulated and unregulated parties. For example, the conservation of forest in some areas may raise prices for forest products and cause displacement of deforestation to other areas (Alix-Garcia, Shapiro and Sims, 2012; Tiew, 2025; Restrepo and Mariante, 2024). Leakage can also occur by shifting pollution up or down a vertical supply chain after one segment of the chain becomes regulated (Hernandez-Cortes, 2025).

Chen et al. (2025) provide a particularly elegant and important example of leakage in a regulation for industrial energy-efficiency. A difficulty with studying leakage is that it is hard to know, exactly, where production displaced by regulation may leak *towards*—it could be other firms in same industry, or other products, or firms making substitute products that also pollute. Leakage may be large, in aggregate, but so diffuse that it is difficult to measure precisely. In the Chen et al. (2025) context, firms are given plant-specific targets for energy-efficiency, which apply only to the largest firms in the country, while other large firms, owned by the same conglomerates and producing the same products, remain unregulated. The paper finds that fully 40% of the output of regulated firms shifts to being produced by smaller firms in the same conglomerates; moreover, this shift lowers aggregate productivity, because smaller firms are less productive than the largest ones.

The leakage in this example arises although the regulation itself is an energy-efficiency target, not a Pigouvian tax or emissions market. The solution to leakage is to include the unregulated firms in the market, which China proceeded to do, by expanding the initial "Top 1,000" firms program that the authors study, which started in 2006, to a "Top 10,000" firms program, from 2012. While broader coverage addresses the problem of leakage it will not achieve efficient abatement, as targets set by the state for e_{gi}, given incomplete information, will not generally equal e^*_{gi}. Leakage therefore may be induced by standards and rules, as well as by markets, and does not justify the use of coarser instruments over market-based regulation.

8 Political economy of regulation and resource use

Environmental regulation is, by the definition of an externality, against the private interests of the regulated party. It is commonly also against the combined private interests of the regulated party and the regulator. The regulator, in practice, is not the society as a whole, but only the front-line department, bureaucrat, auditor or firm that is tasked to carry the rule out. The regulator is an agent of society. A major theme of work on regulation and the environment is to what extent regulations align the interests of society and its agents. This alignment is harder to achieve in developing countries where the rule of law is weaker as a constraint on corruption (misalignment). Gulzar and Baragwanath (2026) survey research on environmental governance and find only weak evidence that alignment is stronger in democracies.

8.1 Externalities across jurisdictions

A basic obstacle to alignment is pollution that flows or blows across borders. In our model, informal regulation is not efficient in part because groups only care about contributions to their own environmental quality. We assume, however, that there is a single government for all groups. In practice, there are governments at the level of the county, state, province or even country g, which, like informal groups, do not internalize the contributions of sources within their borders to the environmental quality of their neighbors (Lemma 1). The problem of cross-group externalities is fractal in nature; it recurs at all scales, for neighbors in a village and for countries on a planet.

An early contribution to measuring the importance of such spillovers studies cross-border externalities in water pollution in Brazil (Lipscomb and Mobarak, 2017). Studies of spillovers are confounded by omitted variables; it may be, for example, that the polities that generate the most environmental spillovers have high pollution because they are especially productive in some unobservable dimension. Lipscomb and Mobarak (2017) circumvent this problem by using panel data to study what happens when a new municipality arises along a river segment. It is convenient to study spillovers for riverine pollution because we know the direction of the externality: downstream. Theoretically, the authors predict that such a municipality should increase pollution at downstream monitors, because municipalities upstream of the new municipality, once the new municipality is born, should care less about controlling pollution that flows downstream. The main empirical finding, in support of this prediction, is that biochemical oxygen demand rises about 4% for each additional municipal border that a river crosses.[30] A risk to this design is that new municipalities may be created in areas with high economic growth and therefore growth in pollution

[30] Burgess et al. (2012) similarly use variation from the introduction of new districts within provinces in Indonesia to find that each new district increases the rate of deforestation by 4% (a sheer coincidence). They attribute this increase to competition between districts weakening the incentives to conserve that arise from quantity withholding raising the rents from illegal deforestation.

emissions. The authors mitigate this risk by controlling for local GDP and population growth.

