

THE DISTRIBUTIONAL CONSEQUENCES OF INCOMPLETE REGULATION

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Abstract

Incomplete environmental regulation can shift production from regulated to unregulated sectors, affecting the spatial distribution of pollution and who bears its burden. I study this phenomenon in the context of sugarcane processing in Mexico. Firms responded to requirements to install air pollution controls in mills by increasing agricultural fires in sugarcane fields by 15%. As a result, PM_{2.5} concentrations rose by 7% with higher impacts in socioeconomically vulnerable communities. These findings highlight an often undiscussed implication of incomplete pollution regulation: its distributional consequences.

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Introduction

Many environmental policies regulate pollution-generating activities instead of regulating pollution directly. As a result, production can be reallocated across locations and within supply chains, escaping the reach of regulation. In such circumstances, the regulation is “incomplete” and firms may substitute production from a regulated to an unregulated activity. Incomplete regulation has well established efficiency consequences (Fowlie, 2009; Gibson, 2018).¹ However, much less attention has been paid to whether incomplete pollution policies have distributional consequences. For example, individuals living near regulated activities might experience relative decreases in pollution as a result of regulation while individuals near unregulated activities experience higher pollution levels.

This paper analyzes supply chain leakage and its distributional consequences in the context of the sugarcane industry in Mexico. Mexico is the world’s sixth largest sugarcane exporter and the sugarcane industry is an important economic activity in southern and central Mexico. While economically important, sugarcane harvest is a heavily polluting activity. The fact that there are two primary harvest methods, mechanical and manual cut, that use different levels of processing for cleaning the sugarcane plant provides the potential for technological and pollution reallocation under incomplete regulation.

These harvest alternatives and the regulatory history of sugarcane production in Mexico provide an interesting setting for studying the distributional consequences of incomplete regulation. As already mentioned, sugar mills have two technological alternatives for harvesting sugarcane: mechanical or manual cut. When sugarcane is cut manually, it is often burned since fires clean excess vegetation on the sugarcane plant. These fires have been found to affect in-utero health outcomes for nearby populations (Rangel and Vogl, 2019). If sugarcane is not cleaned in the field using fires and is instead mechanically cut, it needs to go through an additional cleaning process that uses industrial boilers. Starting in 2015, the Mexican government implemented a policy aimed at decreasing sulfur dioxide emissions from industrial boilers, requiring facilities in all sectors of the economy using

¹Incomplete regulation and leakage have been studied in several settings such as international trade, where countries export pollution to countries with laxer pollution regulation (Levinson and Taylor, 2008; Copeland and Taylor, 2004), climate policies (Bushnell and Mansur, 2011; Bushnell and Chen, 2012; Perino, 2015; Baylis et al., 2013; Fowlie and Reguant, 2020), and other environmental regulations (Becker and Henderson, 2000; Chan and Morrow, 2019). Most leakage studies focus on analyzing the reallocation of the same pollutant or the same economic activity in different areas. These studies find that under incomplete regulation, firms substitute towards unregulated areas, offsetting or even increasing total emissions compared to regulated areas.

oil as fuel to reduce emissions each year by either substituting to less polluting boilers or acquiring abatement technologies. Using rich data on sugar mills operations, technology, and production inputs and outputs, I show that regulated mills (facilities not using biofuels) shifted some of their processing to fields where sugarcane is grown, increasing manual cut and associated harvest fires relative to unregulated mills. Furthermore, I show that mills shifted the type of inputs used (i.e. manual labor), altering the spatial distribution of pollution and the health outcomes of the populations exposed to pollution.

