INTERLINKED FIRMS AND THE CONSEQUENCES OF PIECEMEAL REGULATION

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Abstract
Industrial regulations are typically designed with a particular policy objective and set of firms in mind. When input–output linkages connect firms across sectors, such piecemeal regulations may worsen externalities elsewhere in the economy. Using daily administrative and survey data, we show that in Peru's industrial fishing sector, the world's largest, air pollution from downstream (fishmeal) manufacturing plants caused 55,000 additional respiratory hospital admissions per year as a consequence of the introduction of individual property rights (over fish) upstream. The upstream regulatory change removed suppliers' incentive to "race" for the resource and enabled market share to move from inefficient to efficient downstream firms. As a result, the reform spread downstream production out across time, as predicted by a conceptual framework of vertically connected sectors. We show evidence consistent with the hypothesis that longer periods of moderate air polluting production can be worse for health than concentrating a similar amount of production in shorter periods. Our findings demonstrate the risks of piecemeal regulatory design in interlinked economies. (JEL: D2, L5, O1, I1)

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1. Introduction

Firms that generate externalities do not exist in isolation; they interact with other firms through vertical and horizontal interlinkages in the economy. Those other firms may themselves generate externalities, possibly in a different domain. For example, loggers cut down forests and threaten biodiversity whereas the paper mills they supply pollute the local environment; oil and gas companies emit greenhouse gases while lax safety at the operators they employ put marine life at risk. Yet in practice, regulations are typically designed from a partial equilibrium perspective, with a particular set of firms in mind. If the targeted firms' response affects the extent of externalities generated elsewhere in the economy, such piecemeal regulatory design may help account for the frequent and often dramatic regulatory failures we observe (Lipsey and Lancaster 1956), especially in countries with limited regulatory capacity (Laffont 2005).[1]

The suboptimality of piecemeal regulatory design was shown theoretically in the 1950s (Lipsey and Lancaster 1956), but empirical evidence on its efficacy and on associated welfare consequences is lacking.[2] This paper provides a clean demonstration of costly piecemeal regulatory design in an interlinked economy and attempts to quantify these costs. We do so in the context of one of Latin America's biggest industries—fishmeal production in Peru[3]—which features two textbook externalities: overextraction by upstream suppliers (fishing boats) and air pollution from downstream manufacturers (fishmeal plants). We study the 2009 introduction of individual property rights over fish, an "optimal" policy for preventing overextraction.[4]

We first show that the introduction of individual property rights upstream, while successful in stemming overextraction, dramatically increased the health impact of air pollution from downstream plants. In documenting the mechanisms leading to this effect, we also present evidence that health deteriorated in part because of a shift *not* in the quantity, but in the *time profile* of production. Although the 2009 reform was directed at upstream suppliers, it caused downstream manufacturers to significantly

1. Regulatory failures are common in modern, interlinked economies: recent high profile examples include the 2014 and 2013 Indonesia forest fires (see, e.g., The Guardian 2014), the 2010 Deepwater Horizon oil spill (see, e.g., BOEMRE/U.S. Coast Guard Joint Investigation Team 2011), and the 2006 Ivory Coast toxic waste dump (BBC News 2010).

2. As put by Bento et al. (2014), "In the presence of unpriced externalities or other pre-existing distortions, policies levied to correct an externality can exacerbate or alleviate these other distortions in related markets. A priori, theory cannot shed light on the relative importance of the primary welfare effect of the policy—defined by the welfare gain from correcting the externality addressed by the policy—and the interaction effects—defined as the welfare effect that results from the interaction of the new policy with other unpriced externalities" (Bento et al. 2014, p. 2). We cannot do justice to the theoretical literature on regulatory design in the presence of multiple externalities here—see, for example, Bennear and Stavins (2007) and references therein.

3. Fishmeal is a brown powder made by burning or steaming fish, and often used as animal feed. Peru's fishmeal industry accounts for around 3% of the country's GDP (De La Puente et al. 2011) and is the biggest industrial fishing sector in the world (Paredes and Gutierrez 2008).

4. See, for example, Boyce (2004, p. 1): "In fishery management, an optimal instrument, individual transferable quotas (ITQs), exists."

lengthen their yearly production periods, spreading a roughly fixed amount of production—and any associated pollution—out across time. These contributions both have important implications for the regulation of firms and sectors that operate as part of a larger network.

The paper proceeds as follows. We begin by examining the health impact of the 2009 reform using a difference in difference approach. We compare the health outcomes of the population near and further away from fishmeal plants (hereafter "Near plant" and "control"), pre- and post-reform. As the health impact is mediated by firm responses, we next show how the downstream industry reacted to the reform. Some firms exited the market, whereas others expanded production across time, as predicted by a simple conceptual framework of the two interlinked sectors. Finally, we argue that the reform's impact on health is in part due to this change in the *time profile* of production. To test this hypothesis, we implement a series of triple differences that exploit additional geographic heterogeneity in the reform's impact on the time profile of production, comparing areas that saw more and less drastic shifts in yearly production periods.

The 2009 reform in Peru is an ideal setting to investigate the consequences of piecemeal regulatory design for several reasons. First, although a handful of influential existing papers explore unforeseen effects of regulations imposed on a given set of firms (e.g., due to plant substitution between different pollutants or effects on market power),[5] the Peruvian setting enables us to study a sequential production chain with two distinct—but clearly linked—sets of firms generating different externalities. This allows a clean separation between the targets of the regulation and the firms directly generating the unexpected consequences we identify, while also highlighting the extent to which input–output linkages in the economy can propagate the impact of "regulatory shocks" into other spheres of the economy.

Second, although piecemeal regulation likely leads to significant welfare losses in all countries, Peru represents the type of environment where the potential magnitude of such losses and the challenges of addressing the problem are of greatest concern. Both the severity of externalities and the underlying forces that lead to piecemeal regulatory design—for example, noncoordination between regulating agencies or sequential political regimes with distinct objectives, unobservability of some interlinkages or externalities, and the complexity of optimizing regulations in equilibrium—are amplified in the developing world (Greenstone and Jack 2015).[6]

5. Sigman (1996), Greenstone (2003), Gibson (2015) explore plant substitution between regulated and unregulated pollutants. Becker and Henderson (2000) find that, in the United States, environmental regulations favoring small firms led to a shift in industry structure toward single-plant firms, which in turn contributed to environmental degradation. Ryan (2012) and Fowlie, Reguant, and Ryan (2016) find that allocative inefficiencies due to changes in market power in the U.S. cement market counteract the social benefits of carbon abatement regulations. We do not go into the literature on *individuals* substituting across regulated versus unregulated appliances and transport modes here.

6. Economists have only recently begun to emphasize the ubiquity and greater challenges of regulating industrial externalities in developing countries. See, among others, Hanna and Oliva (2014), Ebenstein (2012), Chen et al. (2013), Rau, Reyes, and Urzua (2013), von der Goltz and Barnwal (2014), Greenstone

Third, natural resources are typically intermediate goods that are later processed by downstream firms, and individual property rights is the most commonly recommended regulatory system for natural resource sectors—including oil and gas, forestry, fisheries, and mining (Ostrom, Janssen, and Anderies 2007). As a result, the particular context we study is relevant to a broad set of sectors that are vertically linked with natural resource suppliers.

Finally, many common regulatory systems will tend to spread production or pollution out over time. This paper's evidence on the unintended consequences of Coasian regulations (due to their impact on the distribution of production across *time*) complements the evidence in the influential study of Fowlie (2010) on the unintended consequences of cap-and-trade programs (due to their impact on the *geographical* distribution of production).

We begin by identifying the causal effect of the 2009 regulatory reform on health.[7] To do so, we compare Near plant and control locations before and after the reform came into effect. We find that the fishmeal plants' production was dramatically more harmful to adult and child health post-reform, for example, causing 55,000 additional hospital admissions for respiratory issues per year. We show extensive evidence supporting the identifying assumption of parallel health pre-trends in fishmeal and control locations, and that the estimated reform effects are not driven by changes in incomes, labor markets, or confined to those who work in the sector.

To investigate *why* the 2009 reform exacerbated the downstream sector's impact on health, we first lay out a simple conceptual framework that illustrates the expected effect of the introduction of property rights over upstream natural resources on plant production patterns. The framework predicts that property rights will remove boats' incentive to race to capture fish, and hence cause fishing activity to spread across time. Because fish must be processed immediately after capture, fishmeal plants will correspondingly spread their production across time. The framework also has predictions regarding heterogeneity across plants, suggesting that the most efficient plants will be responsible for the majority of the spread across time, with less efficient firms decreasing production or exiting the market. These predictions find support in the data. Although there was a minor decrease in the total *amount* of fishmeal produced

and Hanna (2014) on the often extremely high pollutant concentrations in developing countries. Several innovative recent papers also illustrate the need to take regulatory capacity and the prevailing incentive structures into account when designing regulation (Laffont 2005; Estache and Wren-Lewis 2009; Burgess et al. 2012; Duflo et al. 2013, 2014; Jia 2014; Greenstone and Jack 2015). The primary focus in the literature on how to design regulation of industrial externalities has been on rich countries and comparing (i) the magnitude of decreases in the targeted type of externalities (e.g., pollution or over extraction of a resource—see Costello, Gaines, and Lynham 2008 for convincing evidence in the case of ITQs for open access resources) to (ii) the economic costs of compliance (see, e.g., Gray and Shadbegian 1993; Greenstone 2002; List et al. 2003; Greenstone, List, and Syverson 2012a; Natividad 2016).

7. Of course, examining how the 2009 reform changes the relationship between fishmeal production and health presupposes that production is harmful. In Appendix Section A.1 we discuss existing evidence for this relationship and in Appendix Section A.2 we explicit test and quantify the baseline impact of production on health.

post-reform, the average individual in our sample was exposed to 53% more *days* of production per year post-reform.

Having shown that the reform had a drastic impact on the temporal spread of production but little effect on its overall level, we hypothesize that plants' impact on health worsened primarily due to the change in the time profile of production. To test this, we first confirm that changes in the quantity of production are not responsible for our findings. The reduced form effect of the reform is robust to a number of approaches to controlling for the local level of production. We then exploit geographical heterogenity in the impact of the reform on the time profile of production, which arose both from geographic variation in ex ante plant efficiency (as predicted by our framework), and from a slightly different regulatory regime in a smaller southern region. Geographical heterogeneity in the estimated health impact supports our hypothesis. Where the extension of production across time was more extreme—in the north (97% increase in production days) and locations with efficient plants (134% increase)—the exacerbation of the industry's impact on health post-reform was significantly worse. But where plant production days decreased with the reform—for example, the southern region (46% decrease)—the estimated impact on health was insignificant or significantly *favorable*.

The primary objective of this paper is to provide convincing evidence on the potential for, and possible magnitude of, a worsening of externalities elsewhere in the economy due to the introduction of piecemeal regulation. Cost/benefit calculations that are suggestive but conservative indicate that the monetized cost of the reform's impact on health is of the same order of magnitude as the increase in sector profits following the reform.

Additionally, however, the mechanism driving these adverse effects is important. Why is the health impact greater when production is spread out over time? Our results point to a potential explanation, namely that increases in the duration of exposure to air pollution can be harmful to health even when accompanied by proportional decreases in the intensity of exposure. The harmful effects of air pollution on adult and child health outcomes are convincingly documented in existing studies,[8] but none to our knowledge analyze the health consequences of *simultaneous* changes in the duration and intensity of exposure (see, e.g., Pope III et al. 2011). The bulk of the evidence we present is consistent with existing evidence from economics and epidemiology on respectively (a) concavity in dose–response at the levels of pollution seen in developing countries (Chay and Greenstone 2003; Krewski et al. 2009; Crouse et al. 2012; Clay, Lewis, and Severnini 2015; Hanlon 2015; Pope III et al. 2015), and (b) the importance of the concurrent level of exposure (dose) and the duration of exposure (Pope III et al. 2011;

8. See, for example, Brook et al. (2010), Moretti and Neidell (2011), Schlenker and Walker (2016), Chen et al. (2013), Currie et al. (2014) on adult health and Chay and Greenstone (2003), Case, Fertig, and Paxson (2005), Chay and Greenstone (2005), World Health Organization (2006), Jayachandran (2006), Currie and Almond (2011, Chap. 5), Currie and Walker (2011), Gutierrez (2015), Roy et al. (2012), Currie et al. (2014, 2015), Isen, Rossin-Slater, and Walker (2017) on child health.

Beverland et al. 2012; Chen et al. 2013; Anderson 2015; Barron and Torero 2017).[9] The policy relevance of the possibility that prolonged exposure to low levels of air pollution can be worse for health than shorter periods of higher intensity exposure—policymakers face a tradeoff between duration and intensity whenever regulations that affect the time profile of production are designed—highlights the importance of further research on this topic.

We conclude (a) that the cost of the exacerbation of "interlinked externalities" elsewhere in the economy that are ignored when (otherwise successful) regulatory reforms are designed can be of first order magnitude; and (b) that the health impact of air polluting plant production can likely be worse if spread out in time, which may alter the cost–benefit calculus for individual property rights and other regulatory regimes that affect the time profile of production.

The paper is organized as follows. In Section 2 we present the datasets used in our empirical exercise. In Section 3 we discuss background on the setting and institutional setup, why fishmeal production may affect health, and the 2009 ITQ reform. In Section 4 we lay out our empirical strategy and estimate how the introduction of individual property rights upstream changed downstream plants' impact on health. Section 5 analyzes, theoretically and empirically, the industry's response to the 2009 ITQ reform, and Section 6 tests the time profile hypothesis. Section 7 contrasts the magnitude of the unforeseen costs of the piecemeal-designed ITQ reform in Peru and its benefits and Section 8 concludes.

2. Data

For our empirical analysis we combine five different sources of data: hospital admission records, individual- and household-level survey data, administrative regulatory data, administrative production and transaction registries, and pollution data.

Hospital Admission Records. Information on hospital admissions was provided by the Peruvian Ministry of Health. The data contain monthly counts of patient admissions for each public health facility, disaggregated by the cause of admission (using the International Classification of Diseases (ICD) system).

Individual- and Household-Level Survey Data. The nationally representative Encuesta Nacional de Hogares (ENAHO) is the Peruvian version of the Living Standards Measurement Study (LSMS). Since 2004 surveying has taken place

9. The existing literature typically analyzes the two underlying relationships (duration and dose response) separately. Pope III et al. (2015) summarize the epidemiological evidence on dose (concentration) response: "recent research suggests that the C–R (concentration response) function (between $PM^{2.5}$ and health risk) is likely to be supralinear (concave) for wide ranges." Pope III et al. (2011) summarize the epidemiological evidence on duration response for cardiovascular mortality risk of air pollution and conclude that "the evidence suggests that . . . longer duration exposure has larger, more persistent cumulative effects than short-term exposure."

throughout the year, and the order in which sampling clusters are surveyed is randomly determined. A subset of clusters are resurveyed every year and information on the "centro poblado" where each respondent is interviewed is recorded.[10] In our analysis, we use the GPS coordinates of the centro poblado's centroid. The survey focuses on labor market participation, income and expenditures, self-reported health outcomes, and so forth, as in other LSMSs. We use ENAHO to construct our sample of adults.

We also use the nationally representative Encuesta Demográfica y de Salud Familiar (ENDES), which is the Peruvian version of a Demographic and Health Survey (DHS). The sampling framework is similar to ENAHO. A subset of clusters are resurveyed every year. GPS coordinates for sampling clusters are recorded. Women between 15 and 49 years old are interviewed, and information on the women themselves and their children (five years old and younger) recorded. The survey is comparable to other DHS surveys, focusing on self-reported and measured health outcomes. We use ENDES to construct our sample of children. For both surveys, we primarily use the years 2007–2010.