While Lipscomb and Mobarak (2017) only observe pollution, not regulatory enforcement, related research has empirically found support for the mechanism that economic activity and pollution shift in response to the stringency of regulation (Cai, Chen and Gong, 2016; Chen et al., 2018). Chen et al. (2018) find that a national surge in water pollution enforcement causes polluting activity to move upstream, where it affects more, poorer residents. They argue that this shift arises because upstream areas happen to have less stringent pollution enforcement, and so become relatively more attractive after the national crackdown.

In theory, higher levels of government should not only internalize spillovers to reduce pollution, but should do so in service of a more efficient overall regime that raises social surplus. Testing this proposition is hard because it requires not only observing pollution but also estimating the valuation and costs of abatement. Wang and Wang (2024) undertake such an analysis in the context of mergers of townships, the lowest level of government, in China. The authors compare firms that are located near township borders that were eliminated, thereby shifting the firm, which remains at a fixed location, from the border of the old township to near the center of a new, amalgamated township. They find that such firms increase pollution abatement investment by 12% and reduce air pollution emissions, along with their own output and profit. The authors then use property prices from government land auctions to estimate changes in local values. They find that both the quantity of residential land development and property prices increase post-merger near internal boundaries that the merger dissolved. The authors conclude that the benefits from higher valuations, which they attribute to lower pollution, easily outweigh the loss in industrial profit from more stringent regulation.

The evidence reviewed here suggests benefits from centralization due to higher-level governments internalizing externalities across jurisdictions. The natural opposing force is that centralized authorities may not have the local information needed to determine who or what to regulate. If the quality of information available depends on the authority who is gathering it, then it may be that centralization causes regulation to be less efficient. Central regulators may not be aware of what environmental problems are most important locally. It would be valuable to have more research on the limits of centralization and particularly how centralization affects not only the level of enforcement but also the accuracy of targeting.

8.2 Agency problems

The mountains are high, and the emperor is far away. Even if the state, at some abstract level, internalizes the benefits of environmental quality, its bureaucrats, firms, auditors, engineers and so forth may not. An agent that can choose how to enforce regulation may collude with regulated actors to profitably evade regulation instead. A principal line of research has been to measure to what extent such evasion compromises regulation and how changes in monitoring and incentives can strengthen enforcement.

8.2.1 For front-line regulators

A regulation can be undercut by collusion between regulators and the people they regulate. One example comes from the regulation of air pollution emissions from cars. Many polities try to keep old cars from polluting by implementing smog checks to keep cars clean as they age. In principle, this can improve efficiency over outright bans or vintage-specific fees, since smog check can apply a τ_g that varies with e_{gi} car-by-car. However, applying such a rule requires testing each car rather than regulating with a simple proxy like age (or a simpler one, like license plate number). Oliva (2015) uses data on smog check results for cars in Mexico City to estimate that about one in ten cars more than ten years old are likely cheating on their smog check tests. The dominant mode of cheating is to swap in a clear car for a dirty one that is likely to fail the test. Oliva (2015) detects such swaps by testing for the autocorrelation in smog check results across consecutive tests at the same testing centers. About three-quarters of testing centers show evidence of an abnormally high autocorrelation, consistent with car-swapping.

The degree of collusion will depend on the market structure for regulatory enforcement. One reason to expect trouble with smog check is that consumers can shop around, choosing the most lenient testing centers. Similarly, in various markets, a firm seeking an environmental audit or to verify carbon offsets can shop around to find a report that suits their business. For this reason, in regulatory enforcement, typical economic logic is turned on its head: monopoly may be efficient since competition degrades the quality of information reported (Bolton, Freixas and Shapiro, 2012).

Duflo et al. (2013*a*) study how agency problems compromise regulation in a market for environmental audits. The status quo in this market is that regulated industrial firms hire and pay their own auditors. Duflo et al. (2013*b*) show that audit fees are generally low, in some cases too low to properly carry out an audit, though high-quality auditors can differentiate their reputations to an extent, in order to earn business from cleaner firms. The authors of Duflo et al. (2013*a*) collaborated with the environmental regulator to reform the market, so that the regulator instead assigns auditors to firms. In this structure the auditor assigned gains market power over firms, since they are the only way to get an audit that will be recognized. The regulator therefore fixes a price schedule for the environmental audit. The paper studies the effects of this reform in a randomized experiment. They find that: (i) in the status quo, there is widespread misreporting, with most firms falsely reported as being in compliant with pollution standards; (ii) auditors under the reform, by contrast, report almost truthfully; (iii) the firms audited by such independent auditors reduce their pollution emissions. This example highlights that the parameter π is itself endogenous to the structure of regulation; here, π was initially low because of an agency problem. Auditor independence raised π and caused firms to choose a higher contribution e_{gi} (in this case, pollution abatement) in response.