I use a difference-in-differences research design to compare input use and pollution from regulated and unregulated facilities before and after the policy was implemented. In this context, the treatment group is comprised of the fields linked to regulated facilities, whereas the control group is comprised by the fields linked to unregulated facilities. I find that fields in the treatment group increased the number of sugarcane fires by 15% following the regulation. As a result, ambient concentrations of PM_{2.5} over these fields increased by 7%. I corroborate these substitution responses to the regulation using detailed data on various sugarcane production inputs and outputs. Consistent with an increase in fires, I find that fields linked to regulated mills increased manual cut workers by 5% and that the amount of sugarcane harvested using manual cut increased by 8%. I find no evidence of a change in the quantity of sugar produced and provide suggestive evidence of a decrease in processing efficiency after the regulation.

I further examine whether this change in pollution disproportionately affected vulnerable rural areas. Similar to other low- and middle-income countries, the agricultural fields in Mexico are located near rural areas that have higher levels of poverty and lower access to health services than urban areas. I analyze whether pollution concentrations increased in areas exposed to the increase in fires, and whether these areas have higher levels of economic disadvantage. I find that the most vulnerable households experienced the largest increases in pollution driven by the policy compared to less vulnerable populations. These results highlight an important finding that has not been empirically documented in the literature: incomplete regulation can contribute to environmental inequality by altering the spatial distribution and composition of pollution.

Finally, I examine whether the increase in pollution caused by incomplete regulation is associated with worse health outcomes in affected areas. I use individual birth records for the period 2012-2017 to estimate the impacts of pollution exposure on birth outcomes

such as birth weight, gestational length, very low birth weight incidence ($< 1,500$ g), and very preterm birth incidence (< 32 weeks). I link the location of fires to the mother's community of residence and estimate the impact of pollution on birth outcomes. I find that an additional $\mu\text{g}/\text{m}^3$ increase in PM_{2.5} pollution decreases birth weight by 1 grams, increases very low birth weight incidence by 2.4%, and increases very preterm birth incidence by 3% for all newborns. The negative effects of this increase in pollution are higher among populations covered by *Seguro Popular*, the health insurance that covers informal workers and rural communities, which are among the most vulnerable populations in Mexico. These results add to the extensive literature examining the impacts of air pollution on health (Graff Zivin and Neidell, 2013), and in particular, the impact of pollution on birth outcomes (Currie et al., 2014). Consistent with Rangel and Vogl (2019), I find that increases in pollution caused by sugarcane fires are associated with worse birth outcomes for impacted localities. These results further document the negative impacts of incomplete regulation when producers can substitute inputs and this substitution results in higher pollution concentrations for nearby communities.

This paper has two main contributions. First, I contribute to existing studies that find input substitution responses as a result of environmental regulation (Gibson, 2018; Rijal and Khanna, 2020), and the detailed firm data allow me to quantify production complementarities and their pollution consequences. Others have found that the amount of leakage induced by a regulation depends on the structure of the sector and the producers' responses to the regulation (Fowlie, 2009; Baylis et al., 2014). Firms can substitute pollution to unregulated media (Gibson, 2018), sectors (Hansman et al., 2019), other facilities (Rijal and Khanna, 2020), and countries with laxer regulations (Hanna, 2010; Ben-David et al., 2018; Tanaka et al., 2022). By focusing on one sector and using detailed production data, I am able to unravel how firms alter production processes to adjust to regulation. In addition, this paper provides evidence of leakage from point sources (industry) to non-point sources (agricultural fires). Shifting pollution from point sources to non-point sources could be problematic since non-point sources are harder to regulate due to their dispersed nature (Shortle and Horan, 2001). In so doing, I contribute to another literature that explores the role of regulation in incentivizing firms or individuals to adjust margins to avoid regulation (Carrillo et al., 2017; Yang, 2008). In the case of environmental policies, other studies have found that there is heterogeneity on firm deci-

sions in response to regulations, with tradeoffs between capital-intensive investments with high fixed costs and other alternatives with high variable costs (Ryan, 2012; Fowlie, 2010; Cicala, 2015). This paper contributes to this literature by documenting how firms might respond to regulations by substituting to the unregulated sectors (sugarcane fields) characterized by high variable costs (labor) using more polluting technologies (agricultural fires).