From our hospital and survey data we construct five primary outcome variables. We focus particularly on the health issues that are most likely to be affected by short-term variation in air pollution from plant production (see, e.g., Chen et al. 2013)—respiratory issues. The outcome "respiratory admissions" is a count at the hospital level of all admissions due to diseases of the respiratory system (ICD codes J00-J99). As no explicit question on respiratory issues is asked in the ENAHO survey, for adults we construct an outcome labeled "any health issue" as the complement to "No health issue in the last month." We also use expenditure data to construct an estimate of the individual's total medical expenditures. For children, we use ENDES survey data to construct a measure of "Any Health Issue,"[11] and also separately report the outcome of the child experiencing a cough. The survey based outcomes likely capture adverse health episodes of a wider range of severity than those leading to hospital admission.

Administrative Regulatory Data. We coded the dates of all fishing seasons from 2007 to 2011 and the size of each season's aggregate quota from the government gazette *El Peruano*.

Administrative Production and Transaction Registries. The registry of the universe of transactions between industrial fishing boats and fishmeal plants from 2007 to 2011 was provided by the Peruvian Ministry of Production. All offloads by industrial boats are included, that is, all (legal) input into fishmeal production, including "within-firm"

10. Centros poblados are villages in rural areas and neighborhoods in urban areas. After the sample restrictions we impose, 2096 sampling clusters with on average 77 households each are present in our sample. 710 centros poblados are present, with on average 228 households each.

11. This variable is equal to one if the surveyed parent reported that the child had experienced any of the health issues the survey covers in the last two weeks. The covered health issues are cough, fever, and diarrhea. These have all been linked to air pollution in the existing epidemiological literature (see, e.g., Peters et al. 1997; Kaplan et al. 2010), although the evidence linking air pollution to issues that would generate "coughs" is more extensive.

transactions. Information on the date of the transaction, and the boat, plant, and amount of fish involved (though not the price), is included.

We also have access to the ministry's records of fishmeal plants' production/output, recorded at the monthly level, from 2007 to 2011.

Pollution Data. In contrast to many developing countries, daily ground-station measurements of air pollutants are available in Peru. The stations cover a significant fraction of our sample, although they are only present in the area around Lima. Information on the daily concentration of four air pollutants at each of five stations in the Lima region was provided by the environmental division (DIGESA) of the Ministry of Health for the period 2007–2010. The measured air pollutants—PM^{10}, $PM^{2.5}$, NO_2, and SO_2—have been shown to correlate with factory production in many contexts and are commonly used in the health literature.

3. Background

3.1. Two Interlinked Sectors, Downstream Production, and Health

The Peruvian fishing sector is one of the world's largest: the industrial fishing boats supplying Peru's fishmeal plants account for around 10% of global fish capture (Paredes and Gutierrez 2008). Fishmeal plants are present in 22 towns along the coast that have a suitable port. The plants produce about a third of the global supply of fishmeal.

Both the industrial fishing sector and the fishmeal sector are very capital intensive. Paredes and Gutierrez (2008) estimate that there were only about 26,500 jobs in the two sectors as a whole in 2008: 1,194 active industrial fishing boats employed around 17 workers each on average, and 110 fishmeal plants employed around 60 workers each on average (see Paredes and Gutierrez 2008; Christensen et al. 2014).[12] There is little seasonal work migration.

Fishmeal tends to be higher in protein, and hence more valuable, when made from fresh fish. Most fishing boats therefore go out for effectively one day at a time (the average trip lasts about 21 hours, Hansman et al. 2017), and plants process the fish immediately after it has been offloaded. Most of the plants use conveyor belts to transfer raw fish from boats. After cleaning, the fish is dried and converted into fishmeal either by direct exposure to heat or through a steaming process. The final product is a brown powder that is high in protein and typically used as feed in agriculture and aquaculture. Fishing boats that supply fishmeal plants and operate in the North/Central zone, which covers most of Peru's coastal waters, are allowed to fish during only two

12. Because jobs in industrial fishing and fishmeal production are quite stable many fishmeal firms keep the (relatively high-skill) plant workers on payroll outside of the production season. In a country-wide survey of workers in the sector conducted by the consulting firm APOYO in May 2007, 87% report having worked for the same company or fishing boat owner throughout their career, on average for about 14 years APOYO (2008). 40% report not working at all outside of the production seasons; a large proportion of the remainder work as artisan fishermen intermittently.

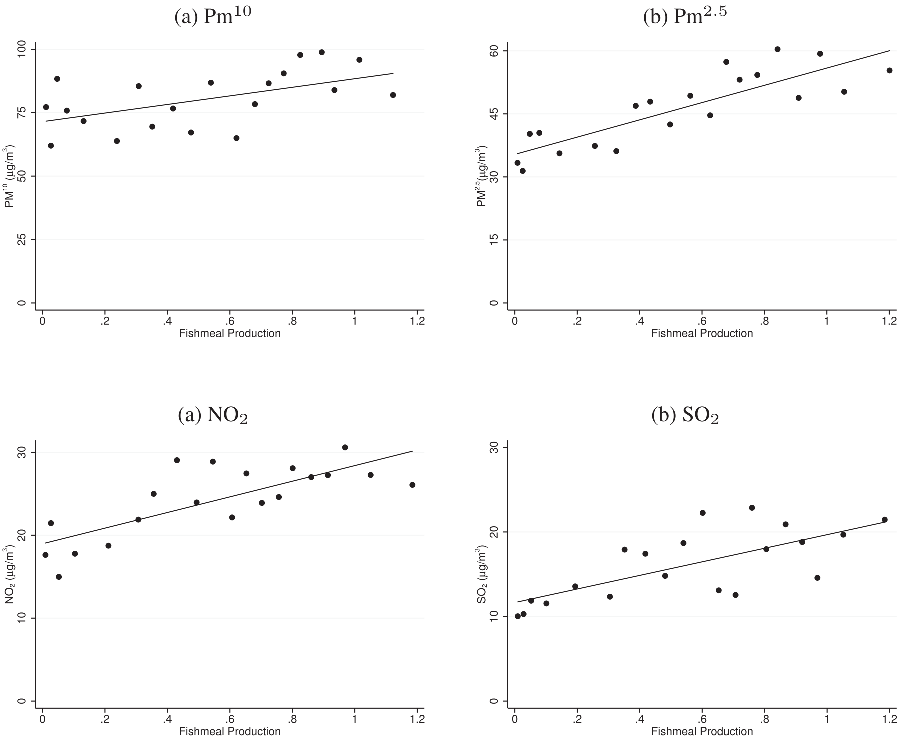

FIGURE 1. Daily fishmeal production and air pollution in Lima. Binned scatter plots of pollutant levels (in μg/m^3) against daily fishmeal production in Callao (measured as inputs in 10,000s of MTs) for days with positive production. Line is a linear fit through the data. Pollutant levels at the port of Callao are calculated as the inverse distance weighted mean of 5 air quality measurement stations in Lima. Missing values at individual stations are imputed using the following method: (i) construct the empirical distributions for each of the five stations. (ii) On days that data is missing at a given station, find the value of the empirical distribution on that day for each of the other stations. (iii) Take the inverse distance weighted mean of those values. (iv) Replace the missing data with the concentration corresponding to the point in the empirical distribution found in (iii).

specific periods (seasons) each year. Because of the need for fresh fish, plants are also constrained to producing during those seasons.

Fishmeal production potentially generates several types of air pollution. This pollution may occur in the form of chemical pollutants (such as carbon dioxide (CO_2) and nitrogen dioxide (NO_2)) from the plants' heavy use of fossil fuels; in the form of noxious gases (e.g., sulfur dioxide (SO_2) and hydrogen sulfide (H_2S)) released as fish decompose; and in the form of microscopic natural particles (PM^{10} or $PM^{2.5}$) released during the drying and burning processes. Case studies have found high levels of air pollution near fishmeal plants during production periods (see Appendix Section A.1 for more details). Using data from Lima, where information on pollution levels has been consistently recorded by five air quality measurement stations, Figure 1 shows a positive and steep association (in the raw data) between daily fishmeal production at

TABLE 1. Impact of fishmeal production on health through air pollution in Lima.

	Port level correlation between fishmeal production and air pollution			
	PM^{10}	$PM^{2.5}$	NO_2	SO_2
Log fishmeal prod. in last 30 days	1.629**	1.412***	0.330	0.536
	(0.760)	(0.514)	(0.367)	(0.389)
Mean of dep. var.	77.9	45.1	25.2	19.2
Durbin–Watson *D*-stat.	0.255	0.207	0.241	0.172
Durbin alt. test *p*-value	0.000	0.000	0.000	0.000
N	1231	1414	1416	1416

Notes: We present pollutant levels regressed on "Log fishmeal production" and month fixed effects. All pollutants are measured in $\mu g/m^3$. Daily pollutant levels are inverse distance weighted averages of readings at 5 pollution stations in Lima. Missing values at individual stations were imputed using the following technique: (i) construct the empirical distributions for each of the five stations. (ii) On days that data is missing, find the value of the empirical distribution on that day for each of the other stations. (iii) Take the inverse distance weighted average of those values. (iv) Replace the missing data for the station with the concentration corresponding to the point in the empirical distribution found in (iii). Fishmeal production is based on daily inputs of fish, measured in 10,000s of MTs. Mean of dep. var. gives unconditional mean for sample included in the corresponding regression. $^{**}p < 0.05$; $^{***}p < 0.01$.

a port that is located in the outskirts of the city—Callao—and four main pollutants: PM^{10}, $PM^{2.5}$, NO_2, and SO_2. In Table 1 we show this relationship quantitatively by regressing daily pollution levels on (the log of) fishmeal production in the last 30 days while including month×year dummies to control for any general time patterns. A 50% increase in fishmeal production in the last 30 days is associated with an increase in PM^{10} of just under 1% and an increase in $PM^{2.5}$ of 1.3%.[13]

The pollutants associated with fishmeal production have been shown to cause respiratory issues and a range of other health problems in adults and children (Appendix Section A.1 provides details on relevant studies).[14] In Appendix Section A.2 we conduct a series of empirical exercises to show that the setting we study is no exception: there is a robust reduced form causal relationship between fishmeal production and

13. The basic time series regressions in Table 1 include Newey-West standard errors with 15 lags to account for autocorrelation in the errors. Both NO_2 and SO_2 become significant with less conservative lag choices. We obtain similar results when running the specification in differences.

14. Travelers passing by fishmeal locations during production season can easily see and smell the severity of air pollution, an observation that motivated this project. In a 2008 article, *The Ecologist* magazine reported that "When we visited one heavily afflicted community [in the fishmeal town of Chimbote], more than a dozen women and children gathered [. . .] to vent their anger at the fishmeal plants. They claim the plants that loom over their houses are responsible for asthma, bronchial and skin problems, particularly in children. "We know the factories are responsible for these [problems], because when they operate the illnesses get worse", says one young woman [. . .] Another says when the plants are operating the pollution is so thick you cannot physically remain on the street. Footage [...] seen by *The Ecologist* illustrates typical conditions when fishmeal plants are operational: billowing black smoke drifts through the streets, obscuring vision and choking passers-by [. . .] Pupils at a Chimbote school [. . .] also complain of health problems. "It causes fungal growths, breathlessness, we cannot breathe", says one boy". Such complaints were supported by case studies (e.g., Cerda and Aliaga 1999), and local doctors Wasley and Wickens (2008).

child and adult health in Peru, and air pollution is the most likely channel driving this reduced form effect.

3.2. *Regulations and the 2009 Upstream Reform*

The regulations imposed on the Peruvian industrial fishing industry are aimed at preserving fish stocks while maintaining industry profitability. Prior to the 2009 reform, industrial boats in the North/Central region (the majority of the country—down to the $-16°$S parallel) operated under a sector-wide "Total Allowable Catch" (TAC) set at the beginning of each season. This system specified a seasonal quota for the region as a whole, with no restrictions on the distribution of that quota across boats. As a result, the TAC system generated an incentive to capture as large a share of the quota as possible as quickly as possible. This, in turn, led to excess capacity and a highly concentrated fishing season, stressing the biomass of Peruvian anchoveta. In 2008, officials estimated excess capacity in the combined sector (the industrial fleet and fishmeal plants) of 35–45% and declining fish stocks (Tveteras, Paredes, and Peña-Torres 2011). The government announced a new law introducing a system of individual, transferable quotas (ITQs) for industrial fishing boats on June 30, 2008, to be implemented in 2009.

The ITQ system assigned each boat with a specific share of the regions' aggregate quota for the relevant season. The quota-share was based on historical catches and a boat's hull capacity, and could be transferred between boats within a region, subject to certain rules. Because ITQs provide property rights, they in theory eliminate the need to compete for fish. An extensive media search reveals no mention of the downstream plants' impact on health in the deliberations leading up to the law, though clear indications of such externalities had received considerable attention in the Peruvian and foreign media for years and were in all likelihood known to Peruvian regulators.

It should be noted that prior to 2009 a small southern region (below the $-16°$S parallel) was not subject to the same TAC regulation as the majority of the country. In this southern region fishing was allowed throughout the year and no aggregate quota was in place before the 2009 ITQ reform. This meant that, in the South, the new ITQ system introduced a quota and fishing seasons for the first time. We discuss the differences between regions further in Section 6, where we exploit the differences across regions in our empirical strategy. The 2009 reform officially went into effect in the North/Central region on April 20, 2009 and in the South on July 7, 2009.

4. Estimating the Effect of the Introduction of Individual Property Rights Upstream on Health

4.1. *Empirical Strategy*

The primary goal of this paper is to identify the impact of the introduction of a new regulatory system upstream—individual property rights—on the extent of the externalities generated by downstream plants. We consider health outcome y_{ijt} for an individual or hospital i in location j at time t. We compare y_{ijt} for those located within a given radius of fishmeal plants ($NearPlant_j = 1$) to those located further away ($NearPlant_j = 0$), before ($Reform_{jt} = 0$) and after the reform ($Reform_{jt} = 1$).[15] For individual level outcomes, we estimate:

$$y_{ijt} = \alpha + \beta_1 NearPlant_j \times Reform_{jt} + \boldsymbol{X}'_{ijt}\boldsymbol{\beta}_2 + \gamma_{c(j)} + \delta_{m(t)} + \varepsilon_{ijt}. \quad (1)$$

For hospital level outcomes, we estimate the analogous:

$$y_{ijt} = \alpha + \beta_1 NearPlant_j \times Reform_{jt} + \boldsymbol{X}'_{jt}\boldsymbol{\beta}_2 + \psi_i + \delta_t + \varepsilon_{ijt}. \quad (2)$$

We are primarily interested in β_1, the coefficient associated with the interaction $NearPlant_j \times Reform_{jt}$.

In equation (1) we estimate the effect of the reform using survey data, where we observe the date of the survey. Hence, here t indicates a specific date. For the same reason, we denote the year×calendar month fixed effects included by $\delta_{m(t)}$. In this regression, we also include location level (centro poblado or district)[16] fixed effects $\gamma_{c(j)}$. $\boldsymbol{X}$ are covariates that include individual-level characteristics,[17] as well as $NearPlant_j \times \theta_{n(t)}$, where $\theta_{n(t)}$ is a calendar month (e.g., May) fixed effect. The latter controls for possibly differential seasonality in $NearPlant_j$ locations. $\boldsymbol{X}$ also includes separate $NearPlant_j$ and $Reform_{jt}$ dummies, although almost all the variation in these two indicators is captured by our location and time fixed effects.[18]

In the hospital data, which we use in the estimation of equation (2), we observe monthly counts. t thus indicates a year×calendar month, and in that regression we denote the year×calendar month fixed effects by δ_t. Here, we can additionally include hospital specific fixed effects ψ_i, as we observe repeated observations of each hospital. Note that the location fixed effects in (1) and the hospital fixed effects control for time-invariant differences across space, including average levels of air pollution. Finally, X is simply $NearPlant_j \times \theta_{n(t)}$, where $\theta_{n(t)}$ is a calendar month.