8.2.2 For bureaucrats and politicians

Agency problems begin at the front line but can rise to any level of government. He, Wang and Zhang (2020) study the enforcement of water pollution regulations in China. They note that, while provincial governors, prefecture leaders and county leaders are incentivized, by career concerns, to improve environmental quality in their polities, this quality is only measured at certain discrete monitoring stations. The paper uses a regression discontinuity design in distance to the station to show that industrial plants upstream of monitoring stations, whose pollution contributes to the station reading, are regulated more stringently than plants downstream, such that upstream water pollution discharge is cut roughly in half, at the expense of productivity falling by one-quarter. A range of analyses suggest that this difference is due to political incentives, as it only appears after the national government began incentivizing environmental outcomes in 2003 and is strongest for leaders who are young and therefore have greater career concerns over their remaining tenure. This analysis is remarkable for measuring both the economic cost and environmental benefit of water pollution regulation and tracing these back to the incentives of local officials.

Since different levels of government have different goals, the devolution of responsibility for the environment to particular bureaucrats can matter. Dipoppa and Gulzar (2024) estimate that crop burning happens less when the smoke from crop burning is dispersed mainly within its origin district, suggesting district-level bureaucrats try to control only local environmental harms. Kong and Liu (2024) use a difference-in-difference design to study a reform that changed the appointment authority for directors of Environment Protection Bureaus from the municipal to the provincial level. They find that such higher-level appointments caused bureaucrats to levy 20% higher pollution penalties and improved air quality. Zhang, Chen and Guo (2018) similarly find that placing certain large firms directly under central supervision reduces their pollution emissions. Fenske, Haseeb and Kala (2023) find that delegating authority to lower-level bureaucrats increases the approval rates for environmental permits, which firms need to build or expand a plant.

Politicians and bureaucrats earn rents from their control over access to common resources. Wade (1982*b*) studies how a hierarchy of bribes, from farmers to irrigation engineers, their bosses in government, and ultimately politicians, dictates the allocation of canal water in a south Indian state. The effect of bribes on efficiency is ambiguous: Wade (1982*b*) writes "the corrupt system *could* promote efficiency and equity" (emphasis original), by bringing water to tail-end villages where it is desperately needed (has high marginal returns). But his "strong impression" is that it does not tend to efficiency, and the scale of rents makes corrupt allocation nearly impossible to reform (Wade, 1982*b*). Resource allocation can be used to reward or influence election outcomes, as a number of papers have demonstrated. For example, Beg (2019) shows that representatives aligned with the national ruling party allocate more river water to their constituencies after narrowly winning an election. Mahadevan and Shenoy (2023), find consistent evidence that party alignment between local politicians and the state in India affects the allocation of public aid in response to water scarcity. In this case, the government's response to an environmental shock (drought) facilitates individual adaptation, but the distribution of aid is distorted by electoral concerns. In particular, drought relief is also used to influence elections where vote margins are close. Tarquinio (2022) shows that this "vote-buying" effect is worsened by bureaucratic discretion over resource allocation. More broadly, vulnerability to environmental harms can increase vote-buying and other forms of clientelism, distorting access to adaptation resources and increasing damages from poor environmental quality relative to an undistorted allocation (Bobonis et al., 2022).

The picture of regulation assembled from the pixels of these studies is that agency and incentive problems are everywhere in environmental regulation. The sharp conflict between private and public incentives makes enforcement a difficult governance problem. Monitoring is not a function only of technology but of market structure and governance. Such agency problems discourage governments from aggressively enforcing environmental regulations. Former Indian Prime Minister Manmohan Singh addressed a major environmental conference by declaring "It is also necessary to ensure that these regulatory standards do not bring back the License Permit Raj which we sought to get rid of in the economic reforms of the early 90s" ({The Hindu}, 2011). These problems may also push governments away from more efficient regulations that depend on precise monitoring (Section 7.2) towards coarser regulations that are inefficient but may be harder to corrupt (Section 7.1). Conversely, as state capacity rises, the government can offer stronger incentives for environmental quality.

8.3 Commitment

A commitment problem is an agency problem between the present and the future, rather than between the layers of a government. Environmental policy often strains the state's power to commit. Successive governments may disagree on policy priorities. These disagreements then interact with asymmetries between environmental protection and degradation or resource conservation and extraction.