Second, I contribute to the literature examining the distributional impacts of environmental policies. Agricultural fields are mainly located in rural areas that are on average poorer and face higher socioeconomic vulnerability than their urban counterparts where mills are located. By increasing the number of fires and pollution in these areas, this incomplete command and control regulation increased pollution in already disadvantaged areas. The environmental justice literature has long studied the unequal distribution of environmental hazards finding that minority and poor populations face higher pollution levels than other communities (Mohai et al., 2009; Banzhaf et al., 2019; Chakraborti and Shimshack, 2020). At the same time, environmental regulations can also lead to concerns related to environmental redistribution: by changing where pollution occurs, an environmental policy that targets a pollutant may disproportionately affect some communities while benefiting others (Fowlie et al., 2012).² This paper contributes to the literature that examines the role of environmental regulation on distributional outcomes by finding another source of environmental disparities: incomplete regulation can cause pollution leakage to vulnerable populations even when a command and control policy targets the reduction of pollution from every regulated facility. This contributes to existing discussions over the environmental justice consequences of environmental policies and the role of the design of these policies exacerbating or decreasing environmental inequities (Fullerton and Muehlegger, 2019; Currie et al., 2020; Holland et al., 2019; Hernandez-Cortes and Meng, 2023). The results of this paper extend beyond the sugarcane industry in Mexico. For instance, several other studies have found supporting evidence of the “pollution haven effect” which highlights that environmental damages might be shifted towards places with less strict regulation (Tanaka et al., 2022; Hanna, 2010; Heilmayr et al., 2020). Other examples of where this could occur include global production chains

²These concerns have been relevant during the introduction and development of different policies such as the RECLAIM program and AB32, both in California (Fowlie et al., 2012; Grainger and Ruangmas, 2018; Hernandez-Cortes and Meng, 2023).

and international trade when regulation is incomplete between two countries (Tanaka et al., 2022). My results suggest that regulators attempting to regulate one input need to be aware of firms' responses in unregulated sectors and the location of these sectors relative to disadvantaged communities.

The rest of the paper proceeds as follows. Section 1 describes the sugarcane sector and regulation context. Section 2 describes the data. Section 3 presents the empirical specification. Section 4 explains the effects of regulation-induced pollution redistribution and its distributional consequences as well as the health effects of incomplete regulation. Section 5 concludes.

1 Background

1.1 Sugarcane harvest and production in Mexico

Sugarcane is the main input of sugar production and is processed in nearly 60 mills across Mexico. The high demand for sugar in Mexico (on average 80 pounds of sugar per capita consumption per year) makes sugarcane among the 10th highest demanded crops in Mexico and Mexico is the 6th largest global sugar exporter. Sugar mills have two technological alternatives for harvesting sugarcane: either mechanical or manual cut. When sugarcane is manually cut, it must also be burned in the field. These fires facilitate harvest by cleaning the excess of vegetation from the sugarcane plant. If sugarcane is not cleaned in the field using fires, it needs to go through an additional cleaning process that uses machines powered by industrial boilers.

Sugarcane is first harvested in the field and then sent to clean and process at the mill. Given that there are only 60 active mills in Mexico that process nearly 865,000 hectares of sugarcane, the harvest needs to be staggered from mid-November to late May.³ Mills generally own the fields where they source the sugarcane which means that mill management has decision power over the type of harvesting alternative used.⁴ It is

³Sugarcane needs to be processed within the same week after harvest or it can lose its caloric content, generating less sugar. However, after sugarcane has been converted into sugar, sugar can be stored for long periods. After sugar has been produced, mills send the sugar to individual packaging facilities that distribute them for retail.