For outcomes drawn from surveys, in which we have precise village/cluster GPS data, we use 5 km as the baseline "treatment" (Near plant) radius, following recent literature on air pollution (see, e.g., Currie et al. 2015; Schlenker and Walker 2016).

15. As we do not have GPS points for surveyed households, nor shape files for the sampling clusters and centros poblados, we define the location of i as the centroid of j (the centro poblado (in ENAHO) or sampling cluster (in ENDES)) to which the household belongs.

16. Although we use centro poblado fixed effects in regressions using ENAHO data, the lowest geographical unit we can condition on when using ENDES data is districts. The reason is that the ENDES sampling framework changed in 2008/2009. Although district information is included in all rounds of ENDES, the data key necessary to link specific sampling clusters/centros poblados before and after 2008/2009 was not stored. Note that Peruvian districts are small; there are 1838 districts in the country.

17. The individual covariates are gender, age, mother tongue, years of education, and migration status for adults, and gender, age, mother's years of education, and the ENDES household asset index for children. These control for possible changes in the sample surveyed across time/space.

18. Because the reform came into effect slightly earlier in the North/Central region than in the south, $Reform_{jt}$ is defined to be one if the reform is in effect in the port (cluster of plants) closest to location j.

For hospital outcomes, we use 20 km as the baseline treatment radius so as to include the facilities used by those living near fishmeal plants in the "treatment group."[19]

Figure 2 shows a map of Peru indicating the locations of ENAHO and ENDES sampling clusters. The map also shows the −16°S parallel that separated the North/Central and South regulatory regimes before the 2009 ITQ reform. The identifying assumption necessary for (1) and (2) to estimate the causal effect of the ITQ reform on health is that trends in health outcomes across the date when the reform took effect would have been similar in Near plant and control locations in the absence of the reform. In the figure, we have enlarged the area around two fishmeal ports (Chimbote and Coishco). As the enlarged area makes clear, our samples contain many observations clustered near—and on either side of—the 5 km radii around (clusters of) fishmeal plants (shown as black circles) we use to define the "Near plant" indicator.

In Table 2, we show the means and standard deviations of both health outcomes and covariates in Near plant and control locations, before and after the 2009 ITQ reform. The relative worsening of health outcomes in Near plant locations after the reform is evident in the raw data displayed. As we show in the last column of Table 2, the unconditional difference in difference coefficients are positive and sizable for all five measures of health. The estimate is significant for respiratory hospital admissions, adult health issues, and medical expenditures, and marginally significant for health issues for children. Although there are some differences in the level of other covariates between Near plant and control locations, the location and hospital fixed effects included in (1) and (2) will control for time invariant differences between hospitals/locations, whereas the time period fixed effects and trends will control for general time effects. We also include all covariates shown in Table 2 for adults and children as controls when estimating (1) and (2).

4.2. The Introduction of Individual Property Rights Upstream and Health

In this and the following section, we show more formal evidence reinforcing the raw difference in difference coefficients shown in Table 2: the 2009 ITQ reform adversely impacted the health of adults and children in locations near to fishmeal plants.

Figure 3 presents graphical evidence of the effects of the 2009 reform on health outcomes, showing trends in Near plant and control locations before and after the reform took effect. First, note that across outcomes we see similar trends in the two groups before the reform, suggesting that the identifying assumption of parallel trends holds. Second, for all outcomes, we see a significant, differential increase in adverse health outcomes in Near plant locations when the reform takes effect.[20] Although descriptive, this figure mirrors the raw differences in differences shown in Table 2.

19. The geographical spread of health facilities is much greater than that of sampling clusters. In many fishmeal locations, the nearest hospital is more than 10 km away.

20. We do not have enough observations around the cut-off (the date then the reform took effect) to estimate the effect of the reform in a regression discontinuity approach.

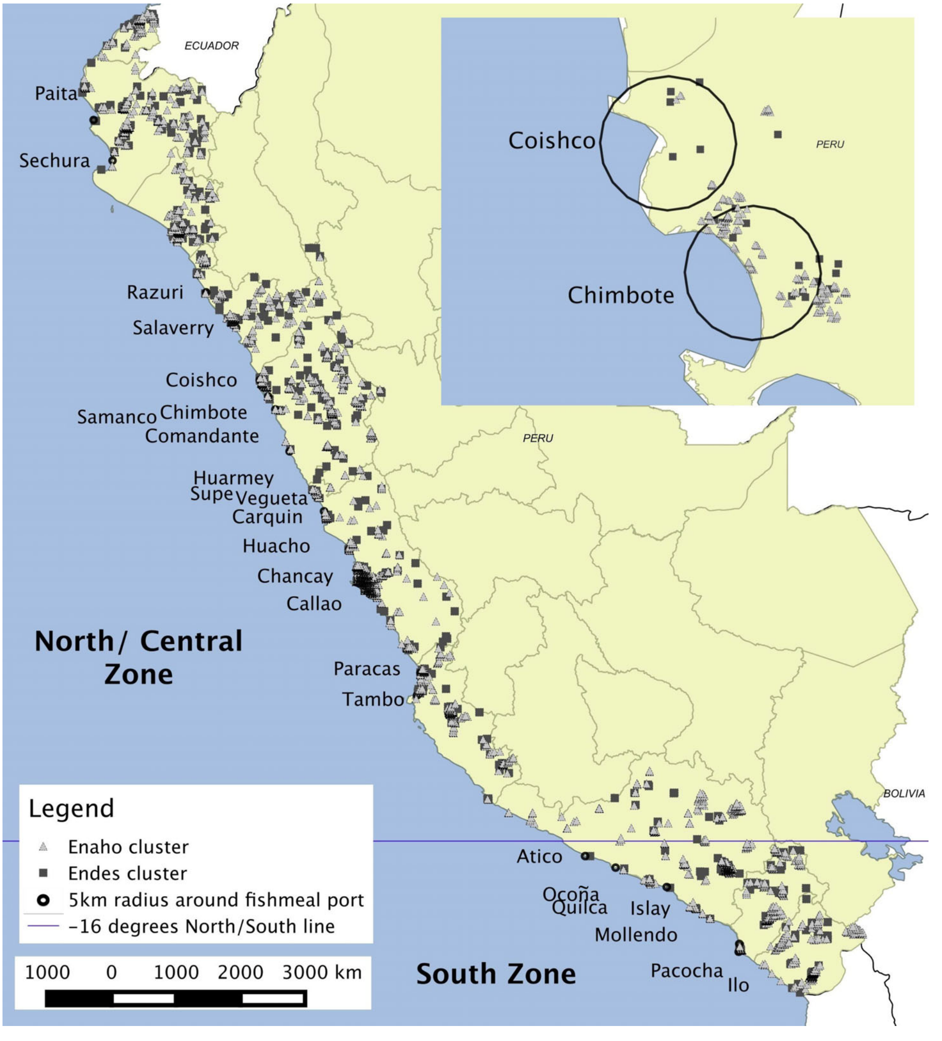

FIGURE 2. Location of fishmeal ports and sampling clusters. The figure shows a map of Peru indicating the locations of ENAHO and ENDES sampling clusters as well as 5 km radii around (clusters of) fishmeal plants, illustrating the cross-sectional variation used in our identification strategy. The map also shows the $-16°$S parallel that separated the North/Central and South regulatory regimes before the 2009 ITQ reform. We have enlarged the area around two fishmeal ports (Chimbote and Coishco). As the enlarged area makes clear, our samples contain many observations clustered near—and on either side of—the 5 km radii around (clusters of) fishmeal plants (shown as black circles) we use to define the "Near plant" indicator.

Table 3 presents estimates of the effect of the 2009 reform on adult and child health from equations (1) and (2). The top panel shows our preferred baseline specification, which considers the years 2008 and 2009—the last year before and first year after the reform. We see respiratory hospital admissions increase by 7.2% in Near plant locations relative to control locations after the reform. For adults, we see large and

TABLE 2. Summary statistics: health outcomes pre- and post-reform.

	Near plant: Pre-reform Mean	Near plant: Pre-reform SD	Near plant: Post-reform Mean	Near plant: Post-reform SD	Control: Pre-reform Mean	Control: Pre-reform SD	Control: Post-reform Mean	Control: Post-reform SD	Diff-in-Diff
Health outcomes									
Respiratory admissions	327.5	352.5	322.3	327.2	136.5	183.6	124.7	169.4	6.70**
									(3.06)
Any health issue (adults)	0.55	0.50	0.64	0.48	0.57	0.50	0.60	0.49	0.059***
									(0.010)
Log medical expend.	3.66	2.89	4.06	2.84	3.59	2.86	3.79	2.88	0.21***
									(0.083)
Any health issue (children)	0.39	0.49	0.43	0.50	0.47	0.50	0.45	0.50	0.063*
									(0.037)
Cough	0.32	0.47	0.35	0.48	0.39	0.49	0.37	0.48	0.056
									(0.037)
Covariates									
Age (adults)	37.7	20.0	35.4	21.3	36.2	19.7	35.7	21.0	−1.72***
									(0.41)
Age (children)	2.39	1.40	2.50	1.43	2.51	1.44	2.49	1.43	0.13
									(0.109)
Male (adults)	0.49	0.50	0.48	0.50	0.49	0.50	0.49	0.50	−0.011
									(0.010)
Male (children)	0.50	0.50	0.53	0.50	0.50	0.50	0.50	0.50	0.026
									(0.038)
Years of education (adults)	9.64	4.27	9.90	4.22	9.32	4.54	9.30	4.57	0.28***
									(0.095)
Mothers' years of educ. (children)	10.9	3.36	11.1	3.38	9.69	4.19	9.60	4.05	0.35
									(0.304)
Current. lives in birth prov. (adults)	0.45	0.50	0.45	0.50	0.40	0.49	0.38	0.49	0.014
									(0.010)
Indigenous language (adults)	0.099	0.30	0.088	0.28	0.13	0.34	0.13	0.34	− 0.0083
									(0.0070)
HH asset index (children)	1.00	0.68	0.80	0.64	0.60	0.90	0.21	0.91	0.19***
									(0.068)
Observations (adults)	4388		5347		69116		82961		
Observations (children)	255		695		4558		9176		
Observations (hospitals)	10210		12332		55136		65773		

Notes: Adult data from ENAHO (2007–2011), child data from ENDES (2007–2011) and hospital admissions from administrative data. Adults older than 13 and children under 6 living in coastal regions are included. All health outcomes excluding "Log medical expenditure" and counts of hospital admissions are binary. Medical expenditure is measured in Peruvian Soles. Post-reform refers to the 2009 ITQ reform, which began on April 20, 2009 in the North/Central region and July 7, 2009 in the South. Near plant is defined as within 5 km for survey data and within 20 km for hospital data. The column labeled Diff-in-Diff shows the raw difference-in-difference coefficient across Near plant and control locations, pre- and post-reform with standard errors below in parentheses. $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

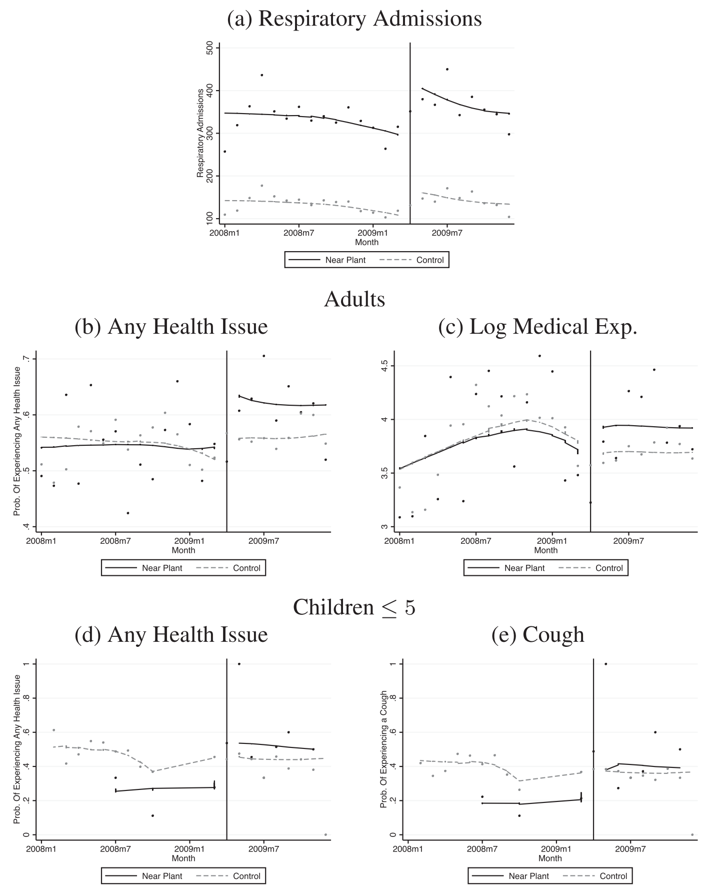

FIGURE 3. Plotting health outcomes across time pre- and post-reform. Scatter plots and lowess smoothing of health outcomes across months. Black lines and dots are based on data for those living near plants, gray lines and dots are based on data for all others. Dots are monthly mean levels for each group. Adult data includes those over 13 years of age living in coastal regions sampled in ENAHO (2008–2009), child data includes those under 6 years old living in coastal regions sampled in ENDES (2008–2009). Note that no clusters in ENDES sampled in the early part of 2008 were near a plant. Noisier graphs for child outcomes are in general due to smaller sample sizes for children. Smoothed separately before and after the start of the reform in the north region (April 2009). The small South region is omitted due to a later reform starting date and different regulatory change.

significant effects on health, with the likelihood of reporting a health issue increasing by over 10%, and medical expenditures by 23.9%, after the reform. We see even bigger effects for children, with the incidence of "any health issue" increasing by 40% and coughs increasing by (an imprecisely estimated) 39%.[21]

21. A possible concern is that the seriousness of health issues may have changed after the reform. Although we ultimately cannot fully test for this possibility, it is important to keep in mind that (a)

TABLE 3. Impact of fishmeal industry on health before and after the 2009 ITQ reform.

	Hospitals	Adults		Children: ≤5	
	Respiratory admissions	Any health issue	Log medical expenditure	Any health issue	Cough
	Baseline (2008–2009)				
Post-reform × Near plant	12.239**	0.059**	0.239*	0.184**	0.146
	(5.245)	(0.027)	(0.140)	(0.092)	(0.090)
Mean of dep. var.	170.5	0.57	3.70	0.45	0.37
N	57554	62158	62167	6602	6599
	Treatment/control specific time trends				
Post-reform × Near plant	19.483***	0.061*	0.198	0.241**	0.206*
	(6.364)	(0.033)	(0.174)	(0.116)	(0.121)
Mean of dep. var.	170.5	0.57	3.70	0.45	0.37
N	57554	62158	62167	6602	6599
	Centro poblado/district specific time trends				
Post-reform × Near plant	1.417	0.066***	0.243*	0.280***	0.346***
	(7.908)	(0.025)	(0.135)	(0.082)	(0.083)
Mean of dep. var.	133.2	0.57	3.70	0.43	0.36
N	48631	62158	62167	4785	4782
	Sample explanded to 2007–2010				
Post-reform × Near plant	9.681*	0.056***	0.181**	0.099***	0.083**
	(5.408)	(0.018)	(0.084)	(0.036)	(0.038)
Mean of dep. var.	167.2	0.58	3.68	0.46	0.37
N	114755	125084	125106	11112	11107
	Sample restricted to first season of 2008 and 2009				
Post-reform × Near plant	17.136***	0.093***	0.317*	0.288***	0.260***
	(5.839)	(0.028)	(0.168)	(0.074)	(0.096)
Mean of dep. var.	188.7	0.57	3.73	0.46	0.38
N	28776	31504	31510	5059	5059
	Sample restricted to within 50 km of port				
Post-reform × Near plant	10.319*	0.023	0.155	0.189**	0.167**
	(6.018)	(0.027)	(0.145)	(0.084)	(0.073)
Mean of dep. var.	279.8	0.55	3.99	0.46	0.39
N	18620	29042	29049	2450	2448

TABLE 3. Continued.