Bard Harstad, in a series of papers, has been the leading proponent of the importance of commitment problems in environmental policy. Consider an old-growth forest. Old trees create a flow of environmental services but, if they are once cut, the conservation value of the denuded land may be trivial. A market for conservation of the forest will not be efficient, since "The seller prefers to conserve if the buyer is expected to buy, but the buyer is unwilling to pay as long as the seller conserves" (Harstad, 2016). At the level of policy, the asymmetry of conservation implies that lobbying for extraction, as a one-time event, is easier than lobbying for conservation, an ongoing commitment, which induces inefficient exploitation in a political equilibrium (Harstad, 2023). Once a forest is cut, moreover, a policy-maker may lose the nerve to enforce an environmental policy. Hsiao (2025) studies the commitment to tariffs against the importation of palm oil, which is commonly grown on plantations established on deforested land, and hence subject to the same asymmetry between rapid deforestation and slow regeneration. Hsiao estimates a model in which tariffs on palm oil discourage imports and hence deforestation. The importing government may not be able to commit to tariffs, however, because, after the land is cleared to start a palm plantation, all the environmental harm has already been done. (See also Harstad (2024).)

A government that anticipates its own inability to commit can try to build institutions that enable commitment, even at some loss in efficiency, relative to the first-best. Harstad (2020) theorizes that the state should subsidize green innovation, rather than only taxing externalities, when it anticipates that improvements in green technology will crowd-in environmental action by future governments. Ryan (2021) estimates that central government backing for state procurement auctions, in an environment where states cannot commit to fully pay solar power producers who win a contract, markedly reduces the cost of solar procurement for risky states. Rexer (2025) shows that the indigenization of oil fields in Nigeria, so that oil extraction is controlled by domestic firms, reduces oil spills and increases output. The evidence suggests that the reduced spills come about because rent-seeking domestic officials exert more effort to protect domestic than foreign firms against gangs that steal oil and cause spills either as a threat or a byproduct of theft. The change in ownership from foreign to domestic firms can therefore be understood as a way for the government to commit to law enforcement.

The severity of commitment and agency problems make it hard to do rigorous, normative analysis of environmental policy in developing countries. It is easy to recognize when a regulatory institution departs from the first-best case, with complete information and environmental policy that aligns private and social incentives. Reiterating that a policy is not fully efficient is of little use in itself. It is hard to understand whether any given second-best policy is in fact second-best. (One could always broadly claim, for example, that "banning cars from the city is the best we could do.") To do so, the analyst must: (i) identify the constraints on information, commitment, politics or redistribution a given policy or institution is operating under; (ii) formulate a second-best policy under those same constraints.

8.4 Citizen demand for environmental regulation

Environmental quality has widely dispersed benefits: when the air is cleaner, we all breathe a little easier. As evidenced in Section 4.2, demand for air quality, at least, as evidenced in personal investment decisions, appears low. People may also want air quality but expect that it should be provided publicly. When and how do citizens demand accountability from their governments for environmental quality? Some of the work on informal regulation reveals citizen demand for regulatory oversight. Other papers identify a relationship between public attention on environmental problems and increased enforcement or regulatory action (Buntaine et al., 2024; Araujo, Costa and Garg, 2024). However, the literature on demand for formal environmental regulation—to our knowledge—has not focused on low and middle income country settings.

9 Conclusion

9.1 Summary

Low- and middle-income countries are much more polluted than high-income countries (Figure 1, Figure 2a, Figure 2b). At the same time, at any given level of environmental quality, citizens of low-income countries are more exposed to these hazards (Figure 4). They cannot turn a tap to draw treated water or turn a dial to cook their food without smoking up their kitchen. They cannot flip a switch to clean and cool their air. They are much more likely to work in agriculture, outside, exposed to poor air quality and temperature extremes.

We review literature that documents large damages from this exposure. Poor environmental quality shortens life spans, lowers quality of life and makes people and firms less productive. Current findings probably systematically understate these damages due to the challenges of studying environmental harms, for reasons that include: (i) direct damage estimates are net of (unobserved) adaptation costs; (ii) researchers measure only some of the likely channels of harm; (iii) most empirical estimates of damages are short-run rather than cumulative impacts from lifetime exposure; (iv) estimates do not typically measure interactions across environmental hazards.