⁴Mills also report part of their production coming from private small landowners. However, the smallholders have contracts with specific mills. The mills are responsible of providing inputs to these smallholders such as machines to harvest sugarcane in the case of mechanical cut and trucks to transport the sugarcane to the mills.

important to note that there is no quality difference between sugarcane cut manually or mechanically. After sugarcane has been cut, the sugarcane is transported to the sugar mill where it is then processed. Sugarcane cut using machines goes through an additional process of cleaning excess vegetation that uses equipment fueled by boilers. These boilers can either use diesel, fuel oil, biofuels, or natural gas. Once clean, machines grind and extract the caloric content of sugarcane to then crystalize and refine the sugar in the mill.

The sugar producing industry is an important economic sector in sugarcane regions. The Mexican Agricultural Agency estimates that sugarcane production has approximately 440,000 direct employees and 2,000,000 indirect employees.⁵ Although the harvest season brings employment to these regions, it has health implications: sugarcane fires increase particulate matter (PM), nitrogen oxides (NO_x), and carbon monoxide (CO) concentrations. 96% of these particles are respirable (França et al., 2012) and have been associated with negative health outcomes in nearby communities. As an example, Rangel and Vogl (2019) found that in utero exposure to pollution from sugarcane fires reduces birth weight and gestational age at birth in Brazil.⁶ Sugar processing after sugarcane has been harvested is also heavily polluting. For instance, the average sugar mill generates, on average, 2,427.65 tons of NO_x per year, which makes it one of the most heavily polluting industries in the country. To put this in context, the average California cement facility generates 1,364.2 tons of NO_x per year.⁷

1.2 Regulating pollution from sugar mills

In 2011, the Mexican government strengthened the maximum pollution limits of all stationary sources via the NOM-085-SEMARNAT-2011. The regulation targeted many sectors including cement production, chemical manufacturing, and general industrial activities. The regulation stated that beginning in 2014-2015 all pollution sources must

⁵Studies have documented the importance of sugar production for local employment and development. For example, Dell and Olken (2020) show that households living within a few kilometeres of historical sugar factories have 10% higher per-capita consumption than other households living further away.

⁶Other studies have shown that exposure to smoke from fires also increases early-life mortality (Jayachandran, 2009; Pullabhotla, 2018) and affects children's human capital outcomes (Graff-Zivin et al., 2020). Agricultural burning can also increase deaths from respiratory problems for adults (He et al., 2020).

⁷Data on mills' emissions are available for 2017 via the National Registry of Emissions (RENE) and data on California's cement emissions are available in the CARB pollution mapping tool.

decrease emissions related to the combustion process.⁸ The regulation stipulated that starting in 2011, the emissions from new and existing equipment must be reported to the environmental agency in Mexico and after 2015, the new emission standards need to be attained for all the combustion sources. The regulation stated an annual reduction of 1,000 ppmv of sulfur dioxide, SO₂, in 2015 relative to pre-existing levels and a reduction of an additional 100 ppmv per year until 2019. In the case of non-attainment at the facility level, the facilities were required to pay a fee to the environmental agency depending on the exceeding emissions. Facilities that used biofuels as the main source of energy were exempt from the policy.

In the case of the sugarcane industry, the regulated equipment was mainly used as a substitute in the cleaning process. This meant regulating the boiling of (unburnt) sugarcane for facilities that were not using biofuels in their operations. As a result of the policy, unregulated facilities could respond by either complying with the regulation or by shifting technologies in the field to decrease the emissions coming from the regulated technology.

The regulation is enforced by the Mexican Environmental Ministry's regulatory entity, PROFEPA. In case of non-compliance, the fine is established by the National Law of Environmental Protection (*Ley General del Equilibrio Ecológico y la Protección al Ambiente*, LGEEPA). According to LGEEPA, non-compliance will be designated by the PROFEPA and penalty for non-compliance includes one or more of the following: a fee (30,000 to 50,000 days of the valid minimum wage in Mexico City at the moment of the non-compliance designation)⁹, partial closure for repeating violators, and suspension of operation permits. In the case of the sugarcane industry, the Mexican Agriculture Agency through the sugarcane regulator entity, the *Comité Nacional para el Desarrollo de la Caña de Azúcar*, CONADESUCÁ, also monitors and reports annual compliance. Although biofuels are exempt from the regulation, there have been some recent efforts to extend environmental regulation to cover sugar mills using biofuels. For instance, the PROY-NOM-170-SEMARNAT-2017 is expected to regulate mills using biofuels once it is approved by the Mexican government.