	Hospitals	Adults		Children: ≤ 5	
	Respiratory admissions	Any health issue	Log medical expenditure	Any health issue	Cough
Hospital/centro poblado/district FEs	Yes	Yes	Yes	Yes	Yes
Month × Year FEs	Yes	Yes	Yes	Yes	Yes
Month × Near plant FEs	Yes	Yes	Yes	Yes	Yes
HH controls	No	Yes	Yes	Yes	Yes

Notes: OLS regressions. Hospital admissions measure total monthly admissions at the hospital level. Adult data includes those over 13 years of age living in coastal regions sampled in ENAHO. Child data includes those under 6 years old living in coastal regions sampled in ENDES. Unless otherwise labeled, the sample includes all observations in 2008 and 2009. The reform began on April 20, 2009 in the North/Central region and July 7, 2009 in the South. All specifications include a dummy variable for living near a plant and month × year fixed effects. Time trends refer to the inclusion of a treatment or centro poblado/district specific monthly linear trend. Adult regressions include controls for age, gender, native language and level of education. Child regressions include controls for age, gender, household assets and mother's level of education. Hospital, adult and child specifications include hospital, centro poblado and district fixed effects respectively, with standard errors clustered at the same level. "Respiratory admissions" is a count, medical expenditure is measured in Peruvian Soles, all other dependent variables are binary. Mean of dep. var. gives unconditional mean for sample included in the corresponding regression. $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

4.3. Robustness

In the remaining five panels of Table 3, we provide a series of alternative specifications that demonstrate the robustness of the baseline results shown in the first panel. We first show that the results are robust to differential linear time trends in Near plant and control locations, as well as to differential location (centro poblado or district) time trends. The inclusion of these trends has little meaningful impact on the estimates, although location trends do lower the estimated coefficient on respiratory admissions somewhat. We next show that the impact on health is not concentrated in the time window around the reform we focus on the baseline specification: the estimates are qualitatively similar when we expand the sample to the years 2007–2010, and also when we restrict the sample further to only include the first fishing season of the year in 2008 and 2009. The point estimates are also similar when we restrict the control group to observations relatively near (within 50 km of) fishmeal plants, although doing so lowers the precision of the estimates, especially for the two adult outcomes. In all, the results in the bottom five panels of Table 3 show that our results hold up to a wide array of alternative specifications. Given this—and the graphical evidence of parallel pre-trends in the outcomes in Figure 3—we conclude that the estimated worsening of the downstream plants' impact on health after the 2009 ITQ reform is robust and likely reflects a causal relationship.

respiratory disease episodes have to be fairly serious to lead to a hospital admission (pre- or post-reform), and, perhaps more importantly, (b) the estimates for medical expenditures suggest that the total health costs to individuals increased significantly post-reform.

TABLE 4. Impact of fishmeal industry on labor market outcomes before and after the 2009 ITQ reform—by job category.

	Has any job	Has 2nd job	Total labor hours	Log total income
	Panel A: All adults			
Post-reform × Near plant	0.023	−0.001	−0.111	−0.675
	(0.020)	(0.015)	(0.110)	(0.973)
Mean of dep. var.	0.63	0.10	3.44	30.3
N	62104	62104	62104	62104
	Panel B: Nonfishing workers			
Post-reform × Near plant	0.022	−0.002	−0.110	−0.148
	(0.022)	(0.014)	(0.127)	(1.067)
Mean of dep. var.	0.62	0.10	3.40	30.0
N	60832	60832	60832	60832
	Panel C: Fishing workers			
Post-reform × Near plant	0.097***	0.085	0.453	−3.334
	(0.036)	(0.090)	(0.330)	(6.480)
Mean of dep. var.	0.93	0.12	5.67	43.8
N	1272	1272	1272	1272
Hospital/centro poblado FEs	Yes	Yes	Yes	Yes
Month × Year FEs	Yes	Yes	Yes	Yes
Month × Near plant FEs	Yes	Yes	Yes	Yes
HH controls	Yes	Yes	Yes	Yes

Notes: OLS regressions. Data from ENAHO (2008–2009). Adults older than 13 living in coastal regions are included. All specifications include a dummy variable for living within 5 km of a port and controls for age, gender, native language, and level of education. Standard errors, clustered at the centro poblado level, are included in parentheses. All specifications include a dummy variable for living near a plant, month × year fixed effects, and centro poblado fixed effects. Total income is measured in Peruvian Soles. Mean of dep. var. gives unconditional mean for sample included in the corresponding regression. Labor categories are based on 3 digit job codes. $^{***}p < 0.01$.

As discussed in Section 3.1, the air pollution generated by fishmeal production in Peru has been linked to worsening health conditions, a finding we confirm in Appendix Section A.2. We therefore expect that the effect of the ITQ reform on health is primarily driven by a change in the impact of air pollution from the plants. Alternatively, the reform might affect health through some change in local economic conditions, labor markets, or migration patterns. There are several reasons why this is unlikely to be the case. First, as described in Section 3, the industry employs few workers, and they represent only 2% of all adult workers in our sample. Second, workers in the industry are mostly permanent employees, and there is virtually no seasonal migration into fishmeal locations. Table 4 confirms this notion by considering the impact of the reform on "economic" outcomes. These results are estimated on our adult sample, with specifications identical to equation (1). In our full sample, and in the subsample of workers not connected to the fishing industry, we find no significant effects on any of the economic outcomes we consider: employment, having a second job, total labor hours, or (log) total income. Similarly, in our sample of fishing workers, we find no statistically significant effect on having a second job, total labor hours, or (log) total employment. We do find a positive and significant impact on the probability of a fishing worker having a job, but having a job would presumably decrease the likelihood of health issues, and the estimated effect is in any case not large enough to drive population-wide outcomes.

In this section we have analyzed the downstream consequences of the introduction of individual property rights in Peru's industrial fishing sector—a reform that was designed piecemeal, without accounting for the interlinkages between the externalities generated by the fishing and fishmeal sectors. We demonstrated that the 2009 ITQ reform upstream significantly exacerbated fishmeal plants' impact on the population's health, and that the estimated effects capture a causal impact of the reform. In the next sections we study (i) the impact of the upstream reform on patterns of plant production and pollution and (ii) the link between these changes and the worsening of the fishmeal industry's impact on health.

5. Plants' Response to the Introduction of Individual Property Rights Upstream

5.1. Conceptual Framework

We begin by discussing a simple conceptual framework to analyze the impact of the introduction of property rights on the activity of fishing boats and, subsequently, on the production patterns of downstream plants. The framework informs how we should expect production to change *on average* across locations, pointing toward a potential explanation for the observed impact of the reform on health. The framework also helps us test the hypothesized explanation, by providing predictions about which characteristics of the fishmeal industry *in a particular location* should predict a large or small local production response. Although we develop a formal model in Appendix Section A.3, we limit ourselves here to discussing the intuition of the framework.

The first—perhaps unsurprising—prediction is that the introduction of individual property rights upstream leads plant production to spread out across time. This follows directly from the goals of the 2009 ITQ reform (and of most property rights policies). An industry wide quota (TAC) regime like the one in place in Peru prior to 2009 generates an incentive for boats to race for fish early in the season, leading to a quickly exhausted quota. Under standard assumptions (and fixing the industry's total seasonal capture), individual quotas lead to a longer fishing season, with a lower quantity captured per day. The impact of this change in fishing activity on plant production—a longer production period, with a lower quantity produced per day—is a result of the fact that fish must be processed immediately after capture. Put simply, industry wide quotas lead to short, high intensity production periods, whereas property rights lead to longer, lower intensity production periods.

Second, the framework predicts that—with heterogeneity in plant efficiency—the spread of the production season should be greater in locations with more efficient plants, whereas less efficient plants will reduce overall production and potentially exit the market. Under an industry wide quota, the high daily capture creates an oversupply and resultantly low daily price of fish. The low input price allows less efficient downstream firms (i.e., those with high costs of production) to survive. As the introduction of individual quotas reduces daily capture, the price of fish rises, and inefficient firms must reduce production or exit the market. The more efficient plants maintain production throughout the elongated season.

5.2. Observed Impact of Individual Property Rights on Plant Production

Overall, the 2009 reform was widely seen as a success. The downstream plants reported an increase in profits, and boats an improvement in the fish stock (International Sustainability Unit 2012). Because the reform did not target the total level of capture or production—which is effectively set deterministically by regulators via quotas—the positive effect on fish stocks can be attributed mainly to changes in the *intensity* of fishing—for example, capture of juvenile fish fell (Paredes and Gutierrez 2008). Panels (a) and (b) of Figure 4 confirm that there were relatively minor changes in total, industry wide, production, and certainly no increase in total production post reform. In fact, there was a marginal decline in production between 2008 and 2009, and a slightly larger decline when comparing 2007–2008 to 2009–2011, mostly reflecting lower overall quotas in 2010. Panels (c) and (d) show that the same pattern holds roughly across the various ports where plants are located, with some heterogeneity. Although a small number of ports expanded production, the majority of ports saw minor decreases.

In line with our predictions, the reform led to longer, lower intensity production periods. Figure 5 plots total seasonal production in the first year before and the first year after the reform. The sample-weighted across-port average increase in days of production post-reform was 26 days per year, or 53%.[22] Production early in the season was considerably greater before the reform, but the decline in output over time was less steep after the reform. As predicted by our framework—and as we would expect given the lower daily supply of fish—Natividad (2016) documents a rise in the price of anchoveta after the reform.

Figure 6 shows that the reform also led to consolidation in the industry. As seen in the top panel, the number of active plants began a steady decline in 2009. It thus appears that the increase in the price of fish after the ITQ reform came into effect led some plants to exit the market. The bottom panel of Figure 6 shows the intensive margin corresponding to the extensive margin in the top panel. Before the reform, the

22. We define a day of production as >1000 MT of input at the port level.

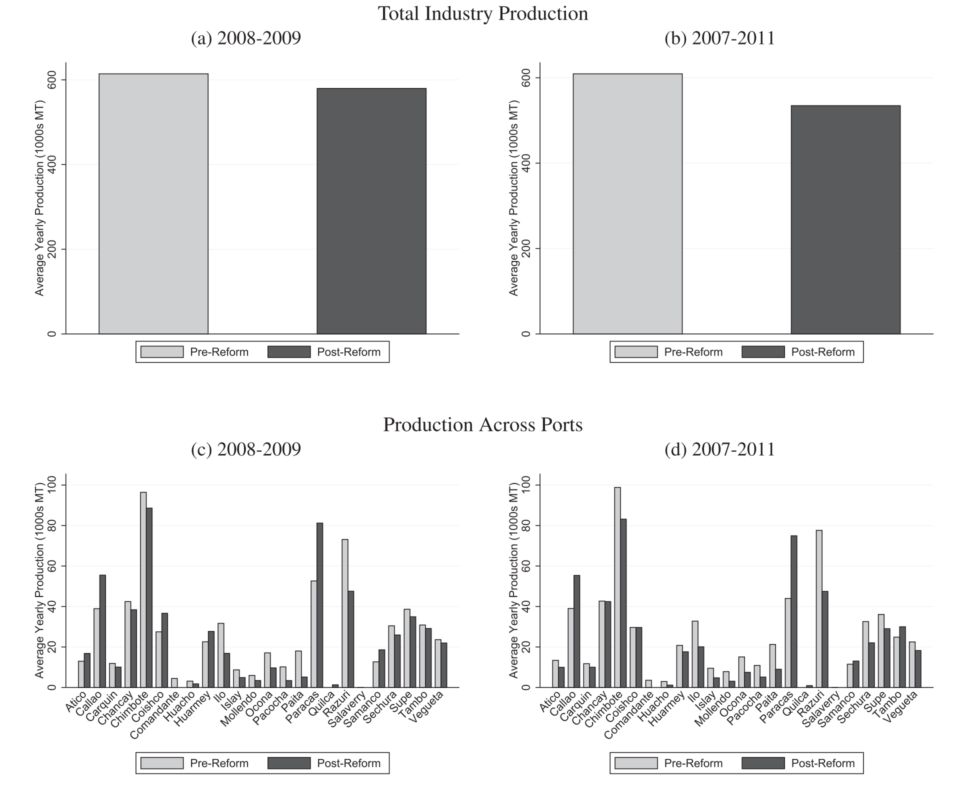

FIGURE 4. Average yearly fishmeal production: pre-reform versus post-reform. Top figures show average yearly production pre- and post-reform, for two years and one year before and after, respectively. Bottom figures show average yearly production at the port level, pre-and post-reform, for the same time frames.

longest- and shortest-producing plants produced for about the same period of time. After the reform, the least productive plants (bottom-quartile) began to decrease or stop production mid-season, whereas top-quartile plants continued to produce.

The predictions of our framework with respect to heterogeneity in efficiency across locations also find empirical support. In panels (a) and (b) of Figure 7 we compare changes in production pre- and post-reform across the top and bottom quartiles of our port-level efficiency measure. To construct this measure, we take advantage of the fact that we observe both inputs of fish and outputs of fishmeal at the plant level. We first compute pre-reform, plant-level "efficiency" (output/input ratio). Because we are interested in a measure that represents a particular location—and there are often several plants clustered in the same port—we aggregate to the port-level by choosing the maximum efficiency amongst the plants in a particular port.[23] As predicted, we

23. This maximum is based on the overall input/output ratio in the year 2008. For ports with only one plant, it is simply the 2008 output/input ratio for that plant. This measure serves as a proxy for the limits

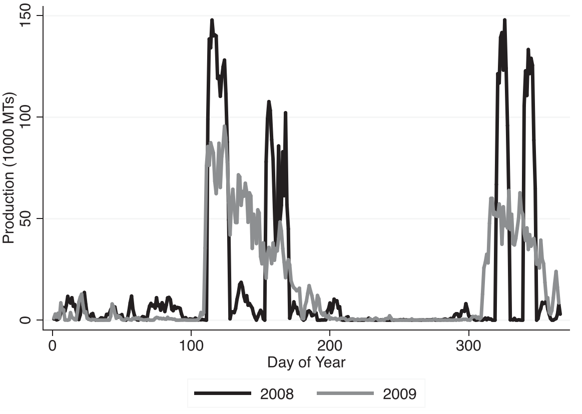

FIGURE 5. Time profile of fishmeal production. Comparisons of daily production (measured as fish inputs) in 1000s of MTs in 2008 and 2009. Before the reform, the seasonal regulation (TAC) had two components; a total amount that could be fished before a specified "pause date" (note that this subquota was reached long before the pause date due to the race for fish) and a second amount that could be fished only after a specified "recommence" date. The removal of the pause rule contributed to production being spread out in time after the reform, along with the forces highlighted in our theoretical framework.

see a substantial increase in the number of days of production in the most efficient locations, and a much lower increase in the least efficient locations. Furthermore, we see little change in total production in either type of location, although both show a marginal decline on average.[24]

There are also substantial differences in the production response to the reform in the North/Central region versus the South region, a result of the different regulatory regimes in place in the two regions prior to 2009. As mentioned previously, the South region was not subject to a quota prior to 2009, and hence fishing took place throughout the year. As a result, the introduction of property rights in the form of ITQs in 2009 actually led to a *reduction* in the length of the fishing season in the South. Panel (c) of Figure 7 shows the difference in production days for the North/Central and South regions. We see a large increase in days in the North/Central region, and a noticeable reduction in the South region. Panel (d) show the analogous change in total production for two regions: there is effectively no difference in the North/Central region, and a modest decline in the South.