Yet, despite scientific evidence of harm, people appear to do remarkably little to protect themselves from environmental hazards. Private adaptation suggests a low willingness to pay for the health and productivity benefits of exposure reductions. Perhaps that is due to a lack of information about environmental harms or effective forms of self protection. Or perhaps researchers mis-measure the costs of adaptation. Alternatively, private adaptation is simply a poor substitute for living in a cleaner environment. The individual cannot clean up her neighborhood or city on her own. This requires collective action.

Some of the earliest work on development and the environment focused on the promise of informal governance of local commons to overcome the social dilemma. While many papers document that informal regulation may be better than nothing, few test for efficiency. Furthermore, local governance has limits: sanctions will be inefficient if information is incomplete, and many environmental hazards are themselves not local in nature.

The role of formal government is to regulate parties so they take account of externalities when their consumption or production affects the environment. By the definition of external costs, it will not be in the private interest of any person or firm to contribute enough to environmental quality on their own. Environmental regulation therefore puts high demands on state capacity. Governments must overcome incomplete information about who is polluting and at what cost and confront agency problems. The result is a tendency to rely on coarse regulations that ignore heterogeneity in the costs of contributing to environmental quality, and often use rough proxies as the basis for enforcement.

In spite of the difficulty of this problem, massive turnabouts in environmental quality are feasible with focused policy effort. We estimate that the elasticity of environmental quality with respect to income is -0.30 for air pollution and -0.25 for water pollution once countries reach their peak level of pollution. Vietnam, China and Korea, all industrial powerhouses and miracles of economic growth, have passed their inflection points and seen marked improvements in air quality in recent years (Figure 2a). The research literature seldom decomposes such aggregate changes, but gives many examples of regulations that have brought large improvements in environmental quality, with benefits in excess of costs. Improvements in technology that lower the costs of monitoring and fix agency problems appear to have especially high returns.

The problems of regulation are not only technocratic. There are deep political economy reasons why regulation has failed for certain environmental harms. We see two factors in common across a range of domains. First, a concern for equity makes governments reluctant to raise the costs of peoples' actions, like energy or water consumption, to the socially efficient level. Second, environmental problems often demand political coordination at a wide scale. Climate change and transboundary air pollution are marquee examples, where neither a local group nor a single state can effectively regulate environmental quality.

9.2 Directions for research

In the course of this review we have covered a rich body of research but also exposed large gaps in the knowledge frontier. We conclude by highlighting several of these gaps.

9.2.1 Environmental damages and individual decision-making

- What are the novel pathways for environmental damages that we have not yet recognized or quantified? There has been recent work on not only air and water quality but also ecosystem services through biodiversity and novel land use externalities. What are the values of these environmental services? What other services are we missing?

- What investments in data sources would fill gaps in knowledge about environmental externalities? The movement to remotely-sensed data increases coverage, but can be at the expense of resolution. Some environmental services may be well-understood but difficult to measure if they act at a fine spatial scale. For example, Tanaka, Teshima and Verhoogen (2022) find lead pollution from battery recycling in Mexico harms birth outcomes within 2 miles of recycling plants. Banares-Sanchez and Wiskamp (2025) measures urban trash neighborhood-by-neighborhood and estimates valuations for trash removal.

- What explains the gap between estimates of environmental damages from epidemiological and economic (revealed preference) approaches? In certain domains, like air quality, it seems that people value protection from environmental harms less than they should, based on direct evidence of the size of those harms. Poor information and market failures such as credit constraints contribute. What other factors are important for this gap? How general is this gap across different kinds of environmental harm?

- What market failures distort the adaptation to environmental harms by individuals and firms?

We observe in the literature on the adaptation to climate change in low- and middle-income countries evidence for constrained responses to climate shocks. For example, when high temperatures lower farm productivity, farmers double down, and farm *more* intensely. What constraints limit responses to environmental shocks and how much do they affect welfare?

