# ONLINE APPENDIX TO: "INTERLINKED FIRMS AND THE CONSEQUENCES OF PIECEMEAL REGULATION"

**Christopher Hansman**
Imperial College London

**Jonas Hjort**
Columbia University

**Gianmarco León**
Universitat Pompeu Fabra,
BGSE and IPEG

**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 $\mu$g/m$^3$ – exceeding the international standard of 80 $\mu$g/m$^3$. Monthly concentrations of hydrogen sulfide ($H_2S$) fluctuated between 20 and 40 $\mu$g/m$^3$ during the fishing seasons, and the hourly concentrations reached 80 to 90 $\mu$g/m$^3$, again exceeding the WHO standard of seven $\mu$g/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-mail: c.hansman@imperial.ac.uk (Hansman); hjort@columbia.edu (Hjort); gianmarco.leon@upf.edu (León)

e.g. Brook RD et al. 2010; Moretti and Neidell 2011; Schlenker and Walker 2016; Chen et al. 2013; Currie et al. 2014). 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. Currie et al. 2014; Currie and Walker 2011; Gutierrez 2015; Roy et al. 2012; Jayachandran 2006; Chay and Greenstone 2005; World Health Organization 2006). 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; World Health Organization 2006; Reiffenstein and Roth 1992; Clarke et al. 2000). (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 to 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 et al. 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 metric tons, 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 $\beta_2$ 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 above.

In addition to summary statistics, Table A.3 shows the "raw" difference in differences, i.e., 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.1. Impact of fishmeal industry on health before and after 2009 ITQ Reform – by job category.

| | Reform Effect | | | | North/Central vs. South | | | | Efficient vs. Inefficient Ports | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Non-Fishing Workers | | Fishing Workers | | Non-Fishing Workers | | Fishing Workers | | Non-Fishing 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 x 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 x Post-reform | | | | | 0.041** | −0.272* | −0.018 | −0.177 | | | | |
| | | | | | (0.019) | (0.149) | (0.198) | (0.784) | | | | |
| North/Central Region x Post-reform x Near Plant | | | | | 0.142** | 0.545** | 0.276 | 0.346 | | | | |
| | | | | | (0.056) | (0.220) | (0.281) | (1.058) | | | | |
| Pre-reform Max. Efficiency x Post-reform | | | | | | | | | −0.021 | −1.415*** | 0.388 | 4.944 |
| | | | | | | | | | (0.068) | (0.481) | (0.490) | (3.236) |
| Pre-reform Max. Efficiency x x Post-reform x 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 x Year FEs | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Month x 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 kilometers, 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 20th, 2009 in the North/Central region and July 7th, 2009 in the South. The port of Ilo is excluded from North vs. 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 vs. inefficient ports – north only.

| | Hospitals | Adults | | Children: $\leq 5$ | |
|---|---|---|---|---|---|
| | Respiratory Admissions | Any Health Issue | Log Medical Expenditure | Any Health Issue | Cough |
| | High vs. Low Cost Ports | | | | |
| Post-Reform x 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. Effciency x 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. Effciency x Post-reform x 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 x Year FEs | Yes | Yes | Yes | Yes | Yes |
| Month x 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 costal regions sampled in ENAHO (2008–2009). The reform began on April 20th, 2009 in the North/Central region and July 7th, 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. ** $p < 0.05$, *** $p < 0.01$.

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 | | | | | | | | |
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Diff-in-Diff |
| 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 5km for survey data and within 20km 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: $\leq 5$ | |
|---|---|---|---|---|---|
| | 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 x 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 x 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 x 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 x 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 x Year FEs | Yes | Yes | Yes | Yes | Yes |
| Month x 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 costal 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 kilometers for survey data and 20 kilometers 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. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

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%age point (1.3%) higher incidence of "Any Health Issue" among adults; and a 3.8% increase in medical expenditures.[1] 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%age point (3.7%) increase in the incidence of "Any Health Issue" and a 1.6%age point (4.2%) increase in the incidence of having a cough among children $\leq 5$. 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.[2] 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 $\leq 5$. Overall, the results in Table A.4 indicate that exposure to fishmeal production leads to worse health outcomes for both adults and children.

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;[3] 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 above, 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. In Table A.3 we see that average educational attainment, the proportion of immigrants, and the proportion speaking an indigenous language are lower in Near plant locations during production periods. While these changes are unlikely to explain a deterioration in health outcomes, to be cautious we include all covariates shown in Table A.3 as controls when estimating (A.1) and (A.2).

1. 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 $e^{[ln(150/100)\times\beta]}$.

2. The results indicate a decrease in hospital admissions (and in some specifications also weaker indications of improvement in child health) in non-fishmeal 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.

3. 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.

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 $\gamma$ is a constant. Boats face 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 $H$.[4] We take boats to be small relative to the industry, and assume they take

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

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,

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

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.[5] If the quota binds, $\lambda_i > 0$.

$\lambda_i$ 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 $c'(e_i^*(t)) = p(\gamma x(t)e_i^*(t))\gamma x(t)$ for $t \le t^*$ and $c'(\tilde{e}_i(t)) = [p(\gamma x(t)\tilde{e}_i(t)) - \lambda_i]\gamma x(t)$ for $t \le \tilde{t}$.

With $\lambda_i$ 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.[6] Together (a) and (b) imply that the highest fish capture,

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

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

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

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.[7]

*Fishmeal Plants.* We now turn to the plant sector. There is a mass $M$ of fishmeal plants with heterogenous 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 $\alpha_j$ is a plant-specific constant. If firms share common technology outside of the $\alpha_j$, 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 $\alpha_j$ – 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 $\bar{q}(p(t), p_j^*)$ (where demand is 0 for $p(t) < p_j^*$). We can then describe the market demand $q(p(t))$ by

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

Under standard assumptions, this gives decreasing market demand. As discussed above, 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 non-zero 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 next section.

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An identical argument holds for the ITQ regime.

7. Note that a necessary condition for $x^*(t) > \bar{x}(t)$, 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.

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