In the next section, we exploit the heterogeneity between the North/Central and South regions, as well as between inefficient and efficient locations, to study the impact of changes in the duration of production on health.

on efficiency imposed by the geography of that port, and hence provides a measure of the port specific component of costs.

24. Note that these figures show averages weighted by our adult population rather than raw averages across locations.

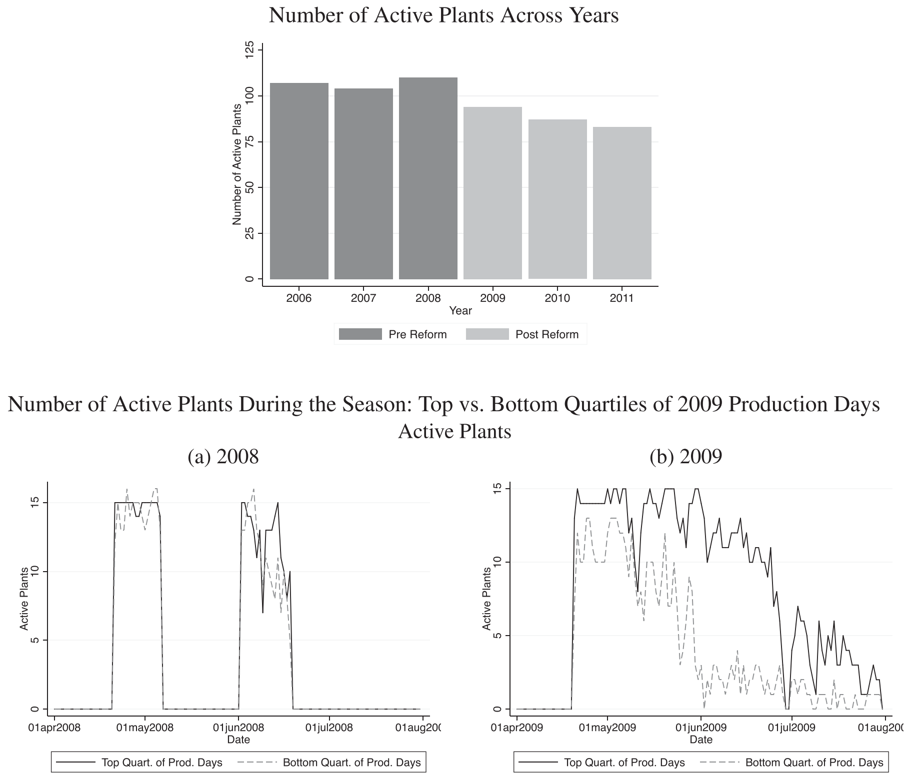

FIGURE 6. Plant activity pre- and post-reform. Top figure plots total number of active plants by year, where a plant is considered active if it purchases fish input any day of the year. The lower figures plot the number of active plants during the first production seasons in 2008 and 2009. The solid line in each shows plants in the top quartile of production days in 2009, whereas the dashed line shows plants in the bottom quartile of production days in 2009.

6. Plants' Response to the Introduction of Individual Property Rights Upstream and their Impact on Health

6.1. Why Individual Property Rights May Affect Health

The most drastic impact of the 2009 reform on production patterns came in the shift toward a longer, lower intensity, production period. Put simply, individuals living close to plants prior to the reform were subject to a "short, sharp" profile of production: a large amount of plant production concentrated in a relatively short period of time. Post-reform, individuals instead faced a "long, low" profile of production, with roughly the same amount of production distributed across a longer period. We hypothesize that the health effects estimated in Section 4 were a result of this shift from a "short, sharp" to a "long, low" production profile.

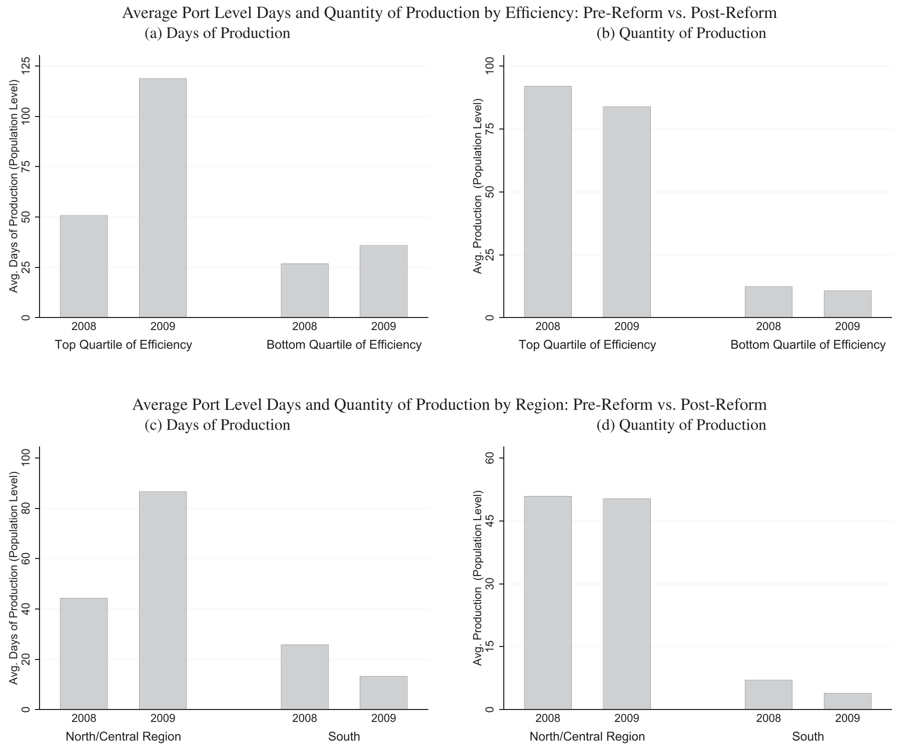

FIGURE 7. Top figures show average yearly days of production at the port level (weighted by representation in our adult sample) pre- and post-reform, split by port level efficiency. Bottom figures show average yearly days of production at the port level (weighted by representation in our adult sample) pre- and post-reform in the North/Central and South regions. A production day is defined by >1000 MTs of input at the port level. Efficiency is measured as the maximum port level yearly output/input ratio.

How might such a change in the temporal distribution of the downstream industry's production matter for health? If plants' impact on health is driven by air pollution, the incidence could depend both on (a) the relationship between production and pollution—plants' "pollution production function"—and (b) the relationship between pollution and health—the health production function. We are aware of no existing evidence on (a), but find it most reasonable to generally expect the amount of pollution emitted at a given point in time to be either concave or linear in the level of plant production. The pollution–production relationships shown in Figure 1 are approximately linear.

When it comes to the health production function, the existing literature generally analyzes the response to duration and dose separately. The few existing studies that overcome the formidable challenges of estimating the causal effects of *sustained* exposure to air pollution generally find much bigger effects on health (e.g., mortality and respiratory infections) than the effects of short term exposure found elsewhere.[25] Moreover, Chay and Greenstone (2003) and Clay et al. (2015) both find evidence consistent with concavity in the dose response function relating infant mortality to the intensity of air pollution, and Hanlon (2015) finds the same for all-ages mortality.

Of course, it is generally accepted that lowering dosages of pollution is beneficial, holding duration constant. However, empirically identifying movements along the duration margin while keeping the overall dose constant is very difficult, since the two dimensions typically co-vary. Despite their importance for policy design, and the fact that "there are likely important risk trade-offs between duration and intensity of exposure" (Pope III et al. 2011, p. 13), to our knowledge, no existing research convincingly compares the health effects of a *given* amount of pollution when concentrated versus spread out in time. We consider the possibility that—within certain ranges of pollution levels—exposing individuals to a longer overall period of pollution may be more harmful than condensing that pollution in a short period.

Before doing so, it is important to establish that other changes in the production environment post-reform cannot explain the deterioration in health. First, as mentioned previously, total production actually *decreased* after the reform. This is true not only on average, but also across the Center/North and South regions, for the efficient and inefficient ports, and individually, for most plant clusters (see Figures 4, 6, and 7). To confirm that neither changes in total production nor the allocation of production across space is responsible for the observed health effects, in Table 5 we repeat the analysis of the health impacts of the reform shown in the first panel of Table 3, but control for local production.[26] We consider several potential specifications for production: the log of production in the last 30 or 90 days, the log of seasonal production, and the level of seasonal production. We allow the measure of production to interact with our Near plant indicator, to capture any differential impacts of production for those living close to plants. In all cases, we see little impact of the inclusion of these controls for production on the estimated effect of the reform on health for those living close to plants. These results suggest that the reform effect is not driven by (i) any effects that the reform might have had on production, or (ii) the reallocation of market share across ports. The estimated reform effects are also robust to excluding the ports that saw an increase in total, yearly production after the reform.

Additionally, as discussed in Section 4.2, the impact of the reform on health is unlikely to be explained by changes in labor markets, incomes, or migration. Further, in Appendix Table A.1, we show that the adverse health impact of the reform estimated in the full sample is not driven by impacts on fishing workers' health. Finally, it is also

25. Examples include Chen et al. (2013), Anderson (2015) and Barron and Torero (2017) (see also Isen et al. 2017). The level of exposure differs considerably across these studies, but they all find large effects of sustained exposure.

26. In these regressions production is reported in 10,000s of metric tons (MTs) in the port (i.e., cluster of plants) nearest to the individual or hospital. Here, and throughout the paper, we use input rather than output to measure fishmeal production because we have data on input at the daily level and output only at the monthly level. The output of fishmeal almost perfectly tracks inputs of fish.

TABLE 5. Impact of fishmeal industry on health before and after the 2009 ITQ reform—controlling for production.

	Hospitals	Adults		Children: ≤5	
	Respiratory admissions	Any health issue	Log medical expenditure	Any health issue	Cough
	Controlling for log production in last 30 days				
Post-reform × Near plant	11.389**	0.052**	0.223	0.188**	0.150*
	(5.302)	(0.026)	(0.144)	(0.081)	(0.087)
Log production in last 30 days	−2.259***	0.006	−0.037	−0.009	−0.001
	(0.756)	(0.004)	(0.024)	(0.017)	(0.018)
Log production in last 30 days × Near plant	11.559***	0.029***	0.088	0.240***	0.174*
	(3.463)	(0.010)	(0.102)	(0.088)	(0.091)
Mean of dep. var.	171.2	0.57	3.70	0.45	0.37
N	57035	62158	62167	6602	6599
	Controlling for log production in last 90 days				
Post-reform × Near plant	11.519**	0.052**	0.241*	0.222***	0.178**
	(5.357)	(0.025)	(0.140)	(0.063)	(0.080)
Log production in last 90 days	−1.330**	−0.001	−0.032	−0.010	−0.006
	(0.631)	(0.004)	(0.021)	(0.012)	(0.014)
Log production in last 90 days × Near plant	9.862**	0.025	0.013	0.142***	0.118***
	(3.833)	(0.017)	(0.080)	(0.035)	(0.032)
Mean of dep. var.	171.2	0.57	3.70	0.45	0.37
N	57035	62158	62167	6602	6599
	Controlling for log seasonal production				
Post-reform × Near plant	7.880	0.059**	0.212	0.216***	0.172**
	(5.762)	(0.027)	(0.141)	(0.059)	(0.068)
Log seasonal production	9.457***	0.017*	0.143***	−0.024	−0.037
	(1.697)	(0.009)	(0.050)	(0.025)	(0.025)
Log seasonal production × Near plant	17.294	0.005	−0.286*	0.258***	0.230***
	(16.646)	(0.019)	(0.149)	(0.043)	(0.048)
Mean of dep. var.	171.2	0.57	3.70	0.45	0.37
N	57035	62158	62167	6602	6599
	Controlling for levels of seasonal production				
Post-reform × Near plant	11.225**	0.061**	0.257*	0.192***	0.144**
	(5.512)	(0.027)	(0.141)	(0.056)	(0.059)
Seasonal production	0.336***	0.001**	0.012***	−0.001	−0.003***
	(0.114)	(0.000)	(0.003)	(0.001)	(0.001)
Seasonal production × Near plant	−0.031	−0.000	−0.013*	0.019***	0.017***
	(0.526)	(0.001)	(0.008)	(0.003)	(0.003)
Mean of dep. var.	171.2	0.57	3.70	0.45	0.37
N	57035	62158	62167	6602	6599

Notes: OLS regressions. Hospital admissions measure total monthly admissions at the hospital level. Adult data includes those over 13 years of age living in coastal regions sampled in ENAHO. Child data includes those under 6 years old living in coastal regions sampled in ENDES. The sample includes all observations in 2008 and 2009. The reform began on April 20, 2009 in the North/Central region and July 7, 2009 in the South. All specifications include a dummy variable for living near a plant and month × year fixed effects. Adult regressions include controls for age, gender, native language, and level of education. Child regressions include controls for age, gender, household assets, and mother's level of education. Hospital, adult and child specifications include hospital, centro poblado, and district fixed effects respectively, with standard errors clustered at the same level. "Respiratory admissions" is a count, medical expenditure is measured in Peruvian Soles, all other dependent variables are binary. Mean of dep. var. gives unconditional mean for sample included in the corresponding regression. Fishmeal production is based on daily inputs of fish, measured in 10,000s of MTs. $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

clear that the impact of the reform on health is not explained by pollution from the fishing boats.[27] Given the lack of evidence for other potential explanations, we next turn to considering the impact of the change in the time profile of production directly.

6.2. A Change in the Time Profile of Production and Health

To explore the hypothesis that the introduction of individual property rights upstream exacerbated plants' impact on health by spreading production across time—that is, by increasing the number of days of production—we exploit the fact that the average change in the time profile of production seen in Figure 5 masks considerable heterogeneity across locations. We first use a triple difference strategy to compare the effects in the North/Central region, where the number of days of production increased significantly post-reform, and the South region, where days of production decreased. We then use the same specification to compare the effects in efficient locations, which saw relatively large increases in production days, to inefficient locations, which saw relatively smaller increases.

The North/Central region covers the large majority of the country (as seen in the map in Figure 2), and we therefore expect the full-sample industrial response to the reform to largely reflect what occurred there. Indeed, as discussed previously, fishmeal locations in the North/Central region saw a striking 97% (sample-weighted) increase in the average number of days of plant production per year, compared to a 48% decrease in the (sample weighted) average number of days produced per year in the South region. The top panel of Table 6 shows results from a triple difference specifications in which we interact the $NearPlant_j \times Reform_{jt}$ indicator in equations (1) and (2) with an indicator for the household residing in the North/Central region. We also include the remaining interactions ($NearPlant_j \times Reform_{jt}$, $NearPlant_j \times North_j$, and $NearPlant_j \times Reform_{jt}$).

The results suggest that the impact of the reform on health outcomes was significantly worse for those living near plants in the North/Central region versus the South, supporting the hypothesis that the observed health effects were due to a spread in production. Indeed, the coefficients on the term representing the differential effect in the North/Central region are positive, significant, and larger than those in our baseline difference-in-difference for the three outcomes we examine (respiratory hospital admissions, adult health issues, and medical expenditures).[28] Furthermore, the coefficients representing the impact of the reform for those near plants in the South—though only significant in one case—are uniformly negative, consistent with

27. The boats spend little time in the ports with their engines on and thus probably do not contribute noticeably to the worse health of those who live near the plants/ports, relative to others, during production. Additionally, however, there was a considerable decrease in port queuing times post-reform as expected (International Sustainability Unit 2012), indicating that post-reform changes in pollution from boats should, if anything, counteract the adverse reform effects we identify.

28. Child outcomes are not included in Table 6 because we have insufficient observations in the South in our ENDES sample.