- Conversely, what new markets or products—for information, for insurance, for novel adaptive technologies—can help people mitigate the effects of environmental hazards?
- How does poor environmental quality affect firm productivity? Under what circumstances do firms adapt on behalf of constrained workers? Is firm adaptation fully efficient? In principle, firms that adapt efficiently to raise worker productivity would gain a competitive advantage. However, firms may be just as poorly informed or constrained as people.
- To what extent do estimates of environmental damages from high income countries generalize to lower income settings? Both better baseline health and lower levels of exposure (conditional on ambient quality) will lead rich-country evidence to understate impacts in poorer countries. But evidence on the importance of these channels, and the shape of the actual dose-response relationship, is scarce.
- Do different environmental harms interact? For example, does worse air quality amplify the negative impact of a hot day worse on health or productivity? Does these interactions occur contemporaneously or via accumulated health stock? Going beyond damages, how does the coexistence of environmental threats affect willingness-to-pay to adapt to any one of them?
- Do the dynamics of resource stocks and environmental service flows mean that existing estimates of damages are biased? We have ignored the physical process of environmental degradation throughout this chapter. Most economics research represents damages crudely. How do resource dynamics interact with market failures and constraints of development (including high discount rates) to determine efficiency?

9.2.2 Environmental regulation and collective decision-making

- How efficiently do informal, cooperative institutions manage common resources and local environmental externalities? Is the variation in efficiency of use consequential for welfare?

Characterizing efficiency requires estimating the complete distributions of costs and benefits from resource management across users. Recent research in development has applied new econometric methods to estimate the distribution of marginal returns to capital across firms (Hughes and Majerovitz, 2025; Carrillo et al., 2023). Similar approaches could be applied to environmental problems, treating natural resources or environmental quality as input factors with heterogeneous returns.

- To the extent that informal institutions are constrained away from first-best (or even informal-best) outcomes, what are the constraints? How large are the costs associated with monitoring, enforcement, equity and commitment within groups? Complementarities between formal and informal regulation depend on these costs, as does the potential for crowd-out of lower-cost informal solutions in response to formal regulatory intervention.

- What are the causes of rapid turnabouts in environmental quality? (Figure 2a, Figure 2b, Table 3). Does regulation drive the relationship between environmental quality and economic development? We observe a fairly regular environmental Kuznets curve with respect to air quality (Figure 2a). India's poor air quality has grown even worse in recent years even as China appears to have turned the corner. To what extent are these changes social choices, carried out through regulation, versus exogenous changes in pollution intensity due to secular economic trends? Past research on the EKC has been aggregative, at a country level, and therefore not very persuasive with respect to causal mechanisms. By contrast, work on the same question in the US gains credibility by building up from firm-level emissions to aggregate trends (Shapiro and Walker, 2018).

- What makes up the institutional wedge between the private marginal cost of pollution abatement and the social marginal cost of pollution abatement? By social marginal cost of abatement, we mean the cost of abatement inclusive of any transactions costs from the imperfect regulations needed to induce firms to take abatement action. Our sense is that this gap is responsible for a large part of overall social abatement costs, but we have few estimates on which to base this judgment.

- Do coarse regulations deliver positive net benefits? Coarse regulations are surely not fully efficient. Much existing research studies the positive question of whether bans, rations and the like have any effect on environmental quality and damages, but does not measure their costs and therefore their net impact on welfare.

- What determines the choice of regulatory regimes? What are the real constraints (information, limited liability, contract enforcement, redistribution) that raise the social cost of pollution abatement, relative to the private cost? Do these constraints justify the coarse regulations that are observed in practice? What are the second-best or constrained-efficient instruments under these constraints?

- What are the costs of carbon abatement in low- and middle-income countries? There are reasons to expect poorer countries to have cost advantages, such as the ability to invest in renewable energy, to meet growing demand, without displacing existing fossil capital before the ends of its useful life. There are also reasons to expect disadvantages, such as weaker contract enforcement or institutions for monitoring. What institutions may allow small-scale carbon mitigation actions to be efficiently aggregated?

- How is the growth of clean energy contributing to environmental quality in LMICs? Renewable energy has fallen dramatically in cost, to the point of being least-cost for a large part of electricity generation and transportation in many parts of the world. This technological leap may help solve some environmental problems (air pollution) and exacerbate others (groundwater over-extraction). How should environmental regulations change in response to cheap clean energy?

- When do citizens demand formal regulation of environmental quality? It is striking to us that, with rare exceptions for crises, there is not more citizen pressure for environmental regulation. Why? If regulations were more effective or lower cost, would citizen demand change? In what circumstances do politicians and bureaucrats supply environmental quality through regulation?

There has been an outpouring of research on economic development and the environment in the last decade. This research has established the importance of the environment for economic development and exemplified a wide range of mechanisms through which development and the environment interact. From the pace of progress and the unanswered questions here, we are hopeful about the social value of the next decade of work in this growing field.

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