⁸The regulation in 2011 stipulated that the beginning of the compliance period should be 2014. However, in 2012 the beginning of the compliance period was extended by one year. Therefore, the beginning of the compliance period was 2015.

⁹In 2017, this was equivalent to \$140,000-\$233,500 USD, considering an exchange rate of \$18.91 MXN to 2017USD, and a minimum wage of \$88.36 in Mexico City.

Sugarcane burning is not regulated in Mexico.¹⁰ The NOM-015-SEMARNAT/SAGARPA-2007 specifies a few rules for agricultural burning. For instance, farmers can only burn one plot if they do not have contiguous fires in an adjacent plot. Farmers should notify neighboring plots in case of wishing to use a controlled fire and notify local authorities if the fire grows uncontrollably. However, sugarcane harvest fires are not regulated.

Sugar mills have several potential strategies to respond to the new regulation: substitute processing in the mill to burning in the field, shift from fossil fuel to biofuel boilers, or otherwise change the production technology to reduce emissions. Although the empirical approach considers the first two avenues, data limitations preclude quantitative analysis of the last. However, this is a potential channel of adjustment under the regulation as other studies have documented (Ryan, 2012; Fowlie, 2010; Cicala, 2015). Based on this regulatory background, Appendix A develops a conceptual framework to derive producers' possible responses to regulation and impacted households. A producer decides the optimal amount of two inputs, and generates pollution associated with the use of either of the two inputs. A social planner implements an emissions tax to only one input (i.e. incomplete regulation). This conceptual framework has three main predictions. The regulation: 1) decreases the use of the regulated input, 2) increases the use of the other input (and its emissions) conditional on inputs being gross substitutes, and 3) the distributional consequences of this policy will depend on the socioeconomic characteristics of the populations living nearby the unregulated technology.

These theoretical predictions have implications for the setting studied in this paper. Under the new regulation of sugar mills, we might expect that regulating the technology used to process sugarcane in the mill translates into higher use of its substitute: manual cut. This prediction implies a shift from the capital intensive technology towards the labor intensive technology, increasing its associated pollution emissions. The rest of the paper leverages variation induced by the regulation to compare regulated and unregulated facilities before and after the regulation was introduced and the distributional and health implications of this incomplete regulation.¹¹

¹⁰Other countries have started regulating sugarcane burning. For example, Brazil's sugarcane growing regions have started adopting mechanical harvesting methods in the last decades and have nearly complete adoption by 2013 (Davis, 2016).

¹¹One potential concern with this approach would be the possibility that fossil fuel facilities could have acquired exempt biofuel boilers at the beginning of the policy to become exempt from the regulation. Such regulation-induced technology adoption could theoretically contaminate the composition of control and treatment groups. In this application, however, only one mill out of 60 acquired a new boiler during

2 Data

I use a combination of remote sensing data and administrative data. Remote sensing data allows me to measure fires, land use, and pollution. Administrative data from sugarcane producers in Mexico allows me to document input-use responses to the regulation. Combining these data sources, I create an exhaustive dataset of weekly input use and outputs, and daily associated fires and pollution from 2012 to 2017. This section provides a description of the data sources and the construction of all the relevant variables.