TABLE 6. Impact of fishmeal industry on health before and after 2009 ITQ reform—North versus South and efficient versus inefficient ports.

	Hospitals	Adults	
	Respiratory admissions	Any health issue	Log medical expenditure
		North versus South	
Post-reform × Near plant	−15.472	−0.080	−0.315*
	(11.603)	(0.054)	(0.178)
North/Central region × post-reform	−20.047***	0.040**	−0.263*
	(3.399)	(0.019)	(0.146)
North/Central region × Post-reform × Near plant	31.151**	0.134**	0.547**
	(12.976)	(0.055)	(0.221)
p-value (row 1 + row 3 = 0)	0.182	0.051	0.152
Mean of dep. var.	169.8	0.56	3.73
N	56570	58143	58152
		Efficient versus inefficient ports	
Post-reform × Near plant	−2.135	−0.072	−0.330
	(22.528)	(0.055)	(0.350)
Pre-reform max. efficiency × Post-reform	−49.622***	−0.016	−1.333***
	(12.454)	(0.068)	(0.479)
Pre-reform max. efficiency × Post-reform × Near plant	56.634	0.356***	1.802**
	(85.399)	(0.129)	(0.813)
p-value (row 1 + row 3 = 0)	0.392	0.001	0.005
Mean of dep. var.	172.3	0.56	3.74
N	54323	57250	57259
Hospital/centro poblado FEs	Yes	Yes	Yes
Month × Year FEs	Yes	Yes	Yes
Month × Near plant FEs	Yes	Yes	Yes
HH controls	No	Yes	Yes

Notes: OLS regressions. Hospital admissions measure total monthly admissions at the hospital level, limited to 2008/2009. Adult data includes those over 13 years of age living in coastal regions sampled in ENAHO (2008–2009). The reform began on April 20, 2009 in the North/Central region and July 7, 2009 in the South. All specifications include a dummy variable for living near a plant and month × year fixed effects. Adult regressions include controls for age, gender, native language, and level of education. Children are excluded due to a lack of observations in Southern ports. Hospital and adult specifications include hospital and centro poblado fixed effects respectively, with standard errors clustered at the same level. "Respiratory admissions" is a count, medical expenditure is measured in Peruvian Soles, all other dependent variables are binary. The port of Ilo is excluded from both specifications due to production outside of designated seasons. The North/Central region includes all of Peru above the −16 °S parallel. Efficiency is determined by the maximum 2008 output/input ratio for any plant within the port. Efficiency is included as a continuous variable interacted with both living near a plant and post-reform. Mean of dep. var. gives unconditional mean for sample included in the corresponding regression. $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

the possibility that health actually improved in the South, where the number of days of production decreased.

We next exploit variation in the spread of production generated by heterogeneity in pre-reform port-level efficiency. As noted in Section 5 (and shown in Panel (a) of Figure 7) the observed increase in days of production following the 2009 reform was significantly larger in ports in the top quartile of efficiency (a 136% increase) versus the bottom quartile (46%). The bottom panel of Table 6 shows results from a similar triple difference specification as in the top panel. Here, we include an interaction between the $NearPlant_j \times Reform_{jt}$ indicator in equations (1) and (2) and our continuous measure of port-level efficiency, as well as the relevant remaining interactions.

The results again support the hypothesis that the spread of production contributes to the adverse health impact of the reform. Point estimates on the triple difference term for the three outcomes we consider all suggest that the adverse health effects are considerably worse in more efficient locations (although the coefficient is not statistically significant for respiratory hospital admissions). Although the majority of locations with efficient plants are in the North/Central region, the relationship between efficiency and the health consequences of the reform holds also *within* the North/Central region as shown in Appendix Table A.2.[29]

6.3. The General Relationship Between the Time Profile of Production and Hospital Admissions

The ideal way to understand the connection between duration of polluting production, production intensity, and health would be to randomly vary both the level and spread of production and trace out the full three-dimensional relationship. Given the infeasibility of such an exercise in practice, the 2009 ITQ reform in Peru provides a unique opportunity to consider the impact of the spread of production while holding the level roughly constant. Both our main specification in Table 3 and the triple differences presented in Table 6 are consistent with the hypothesis that spreading a given level of production over longer periods is worse for health than concentrating that production in a shorter period of time. As a final exercise, we now move away from the reform itself. Instead, we take advantage of the panel nature of our hospital admissions data to provide further evidence on the health impacts of the spread of production, holding the level of production fixed.

We consider the hospital×season as a unit of observation (where, for a hospital, each year is divided into two 6 month seasons), and simply ask whether—controlling for total seasonal production—hospitals see a higher number of hospital admissions in seasons with more total days of production. We limit ourselves to Near plant hospitals

29. Note also that our triple difference effects cannot be explained by the impact on workers within the industry: the results remain similar even when considering only nonfishing workers, as can be seen in Appendix Table A.1. Furthermore, there is little change in the results when explicitly controlling for production levels in these specifications (results available on request).

TABLE 7. Impact of seasonal days of fishing on health—controlling for fishmeal production.

	Total admissions	Respiratory issues	Digestive issues	Muscoskeletal issues	Infectious diseases	Nutritional issues	Skin issues
Production days this season	2.419**	0.487*	0.484**	0.239*	0.231*	0.162	0.120*
	(1.184)	(0.264)	(0.244)	(0.139)	(0.131)	(0.121)	(0.072)
Mean of dep. var.	1174.5	321.1	168.9	61.0	116.4	55.6	53.6
N	4142	4142	4142	4142	4142	4142	4142
	Genitourinary issues	Ear/eye issues	Injury/poison	Pregnancy issues	Other issues	Neoplasms	Abnormality
Production days this season	0.120	0.105	0.102	0.098	0.085**	0.078*	0.068
	(0.129)	(0.131)	(0.074)	(0.074)	(0.033)	(0.040)	(0.077)
Mean of dep. var.	89.9	58.2	46.1	32.4	12.7	13.6	40.7
N	4142	4142	4142	4142	4142	4142	4142
	Congenital issues	Circulatory issues	Mental health issues	Nervous system issues	Blood diseases	Perinatal issues	Ext. mobility issues
Production days this season	0.038*	0.030	0.030	0.008	−0.002	−0.032	−0.033
	(0.023)	(0.061)	(0.042)	(0.032)	(0.021)	(0.033)	(0.053)
Mean of dep. var.	4.55	30.6	32.9	16.0	6.06	5.66	8.62
N	4142	4142	4142	4142	4142	4142	4142
Total seasonal production	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hospital FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month × Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: OLS regressions. Hospital admissions measure total monthly admissions at the hospital level, limited to 2007–2011. Categorizations are based on ICD codes. A "Production day" is defined by >1000 MTs of input at the port level. Fishmeal production is based on seasonal inputs of fish, measured in 10,000s of MTs. All regressions include the level of fishmeal production, hospital fixed effects, and month × year fixed effects. Standard errors, clustered at the hospital level, are included in parentheses. Mean of dep. var. gives unconditional mean for sample included in the corresponding regression. $^{*}p < 0.10$; $^{**}p < 0.05$.

(defined previously), but utilize the full window of our data between 2007–2011. We consider specifications of the form

$$y_{jt} = \alpha + \beta_1 ProductionDays_{jt} + \beta_2 Production_{jt} + \gamma_j + \delta_t + \varepsilon_{jt}. \quad (3)$$

$Production_{jt}$ measures the seasonal level of production in the port closest to hospital j and $ProductionDays_{jt}$ is a count of seasonal days of production in the port closest to hospital j. γ_j and δ_t are hospital and season fixed effects, respectively. We exploit the richness of our hospital data and present results for the full array of observed ICD categories (with rare codes collapsed into an "Other issues" category).

Coefficients on $ProductionDays_{jt}$ from the above specification—controlling for the level of production—are shown in Table 7. We see a large and statistically significant coefficient for the total hospital admissions outcome, suggesting that an additional day of production is associated with 2.4 additional admissions per hospital. Furthermore, the two disease categories that account for the largest share of this effect on total admissions are exactly the ones we a priori expect to be most influenced by air pollution:

respiratory and digestive issues.[30] Note also that the magnitude of the coefficient on respiratory admissions is remarkably consistent with our estimates in Table 3. The result here suggests that an additional day of production is associated with just under 0.5 additional respiratory admissions. If we were to interpret this causally, the sample-weighted average 26 additional days of production generated by the reform would be expected to generate just over 12.5 additional respiratory admissions, extremely close to our estimated reform effect.

These regressions do not explicitly attempt to isolate exogenous variation in the level or spread of production. However, the results shown in Table 7 provide an additional layer of evidence for the possibility that a given amount of air polluting production is more harmful to health when occurring at low concentrations for long periods of time, at least within the ranges observed in Peru during our sample period. If confirmed in future research, this may alter the cost–benefit calculus for individual property rights and other regulatory regimes that affect the time profile of production in interlinked polluting industries downstream. On the other hand, a "long, low" profile of polluting production being worse for health than a "short, sharp" one need not be at odds with traditional approaches to environmental regulations such as emissions standards. Although such regulations *may* affect the time profile of production, they also generally reduce pollution *levels*, especially in industries that operate continuously. Our results suggest that—in cases where regulations may cause firms to spread polluting production across time—regulators should be wary of focusing *only* on the instantaneous or maximum level of generated pollution.

7. Quantifying the Risks of Piecemeal Regulation

In this section we analyze what our estimates imply about the potential magnitude of the risks of piecemeal regulatory design. We do so by comparing the cost of the estimated worsening of the incidence of downstream externalities to the benefit of the decrease in the targeted upstream externality. Our results show that the introduction of individual property rights upstream exacerbated downstream plants' impact on the health of the local population. However, there was a corresponding benefit: fishmeal

30. Some debate surrounds the expected effect of air pollution on digestive health in the economics literature (e.g., Arceo, Hanna, and Oliva 2016 point out that digestive issues represent a cause of death that is less likely to be pollution related than, for example, respiratory causes of death). However, there appears to be consensus in the medical/public health literature that air pollution adversely affects digestive health (see, e.g., Pintos et al. 1998; Ananthakrishnan et al. 2010; Beamish, Osornio-Vargas, and Wine 2011; Kish et al. 2013; Salim, Kaplan, and Madsen 2014). Note also that the estimated coefficients are small and insignificant for most disease categories whose response to air pollution we a priori expect to be limited or nonexistent, such as nervous system issues and blood diseases. We do estimate positive coefficients for a wide range of disease categories, and statistically significant responses also for some disease categories whose connection to air pollution is less obvious, such as musculoskeletal issues. It is worth noting, however, that each of the disease categories we find significant responses for have in fact been connected to air pollution in the existing medical/public health literature. Air pollution lowers the body's oxygen intake and weakens the autoimmune system, making it more vulnerable to a wide range of health problems (Essouma and Noubiap 2015).

companies reported an increase in profits and their suppliers an increase in fish stocks post-reform, as the reform's designers intended.[31]

In the costs and benefits of the ITQ reform we include the (monetized) value of the deterioration in health and the increase in sector profits after the reform.[32] We obtained data on the profits of the fishmeal companies that are publicly listed from publicly available financial statements. Since not all companies are listed, we scale these up by extrapolating based on the share of production the publicly listed firms account for in each year to arrive at a yearly, sector-wide estimate. The resulting estimate of the increase in sector-wide profit in the first post-reform year is US $219 million. (The details of the cost/benefit calculations are in the notes of Table 8.)

We consider only the increase in disease episodes associated with a respiratory hospital admission and medical expenditures in the total health costs of the reform.[33] We start with 55,516 additional respiratory hospital admissions caused each year, which is derived by scaling the estimated post-reform monthly increase in Table 3 to the yearly level, and multiplying by the number of hospitals within 20 km of a plant. To quantify the cost of these respiratory disease episodes, we first convert to the equivalent number of "years lived with disability (YLDs)", using standard weights from the Global Burden of Disease Study 2010 (Murray 2012; U.S. Environmental Protection Agency 2010). Assuming conservatively that the estimated additional disease episodes did not result in increased mortality, our results imply that in the first post-reform year, 5,681 disability-adjusted life year equivalents were lost due to the reform's impact on respiratory diseases. Finally, we use a conventional "value of statistical life (VSL)" method to monetize the DALYs lost.[34] As there are no existing convincing estimates of the VSL in Peru, we present estimates from using both the value estimated for Africans in León and Miguel (2017)—the only existing paper to estimate VSL in a developing country setting with revealed preference methods and using a sample fairly close to ours in average income levels—and the VSL for Americans estimated and used by the U.S. Environmental Protection Agency (Murray 2012; U.S. Environmental Protection Agency 2010). To scale these VSL estimates, we use the GNI per capita in Sub-Saharan Africa, the U.S., and Peru with the commonly used elasticity recommended by Hall and Jones (2007). The per-year costs of the 2009 ITQ reform due to its impact on respiratory disease episodes estimated using this methodology is between US $297 million (with the León and Miguel 2017 VSL) and US $128 million (with the EPA

31. The increase in fish stocks was likely due to lower juvenile fish capture after the reform, when boats no longer "raced" for fish early in the season. There were likely several reasons for the increase in profits. These include, for example, a decrease in overcapacity. See also Natividad (2016).

32. Local incomes are not considered in our cost/benefit calculations as we find no significant effect of the reform on average incomes.

33. We do not count the health issues measured in the ENAHO and ENDES surveys because it is difficult to estimate the monetary cost of "any health issue", and because the extent to which the health issues reported in the surveys also led to hospital admissions and hence would be double counted if included is unclear.

34. See, for example, Ashenfelter and Greenstone (2004), Ashenfelter (2006), Hall and Jones (2007), Greenstone, Ryan, and Yankovich (2012b), León and Miguel (2017).

TABLE 8. Cost benefit analysis of 2009 ITQ reform.

Panel A: Increase in sector profits		
Increase in net income for listed companies (USD)	$58,526,966	
Estimated sector wide increase in net income (USD)	$219,237,448	
Panel B: Health costs		
Medical expenditures:		
Estimated increase per person/year	$38	
Estimated total increase (USD)	$45,523,379	
Respiratory hospital admissions:		
Estimated increase in total hospital admissions	55,516	
Estimated increase in years lived with disability (YLDs)	5,681	
Estimated cost of years lived with disability (YLDs) A:	$297,455,874	(Leon and Miguel)
Estimated cost of years lived with disability (YLDs) B:	$128,097,109	(US EPA)
Panel C: Total Costs and Benefits		
Estimated benefit to sector (USD)		$219,237,448
Estimated total cost A: (medical exp. + cost of YLDs)		$342,979,253
Estimated total cost B: (medical exp. + cost of YLDs)		$173,620,488

Notes: Net income from public available firm financials, calendarized for April–April fiscal years. Sector wide estimates based on 2008 proportion of fishmeal production represented by publicly listed firms. Population estimates are based on total 2009 population living in locations with fishmeal plants from the Peru Institute of National Statistics and Information. Medical expenditure is annualized and extrapolated to the population based on estimates in Table 3. Disability weights translate health conditions over a given duration into an equivalent number of years lived with disability (YLDs). We estimate YLDs using the average disability weight for respiratory diseases (from the Global Burden of Disease Study 2010), and assume a total duration per disease episode of one year. VSL (value of statistical life) estimates for Peru are estimated as $5.42 million, based on an African VSL of $577,000 (from León and Miguel 2017), scaled to Peru GNI using the elasticity in Hall and Jones (2007). We calculate the value of a statistical life year by dividing our VSL estimates by the average life expectancy in the relevant population (40.88, based on remaining life expectancy in Peru for the average individual experiencing a respiratory disease). We alternatively conduct our calculation using a United States VSL estimate of $7.87 million, per US EPA recommendations, again scaled by GNI. All numbers reported are in 2009 USD, calculated using the USA BLS inflation calculator. Scalings use World Bank estimates of GNI per capita (PPP).

VSL). To this we add the additional medical expenditures caused to finally arrive at a total, yearly health cost of the reform of US $174–343 million.[35]

Comparing these cost estimates to the estimated yearly benefits of the reform to the industry of US $219 million, it appears that the costs of the 2009 introduction of individual property rights among industrial fishing boats in Peru, due to the

35. To consider also the reform's impact on fish stocks, we can potentially use government data on stocks to inform how far into the future we should "project" the additional, yearly profits and health costs due to the ITQ reform. There is suggestive evidence that the reform succeeded at slowing the decline in the fish stock. We expect the health costs to be more persistent than the increase in profits, and thus the net cost of the reform to grow over time. (For example, some of the increase in profits in the first year post-reform likely came from a one-time sale of excess plant capacity. Comparing 2011 to 2006, Paredes and Gutierrez (2008) estimate that sector-wide profits increased by US $144 million.) But we prefer to be conservative and count only the per-year gap.

unintended add-on effect on downstream plants' impact on health, are of the same order of magnitude as the benefits of the reform. Although our calculation probably underestimates the total health costs (as we include only the impacts on respiratory diseases), the methodology used to monetize health costs rests on strong assumptions. We thus cannot—and do not attempt to—conclusively say whether the costs of the reform exceeded the benefits, but the cost–benefit calculation presented here nevertheless illustrates that the unexpected health impacts of the reform are a first order concern.

8. Conclusion

This paper considers the interplay of externalities generated in different parts of the economy due to the interlinkages between firms, and how regulation designed from a partial equilibrium perspective affects the overall consequences of externalities generated in a production chain. We analyze how a Coasian solution—individual property rights—to overextraction among suppliers in one of the world's largest natural resource sectors affected the impact on health of the downstream manufacturing plants that process the resource.

Using hospital admissions records and survey data on individual health outcomes, we first confirm empirically that air polluting production by the downstream plants that convert fish from Peru's industrial fishing boats into fishmeal harms adult and child health. We then analyze how the impact on health changed with a 2009 reform that introduced individual, transferable quotas (ITQs) upstream so as to sustain fish stocks. We find that, on average across locations, plants' adverse impact on health increased substantially after the reform, leading to, for example, 55,000 additional respiratory hospital admissions per year and a total, yearly health cost of the reform exceeding US $174 million.

Although total downstream production fell slightly, the quotas removed boats' incentive to "race" for fish early in the season and led inefficient plants to decrease production or exit the market and efficient plants to expand production across time, as predicted by a two-sector model with heterogeneous plants. As a result, downstream production was spread out in time on average across locations. We show that the exacerbation of plants' impact on health after the reform was in part due to this change in the time profile of production. In interlinked sectors where suppliers deliver natural resources to downstream manufacturing plants, regulators thus face a trade-off. On the one hand, the objective of preventing depletion of the resource suggests "internalizing the externality" by giving upstream market participants individual property rights. Such Coasian solutions will tend to spread out production in time. On the other hand, the evidence in this paper suggests that the impact of polluting production on health may in some contexts be ameliorated if production is concentrated in time.[36]

36. Our findings do not speak to the relative merits of the many regulatory methods that can be used to restrict or influence the time profile of production

The case analyzed in this paper illustrates a general take-away: the exacerbation of externalities elsewhere in the economy that are ignored when regulatory reforms are designed can be very large. The method and "level" of regulation used to restrict each externality being optimally chosen *in equilibrium*, taking into account the input-output links that connect different firms in the economy, is important.

Appendix

A.1. Background on Fishmeal Production, Pollution and Health in Peru

Case studies have found high levels of air pollution near fishmeal ports during the production seasons. Sueiro (2010) investigated the environmental situation in 2008 in the city surrounding the port of Chimbote, the largest in the country with 27 fishmeal plants operating at the time. The Swedish Meteorological and Hydrological Institute (SMHI) monitored the air quality in the same port area between April 2005 and April 2006. These studies found very high levels of air pollution. (SMHI found that the annual levels of SO_2 were around 110 μg/m^3—exceeding the international standard of 80 μg/m^3. Monthly concentrations of hydrogen sulfide (H_2S) fluctuated between 20 and 40 μg/m^3 during the fishing seasons, and the hourly concentrations reached 80–90 μg/m^3, again exceeding the WHO standard of seven μg/m^3.) In their reports, focusing especially on Ferrol Bay, the Ministry of the Environment (MINAM) cite investigations that found levels of sulfur dioxide near twice the level of international standards, hydrogen sulfide levels beyond international standards, and PM^{10} levels that vary dramatically over time and can at times reach more than twice the international standard. PM^{10} levels were higher near fishmeal plants (MINAM 2010, 2011). A study by Consejo Nacional del Medio Ambiente (2010) of air pollution levels in Chimbote from April to August 2006 found a high correlation between PM^{10} and fishmeal production. The concentration of PM^{10} exceeded international standards throughout the study period.

Air pollution in the form of particulate matter has been shown to cause respiratory diseases, cardiovascular diseases, and affect mortality in adults (see, e.g., Brook et al. 2010; Moretti and Neidell 2011; Chen et al. 2013; Currie et al. 2014; Schlenker and Walker 2016). Some PM components are also associated with heartbeat irregularities, arterial narrowing, issues with lung function and increased emergency room visits (Stanek et al. 2011). PM has also been shown to cause respiratory diseases, skin diseases, eye diseases, and affect lung growth and mortality in children (see, e.g., Chay and Greenstone 2005; Jayachandran 2006; World Health Organization 2006; Currie and Walker 2011; Roy et al. 2012; Currie et al. 2014; Gutierrez 2015). Chemical pollutants and gases associated with fishmeal production have been linked to respiratory complications, heart disease, low blood cells counts and increased mortality (see, e.g., Mustafa and Tierney 1978; Reiffenstein and Roth 1992; Clarke et al. 2000; World Health Organization 2006). Nitrogen oxide exposure is linked to respiratory effects, airway irritation and lung injury (Mustafa and Tierney 1978).

Short-term sulfur dioxide exposure is associated with higher hospital admissions due to heart disease and pulmonary complications and greater mortality (World Health Organization 2006). Most organ systems are susceptible to hydrogen sulfide, including the nervous and respiratory systems (Reiffenstein and Roth 1992). Clarke et al. (2000) found that dogs had reduced blood cell counts when exposed to sulfur.

We are aware of one study of the health effects of air pollution generated by fishmeal plants in Peru. The Regional Health Offices found that, among children 3–14 years of age, those in schools located near fishmeal plants had a 10% incidence of respiratory diseases in 2003; much higher than in comparable populations (see Sueiro 2010).

Peru's fishmeal plants are also alleged to pollute the ocean by releasing "stickwater" onto the beaches or into the ocean (see, e.g., Rivas, Enriquez, and Nolazco 2008; Rodríguez et al. 2012). Stickwater can cause skin- and gastrointestinal diseases and conjunctivitis in humans (a) through direct exposure and (b) indirectly, by stimulating the growth of pathogens in the ocean, which can enter seafood and thus, ultimately, humans (Pruss 1998; Fleming and Walsh 2006; Gar 2009).

A.2. Fishmeal Production and Health

In this section, we estimate how exposure to fishmeal production affects health. In our approach, we are flexible in our specification of the extent of production activity: we show results using both the amount produced and days of production within a given time window. As in the analysis evaluating the effects of the reform, we consider the health outcomes y_{ijt} of an individual or hospital i in location j at time t. We compare y_{ijt} for those located within a given radius of fishmeal plants, $NearPlant_j = 1$, to those located further away, at times of varying production intensity in the cluster of plants closest to the individual or hospital in question, $Production_{jt}$:

$$\begin{aligned} y_{ijt} = \alpha &+ \beta_1 Production_{jt} + \beta_2 NearPlant_j \times Production_{jt} \\ &+ \boldsymbol{X}'_{ijt}\boldsymbol{\beta_3} + \gamma_{c(j)} + \delta_{m(t)} + \varepsilon_{ijt}, \end{aligned} \tag{A.1}$$

$$\begin{aligned} y_{ijt} = \alpha &+ \beta_1 Production_{jt} + \beta_2 NearPlant_j \times Production_{jt} \\ &+ \boldsymbol{X}'_{jt}\boldsymbol{\beta_3} + \psi_i + \delta_t + \varepsilon_{ijt}. \end{aligned} \tag{A.2}$$

The notation and variables are similar to the ones used in the main specification in the text. For the main independent variables, we initially consider two natural measures of fishmeal production: the number of days on which fishmeal production took place and log total input into fishmeal production reported in 10,000s of MTs in the previous X days in the port (i.e., cluster of plants) nearest to the individual or hospital (we use input rather than output to measure fishmeal production because we have data on input at the daily level and output only at the monthly level. The output of fishmeal very closely tracks the input of fish). Our baseline lookback window—30 days—matches the way the ENAHO survey questions are asked. To capture health responses to more persistent exposure to production, we also show results for a 90 day window—approximately the longest period of continuous exposure observed in our data period. It is important to note that β_2 in (A.1) and (A.2) captures the health response to exposure to fishmeal production in the recent past—the marginal effect of an additional day or amount of production in the last 30 or 90 days. There may additionally be health consequences of long-term exposure to fishmeal production that we do not capture.

The assumption necessary for (A.1) and (A.2) to identify the impact of exposure to fishmeal production on health is that trends in health outcomes across periods with more versus less fishmeal production in the nearest cluster of plants would have been similar in Near plant and control locations in the absence of fishmeal production. In Table A.3 we display the means and standard deviations of both health outcomes and covariates in Near plant and control locations during and outside of production periods. When the plants are not operating, respiratory hospital admissions and medical expenditures are higher in Near plant locations, whereas child health issues occur more frequently in control locations. Most household demographic characteristics are similar in Near plant and control locations, but education levels and assets are somewhat higher and the proportion of adults speaking an indigenous language is somewhat lower in Near plant locations. We include these variables as controls in all of our regressions. The numbers also indicate that there is little seasonal work migration to the fishmeal locations, probably because jobs in the industrial fishing sector are quite stable, as discussed previously.

In addition to summary statistics, Table A.3 shows the "raw" difference in differences, that is, without any fixed effects or controls included, in health outcomes between Near plant and control locations during and outside of production periods. These are positive—indicating that health is relatively worse in Near plant locations during fishmeal production—and sizeable for all five health outcomes. The estimates are significant for respiratory hospital admissions and adult health issues.

Table A.4 shows the effect of fishmeal production on adult and child health from estimating (A.1) and (A.2). We find that fishmeal production during the previous 30 or 90 days, whether measured as production days or total input into production, negatively affects adult and child health. A 50% increase in fishmeal production during the previous month leads to 1.6 (1%) more hospital admissions for respiratory diseases; a 0.77 percentage point (1.3%) higher incidence of "Any Health Issue" among adults; and a 3.8% increase in medical expenditures.[37] For these outcomes the estimated effects are similar when using a 90 day window. We also find that a 50% increase in fishmeal production during the last 90 days leads to a 1.7 percentage point (3.7%) increase in

37. As we estimate the effects of log production on health outcomes, we compute the effects shown here, the impact of a 50% change in production, as $\beta \times \ln(150/100)$. For medical expenditures, which is in logs, we report $e^{[\ln(150/100)\times\beta]}$.

TABLE A.1. Impact of fishmeal industry on health before and after 2009 ITQ reform—by job category.

	Reform effect				North/Central versus South				Efficient versus inefficient ports			
	Nonfishing workers		Fishing workers		Nonfishing workers		Fishing workers		Nonfishing workers		Fishing workers	
	Any health issue	Log medical expenditure	Any health issue	Log medical expenditure	Any health issue	Log medical expenditure	Any health issue	Log medical expenditure	Any health issue	Log medical expenditure	Any health issue	Log medical expenditure
Post-reform × Near plant	0.053**	0.225	0.143	0.679	−0.091	−0.325*	−0.154	0.636	−0.086	−0.359	−0.127	0.118
	(0.027)	(0.145)	(0.124)	(0.531)	(0.057)	(0.180)	(0.315)	(0.971)	(0.053)	(0.342)	(0.282)	(1.376)
North/Central region × Post-reform					0.041**	−0.272*	−0.018	−0.177				
					(0.019)	(0.149)	(0.198)	(0.784)				
North/Central region × Post-reform × Near plant					0.142**	0.545**	0.276	0.346				
					(0.056)	(0.220)	(0.281)	(1.058)				
Pre-reform max. efficiency × Post-reform									−0.021	−1.415***	0.388	4.944
									(0.068)	(0.481)	(0.490)	(3.236)
Pre-reform max. efficiency × Post-reform × Near plant									0.388***	1.872**	0.585	1.871
									(0.119)	(0.806)	(0.846)	(3.726)
Mean of dep. var.	0.57	3.71	0.52	3.16	0.59	3.75	0.54	3.16	0.59	3.75	0.54	3.16
N	60886	60895	1272	1272	56979	56988	1164	1164	56097	56106	1153	1153
Centro poblado	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month × Year FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month × Near plant FEs	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
HH controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: OLS regressions. Data from ENAHO (2007–2011). Adults older than 13 living in coastal regions are included. "Near plant" is defined as within 5 km, and all specifications include a "Near plant" dummy. Also included are controls for age, gender, native language, and level of education. Standard errors, clustered at the centro poblado level, are included in parentheses. The reform began on April 20, 2009 in the North/Central region and July 7, 2009 in the South. The port of Ilo is excluded from North versus South specification due to production outside of designated seasons. Efficiency determined by the maximum 2008 output/input ratio for any plant within the port. Efficiency is included as a continuous variable interacted with both living near a plant and post-reform. Mean of dep. var. gives unconditional mean for sample included in the corresponding regression. Labor categories are based on 3 digit job codes. $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

TABLE A.2. Impact of fishmeal industry on health before and after 2009 ITQ reform—efficient versus inefficient ports—North only.

	Hospitals	Adults		Children: ≤5	
	Respiratory admissions	Any health issue	Log medical expenditure	Any health issue	Cough
			High versus low cost ports		
Post-reform × Near plant	2.021	−0.059	0.167	−1.490***	−0.831***
	(26.470)	(0.065)	(0.407)	(0.176)	(0.250)
Pre-reform max. efficiency × Post-reform	−36.093***	−0.054	0.427	0.115	0.467
	(17.590)	(0.115)	(0.614)	(0.500)	(0.455)
Pre-reform max. efficiency × Post-reform × Near plant	38.986	0.328**	0.058	4.170***	2.956***
	(98.722)	(0.162)	(0.887)	(0.504)	(0.592)
Mean of dep. var.	174.3	0.56	3.80	0.46	0.38
N	47815	49902	49910	4445	4443
Hospital/centro poblado/district FEs	Yes	Yes	Yes	Yes	Yes
Month × Year FEs	Yes	Yes	Yes	Yes	Yes
Month × Near plant FEs	Yes	Yes	Yes	Yes	Yes
HH controls	No	Yes	Yes	Yes	Yes

Notes: OLS regressions. Hospital admissions measure total monthly admissions at the hospital level, limited to 2008/2009. Adult data includes those over 13 years of age living in coastal regions sampled in ENAHO (2008–2009). The reform began on April 20, 2009 in the North/Central region and July 7, 2009 in the South. All specifications include a dummy variable for living near a plant. Adult regressions include controls for age, gender, native language, and level of education. Hospital, adult, and child specifications include hospital, centro poblado, and district fixed effects respectively, with standard errors clustered at the same level. "Respiratory Admissions" is a count, medical expenditure is measured in Peruvian Soles, all other dependent variables are binary. Efficiency is determined by the maximum 2008 output/input ratio for any plant within the port. Efficiency is included as a continuous variable interacted with both living near a plant and post-reform. Mean of dep. var. gives unconditional mean for sample included in the corresponding regression. $^{**}p < 0.05$; $^{***}p < 0.01$.

the incidence of "Any Health Issue" and a 1.6 percentage point (4.2%) increase in the incidence of having a cough among children ≤5. We do not find significant effects for children of production in a 30 day window. The reason may be that our statistical power to detect effects on child health is lower than for adult health due to much smaller sample sizes.[38] The last two panels of Table A.4 show the estimated effect of days of production on health. The patterns are similar to those found in the top panels; for example, 10 additional days of production during the last 90 days increases the incidence of "Any Health Issue" by 8.9% for children ≤5. Overall, the results in Table A.4 indicate that exposure to fishmeal production leads to worse health outcomes for both adults and children.