2.1 Fires data

I obtain data on the universe of daily fires in Mexico from the Active Fire Data product based on NASA's Visible Infrared Imaging Radiometer Suite (VIIRS). This product provides data on all fire occurrences starting in February 2012. NASA detects fires in a 375 m × 375 m grid and provides the centroid of the pixel with a fire event.¹² I restrict the fires to the November to May period to cover the sugarcane harvest season.¹³

2.2 Sugarcane coverage data

In order to identify the extent of sugarcane fields in Mexico, I use data from Mexico's National Committee for Sugarcane Sustainable Development (CONADESUCA). The data include confidential information on sugarcane plots in Mexico. CONADESUCA uses Landsat 8 images from 2014-2015 to map the sugarcane plots in Mexico. To do so, they classify sugarcane fields using the Normalized Difference Vegetation Index (NDVI) and validate them using Landsat data and field visits.¹⁴ Given the confidentiality of the data, CONADESUCA links the fires' centroids from VIIRS with the sugarcane field

the period of analysis. Ingenio San Francisco Ameca acquired a biofuel boiler in 2016, while most boiler investments by mills occurred during 1980-2000. In general, the decision to invest in boilers for the facility operations/electricity generation can be a long-run decision, whereas this paper focuses on the three years (short run) of the policy. Indeed, studies have found that facilities' technology adjustments occur over longer time horizons (Clay et al., 2021). Table 2 column 4 shows that results are robust to removing this facility from the analysis, however, they are less precise than the base specification.

¹²The average size of sugarcane fields in Mexico is approximately 4.7 hectares (Campos Ortiz and Oviedo Pacheco, 2015). This means that the VIIRS pixel covers approximately two average fields.

¹³CONADESUCA reports the start and end of the general harvesting season. For the years in the sample, the harvest begins around the third week in November and finishes at the end of May.

¹⁴After processing the NDVI, CONADESUCA calculates the average lifetime of sugarcane to estimate the plant's maximum growth in order to correctly monitor the NDVI changes. They estimate the month with the highest sugarcane height and cross-validate with other SPOT images from Landsat. Furthermore, they perform field visits to sugarcane fields in Mexico to cross-validate the information.

polygons for this project. Therefore, I am able to identify whether a particular fire event happens inside a sugarcane polygon. I obtain a total of 23,106 sugarcane fires for the study period 2012-2017.¹⁵ These fires are classified as sugarcane-harvest fires. I linked these sugarcane-harvest fires to sugar mills location by calculating the distance from the sugarcane fires to all existing mills and assigning fires to the closest mill. I corroborate this assignment by looking at the actual supply fields for the mills in the state of Veracruz and performed robustness checks using this subsample. More data details about this assignment can be found in Appendix B. In order to perform a falsification test, I obtain information on non-sugarcane fires using the set of fires that are located outside sugarcane plots but in agricultural land area. More data details about these placebo fires can be found in Appendix B.

2.3 Sugar mills characteristics

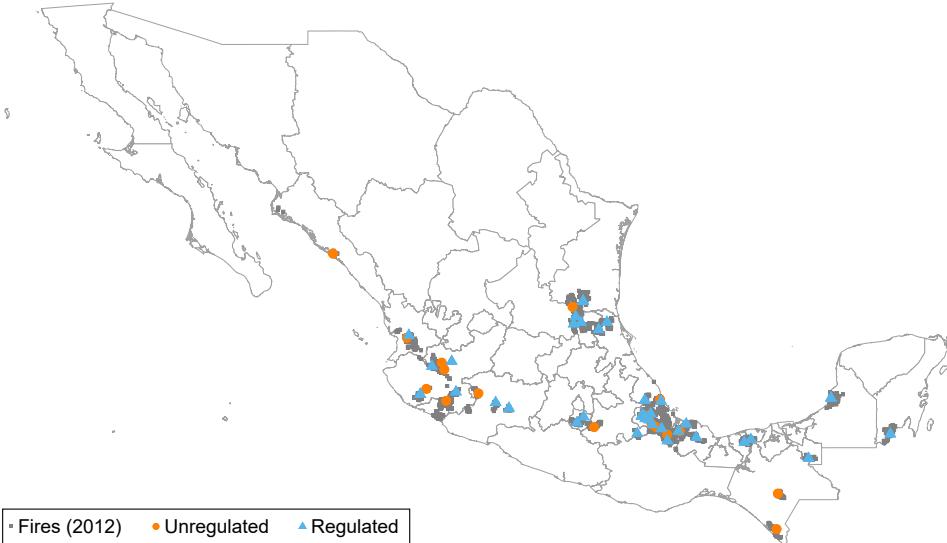
I obtain the geographic location of all sugar mills from from the National Statistical Directory of Economic Units from INEGI, based on the 2009 Economic Census performed by INEGI. Figure 1 panel a) shows the geographic coverage of the sugar mills along with their regulation classification based on fuel use pre-policy. The fuel use pre-policy comes from CONADESUCA sustainability annual reports. A mill is considered to be part of the regulated group if it did not use biofuels in its production process or if it did not use biofuels to co-generate electricity for its production activities during 2010 and 2011.¹⁶ Figure 1 panel b) shows the percentage change in number of fires before and after the regulation at the municipality level.