38. The results indicate a decrease in hospital admissions (and in some specifications also weaker indications of improvement in child health) in nonfishmeal locations during the periods when production takes place. The explanation is most likely that differences in health between regions have changed over time in a way that happens to correlate with the extent of fishmeal production in the region. Such a pattern is not a concern for our estimates as it would lead us to underestimate the impact of plant production on health.

TABLE A.3. Summary statistics: health outcomes in near plant and control locations.

	Health outcomes								
	Near plant				Control				
	No prod.		Prod. season		No prod.		Prod. season		
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Diff-in-Diff
Respiratory admissions	317.8	331.9	334.9	348.9	129.7	173.4	132.7	183.0	14.1*** (4.49)
Any health issue (adults)	0.58	0.49	0.62	0.49	0.59	0.49	0.59	0.49	0.041*** (3.99)
Log medical expend.	3.88	2.88	3.88	2.86	3.71	2.86	3.68	2.88	0.027 (0.45)
Any health issue (children)	0.40	0.49	0.46	0.50	0.44	0.50	0.48	0.50	0.019 (0.54)
Cough	0.32	0.47	0.38	0.49	0.36	0.48	0.40	0.49	0.022 (0.64)
	Covariates								
Age (adults)	35.8	21.3	37.2	20.0	35.7	20.6	36.3	20.2	0.85** (2.08)
Age (children)	2.44	1.42	2.54	1.42	2.50	1.43	2.50	1.43	0.095 (0.94)
Male (adults)	0.49	0.50	0.48	0.50	0.49	0.50	0.48	0.50	0.00049 (0.05)
Male (children)	0.52	0.50	0.52	0.50	0.51	0.50	0.50	0.50	0.0017 (0.05)
Years of education (adults)	9.87	4.21	9.69	4.29	9.21	4.60	9.47	4.48	−0.44*** (−4.59)
Mothers years of educ. (children)	10.8	3.51	11.6	3.04	9.54	4.14	9.81	3.99	0.54* (1.89)
Current. lives in birth prov. (adults)	0.43	0.49	0.47	0.50	0.39	0.49	0.40	0.49	0.031*** (2.99)
Indigenous language (adults)	0.078	0.27	0.11	0.31	0.13	0.34	0.13	0.34	0.038*** (5.32)
HH asset index (children)	0.83	0.67	0.90	0.65	0.29	0.93	0.44	0.91	−0.080 (−1.24)
Observations (adults)	5172		4563		93852		58225		
Observations (children)	631		319		9203		4531		
Observations (hospitals)	13563		8979		77463		41976		

Notes: Adult data from ENAHO (2007–2011), child data from ENDES (2007–2011), and hospital admissions from administrative data. Adults older than 13 and children under 6 living in coastal regions are included. All health outcomes excluding “log medical expenditure” and counts of hospital admissions are binary. Medical expenditure is measured in Peruvian Soles. Production seasons are periods in which there has been a production day (>1000 MTs of input at the port level) in the last 30 days. Near plant is defined as within 5 km for survey data and within 20 km for hospital data. The column labeled Diff-in-Diff shows the raw difference-in-difference coefficient across Near plant and control locations, within and outside production periods, with t-statistics below in parentheses. $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

TABLE A.4. Impact of fishmeal production on health.

	Hospitals	Adults		Children: ≤5	
	Respiratory admissions	Any health issue	Log medical expenditure	Any health issue	Cough
	Log fishmeal production in last 30 days				
Log fishmeal prod. in last 30 days	−2.340***	0.010***	0.006	0.002	0.000
	(0.555)	(0.003)	(0.014)	(0.009)	(0.010)
Log fishmeal prod. in last 30 days × Near plant	3.952**	0.019***	0.092**	0.014	0.014
	(1.591)	(0.006)	(0.043)	(0.028)	(0.029)
	Log fishmeal production in last 90 days				
Log fishmeal prod. in last 90 days	−1.800***	0.006**	0.017	−0.001	−0.005
	(0.483)	(0.003)	(0.014)	(0.007)	(0.007)
Log fishmeal prod. in last 90 days × Near plant	4.374**	0.010*	0.073**	0.041***	0.039**
	(2.047)	(0.006)	(0.033)	(0.015)	(0.019)
	Production days in last 30 days				
Production days in last 30 days	−0.268***	0.001***	0.001	0.000	0.000
	(0.066)	(0.000)	(0.002)	(0.001)	(0.001)
Production days in last 30 days × Near plant	0.228	0.003***	0.010**	0.000	0.000
	(0.174)	(0.001)	(0.005)	(0.003)	(0.003)
	Production days in last 90 days				
Production days in last 90 days	−0.172***	0.000**	0.000	−0.000	−0.001**
	(0.038)	(0.000)	(0.001)	(0.000)	(0.000)
Production days in last 90 days × Near plant	0.219*	0.001**	0.006***	0.004***	0.003**
	(0.116)	(0.001)	(0.002)	(0.001)	(0.001)
Mean of dep. var.	161.6	0.59	3.71	0.45	0.37
N	141981	161773	161806	14684	14678
Hospital/centro poblado/district FEs	Yes	Yes	Yes	Yes	Yes
Month × Year FEs	Yes	Yes	Yes	Yes	Yes
Month × Near plant FEs	Yes	Yes	Yes	Yes	Yes
HH controls	No	Yes	Yes	Yes	Yes

Notes: OLS regressions. Hospital admissions measure total monthly admissions at the hospital level. Adult data includes those over 13 years of age living in coastal regions sampled in ENAHO (2007–2011), child data includes those under 6 years old living in coastal regions sampled in ENDES (2007–2011). Last 30 or 90 days is calculated as last 1 or 3 months for hospital data. "Near plant" is defined as 5 km for survey data and 20 km for hospital data. All specifications include a dummy variable for living near a plant. Adult regressions include controls for age, gender, native language and level of education. Child regressions include controls for age, gender, household assets and mother's level of education. Hospital, adult and child specifications include hospital, centro poblado and district fixed effects respectively, with standard errors clustered at the same level. A "Production Day" is defined by >1000 MTs of input at the port level. Fishmeal production is based on daily inputs of fish, measured in 10,000s of MTs. "Respiratory Admissions" is a count, medical expenditure is measured in Peruvian Soles and all other dependent variables are binary. Mean of dep. var. gives unconditional mean for sample included in the corresponding regression. $^{*}p < 0.10$; $^{**}p < 0.05$; $^{***}p < 0.01$.

The results are robust to instrumenting for production and production days using non-ban days; to specifying hospital admissions in logs; to varying the treatment radius and look-back window used;[39] to restricting the sample to the period prior to the ITQ reform; and a falsification exercise shows no significant effects on health outcomes that we would not expect to respond to plant production. All these results are not shown in this appendix, but are available from the authors upon request. As discussed previously, we are intentionally flexible in how we specify the extent of production activity: we simply wish to establish that there is an effect of plant production on health.

Finally, fishmeal production affects the health of whole communities (not just those who work in the sector), and that the effect is not driven by labor market responses (average incomes and labor market outcomes are not significantly different during production periods). We also show that the adverse impact on health is not driven by ocean pollution or direct fish consumption. Again, these results (as well as additional robustness and specification checks) are all available upon request from the authors.

A.3. Theoretical Framework

In this section, we present a simple two-sector model with homogeneous suppliers (boats) upstream and heterogeneous final good producers (plants) downstream. The model predicts how the introduction of individual property rights over intermediate goods will tend to affect the spatial and temporal distribution of final good production. With an added hypothesis on how the distribution of final good production matters for the impact of downstream externalities, the model thus delivers a prediction for upstream Coasian solutions' downstream consequences. As explained in the body of the paper, the model's predictions will help us test hypotheses on why the fishmeal industry's impact on health may have changed as a result of Peru's ITQ reform.

The intuition of the model is as follows. An industry wide quota regime encourages boats to "race" for fish early in the season. A high per-period fish capture early in the season in turn decreases the price of fish and thereby allows less efficient fishmeal plants to survive. When boats' incentive to race for fish is removed with the introduction of individual quotas, fishing is spread out in time, the price of fish increases and less efficient plants are forced to reduce their production or exit the industry.

The model consists of two sectors: homogeneous fishing boats, who capture and sell fish, and heterogeneous fishmeal plants, who buy fish to use as an intermediate good and sell fishmeal on the international market. We assume that the price of fishmeal is fixed, and that the price of fish is determined in equilibrium based on the contemporaneous demand for and supply of fish.

Fishing Boats. Our specification of the boat sector follows Clark (1980) and subsequent research. There are N identical boats, who capture fish (q_i) as a function of (costly) effort e_i and the stock of fish x, according to $q_i = \gamma x e_i$, where γ is a constant. Boats face

39. Note that we can also compare individuals/hospitals in fishmeal locations only to individuals/hospitals in locations that are contiguous to the fishmeal locations; this gives very similar results to those in Table A.4.

an increasing and convex cost of effort $c(e_i)$, and a decreasing inverse market demand $p(q)$. Within each season, the fish stock declines according to the amount captured, that is $x(t) = x_0 - \int_0^t \gamma x(t') \sum_i^N e_i(t')dt'$.

Let the maximum length of the season under any regulatory regime be T. We first consider the case of an industry wide total allowable catch (TAC) quota, with magnitude H.[40] We take boats to be small relative to the industry, and assume they take the path of prices $p(t)$ and the fish stock $x(t)$ as given. Each boat chooses $e_i(t)$ for all t to maximize

$$\pi_i = \int_0^{t^*} [p(t)\gamma x(t)e_i(t) - c(e_i(t))]dt, \tag{A.3}$$

which gives optimal effort $e_i^*(t)$ defined by the first order condition $c_i'(e_i^*(t)) = p(t)\gamma x(t)$. Under the TAC regime, boats simply choose effort to equate marginal revenue and marginal costs, without internalizing their impact on the fish stock.

We next turn to the individual quota regime (ITQ). We assume that each boat is assigned a quota of H/N. There is no fixed t^*; instead each boat implicitly chooses a path of effort that determines when their quota is exhausted (time $\tilde{t}$)—an optimal control problem for each boat's cumulative catch, $y_i(t)$. Each boat solves

$$\begin{aligned}
\max \quad & \int_0^{\tilde{t}} [p(t)\gamma x(t)e_i(t) - c(e_i(t))]dt, \\
\text{subj. to} \quad & \frac{dy_i}{dt} = \gamma x(t)e_i(t) \text{ for } 0 \leq t \leq \tilde{t}, \\
& y_i(0) = 0, \\
& y_i(\tilde{t}) = H/N, \\
& \text{and } \tilde{t} \leq T.
\end{aligned} \tag{A.4}$$

This gives $c'(e_i(t)) = (p(t) - \lambda_i)\gamma x(t)$ and $d\gamma_i/dt = -\partial\mathcal{H}/\partial y_i = 0 \Rightarrow \lambda_i$ constant.[41] If the quota binds, $\lambda_i > 0$.

λ_i represents each boat's internalization of the reduction in season length generated by an additional unit of effort. We can write the inverse demand in equilibrium in terms of the individual effort decision and stock of fish. We can then rewrite the first order conditions (with e^* representing the optimal effort level of a boat under the TAC regime, and $\tilde{e}$ representing the optimal effort level under the ITQ regime) as

$$\begin{aligned}
c'(e_i^*(t)) &= p(\gamma x(t)e_i^*(t))\gamma x(t) \ \text{ for } \ t \leq t^*, \\
c'(\tilde{e}_i(t)) &= [p(\gamma x(t)\tilde{e}_i(t)) - \lambda_i]\gamma x(t) \ \text{ for } \ t \leq \tilde{t}.
\end{aligned}$$

40. We focus on situations where the quota binds. The season ends when the total quantity of fish captured is equal to the industry quota H.

41. The Hamiltonian is: $\mathcal{H} = p(t)\gamma x(t)e_i(t) - c(e_i(t)) + \lambda_i\gamma x(t)e_i(t)$.

With λ_i in hand the effort decision at any t is determined by $x(t)$ at all points. It is thus helpful to consider each boat as simply solving a static problem (at any t) that differs under the two regimes as follows:

$$c'(e_i^*) = p(\gamma x e_i^*)\gamma x, \tag{A.5}$$

$$c'(\tilde{e}_i) = [p(\gamma x \tilde{e}_i) - \lambda_i]\gamma x. \tag{A.6}$$

These two equations imply that (a) facing an equal stock of fish x, effort at any t must be weakly higher in the TAC regime, and (b) fish capture is decreasing in the stock of fish under both regimes.[42] Together (a) and (b) imply that the highest fish capture, and lowest price, occur under the TAC regime (when the stock of fish is at its initial x_0). Finally, (c) the fish stock must always be weakly higher under the ITQ regime than under the TAC regime. Hence, the season must be longer under the ITQ regime.[43]

Fishmeal Plants. We now turn to the plant sector. There is a mass M of fishmeal plants with heterogeneous marginal costs that require one unit of intermediate good q to produce each unit of the homogeneous final good q^f. The price of the final good is normalized to one. The price of the intermediate good at time t is $p(t)$. Let plant j's marginal cost be given by

$$MC_j(q^f, p(t)) = MC(q^f) + \alpha_j + p(t), \tag{A.7}$$

where α_j is a plant-specific constant. If firms share common technology outside of the α_j, the minimum average cost for each firm can be described as $r + \alpha_j + p(t)$, where r is the minimum average cost for a firm with $\alpha_j = 0$ and facing 0 cost of the intermediate good. Firm j produces some positive amount so long as $r + \alpha_j + p(t) < 1$. This means that as firms face higher input prices $p(t)$, the less efficient firms—those with high α_j—decrease production and eventually drop out of the market. Each firm has a threshold price

$$p_j^* = 1 - r - \alpha_j \tag{A.8}$$

above which it will not produce. Let p_j^* be distributed among firms in the industry on [0,1] according to $F(\cdot)$. For firm j, denote demand by $\tilde{q}(p(t), p_j^*)$ (where demand is 0 for $p(t) < p_j^*$). We can then describe the market demand $q(p(t))$ by

$$q(p(t)) = M \int_{p(t)}^{1} \tilde{q}(p(t), p_j^*) dF(p_j^*). \tag{A.9}$$

42. Suppose, for the TAC regime, that $x > x'$, but $\gamma x' e_i' \geq \gamma x e_i$. Then $e_i' > e_i$, so

$$c'(e_i) < c'(e_i') = p(\gamma x' e_i')\gamma x' < p(\gamma x e_i)\gamma x = c'(e_i).$$

An identical argument holds for the ITQ regime.

43. Note that a necessary condition for $x^*(t) > \tilde{x}(t)$, for some t, is that there be some x such that the equilibrium effort at fish stock x is higher under the ITQ regime than under the TAC regime.

Under standard assumptions, this gives decreasing market demand. As discussed previously, the highest per-period production, and lowest price, occur under the TAC regime. For fishmeal plants, this implies that (d) a greater mass of plants have nonzero production (at some point in the season) in the TAC regime than in the ITQ regime, and (e) the plants that produce in the TAC regime but not in the ITQ regime are those with the lowest p_j^*, that is, those with the highest marginal cost. We test the model's predictions in the main text.

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