¹⁵In order to correct for measurement error between the VIIRS resolution and the sugarcane fires provided by CONADESUCA, I also create a 50 m buffer around the fires and classify as sugarcane fires other fires in the VIIRS dataset that were not classified as a sugarcane fire but that were captured at the same date, time, and within the 50 meters of the sugarcane fires. This is done in order to account for fires that are not classified as sugarcane fires. This procedure yields a total of nearly 200 additional sugarcane fires.

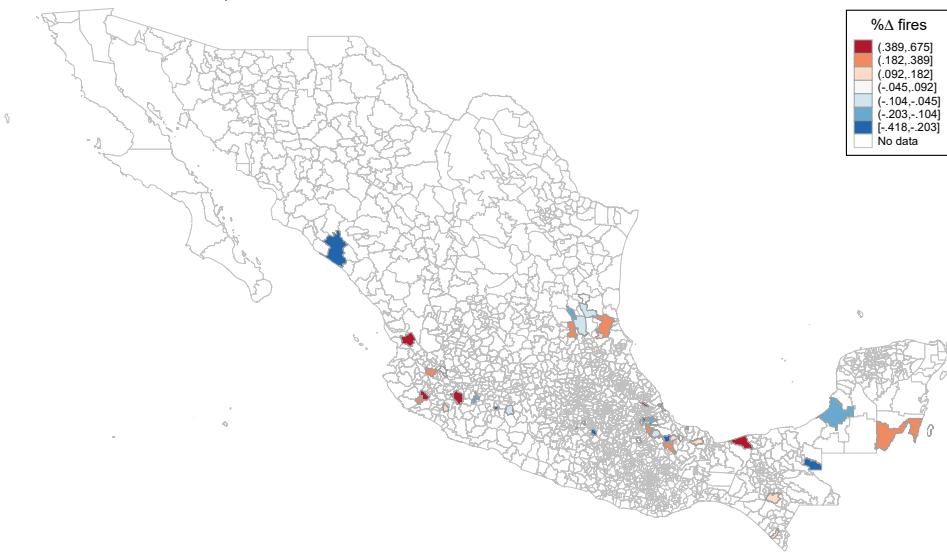
¹⁶I obtained information on biofuel use for 50 mills. I obtained information of the 10 additional mills that used oil either for generating electricity or oil-fueled boilers in their production using CONADESUCA annual reports. I cross-validated the regulated vs. unregulated definition using a list of compliance at the mill level provided by PROFEPA.

Figure 1: Mills location

Panel a) Location of mills by regulation status



Panel b) Changes in number of fires after regulation



Notes: Panel a) shows the location of mills classified by regulated and unregulated status. Shadow areas are the centroid of the sugarcane fires in 2012. Panel b) shows the percentage change in the number of fires before and after the regulation at the municipality level.

2.4 Production inputs and outputs

I add the mills' location information to detailed mill-level production data from the Sinfocaña system updated by CONADESUCÁ.¹⁷ This includes information on inputs and outputs for each mill and its associated fields. Information on inputs includes the total number of field workers, total harvested sugarcane (tons and hectares), total sugarcane

¹⁷Source: <https://www.siiba.conadesuca.gob.mx/infocana/>

cut using manual and mechanical cut, and hours worked among other field information.¹⁸ The outputs information includes the amount of raw processed sugarcane, processed sugarcane per day, total sugar produced, total sugar produced per day of operation, sugar-by products like alcohol and molasses, and indicators for sugar production efficiency.¹⁹ Table A1 shows descriptive statistics for facilities using biofuels (unregulated) and oil (regulated). Unregulated facilities have on average lower daily fires, and lower amounts of mechanical and manual sugarcane harvested. The empirical specification accounts for underlying differences in these facilities by using a difference-in-differences design.

I also obtain agricultural daily wages for employed workers at the municipality level which is based on payroll contributions to the Social Security Institute (*Instituto Mexicano del Seguro Social*, IMSS). The data contain total workers by sector, age, and gender at the municipality level. IMSS covers mainly formal workers which might not be a good representation of agricultural workers in subsistence agriculture areas. However, in the case of sugarcane production, sugarcane workers are among the workers that have access to social security. Payroll data are reported at the municipality level, not at the mill level like the rest of the results from mills, therefore, for the analysis of wages I drop the municipalities that have more than one mill within the municipality with different regulation status.

2.5 Pollution data

I obtain daily pollution data from NASA's MERRA-2 aerosol optical depth product.²⁰ Daily pollution data has a $0.5^\circ \times 0.625^\circ$ resolution. This reanalysis AOD product has information on particulate matter precursors and I calculate PM_{2.5} following Buchard et al. (2016). This methodology is analogous to other work that uses satellite data to measure pollution in areas that are remote and without a close pollution monitoring station (Chen et al., 2022). I link the fires' and mills' coordinates to the pollution pixels and calculate the pollution associated with the mill or the fire in that pixel during the day of the event (in the case of the sugarcane fires) or the day of the production season

¹⁸This information includes information on the fertilizers, the number of days of active production, pests in fields, and observed temperature and precipitation.

¹⁹Source: <https://www.siiba.conadesuca.gob.mx/sicostossustentabilidad/consultapublica/IndicadoresPublico.aspx?app=sustenta>

²⁰Specifically, I use the diurnal, time-averaged, single level assimilation, Aerosol Diagnosis V5.12.4 (M2TUNXAER).

(in the case of the mills).

One limitation of the data from MERRA-2 is the spatial resolution, especially for obtaining pollution for small areas such as the location of mills. In order to address this problem, I use data from Hammer et al. (2020) that estimates global annual surface fine particulate matter ($\text{PM}_{2.5}$) for 2012-2017. The data have a resolution of $0.01^\circ \times 0.01^\circ$. The dataset provides measurements of $\text{PM}_{2.5} \mu\text{g}/\text{m}^3$ from aerosol optical depth and accounts for transport of pollutants using the GEOS-Chem chemical transport model. The data have been used in other contexts (Fowlie et al., 2019; Garg et al., 2024) and the spatial definition is desirable to analyze detailed spatial units such as mills. The downside of the data is the temporal scale since it only provides annual estimates of particulate matter which are likely a poor measurement for seasonal pollution patterns such as agricultural fires, therefore I used the MERRA-2 data to calculate fire-induced pollution concentrations.

2.6 Birth outcomes data

Data on birth outcomes come from the Mexican Health Ministry (*Secretaria de Salud*) that collects data from individual birth certificates and has information on all birth records and mother's demographic and residence information such as number of doctor visits, age, education, employment, and community of residence.²¹ I link the community of the mother's residence to the sugarcane fire catchment areas by obtaining all the rural villages and cities located within 10 km from sugarcane fields and associating the average pollution exposure in the last pregnancy trimester.²² I merge average daily birth outcomes at the community level to the average monthly pollution concentrations due to fires in each month of the last pregnancy trimester.

2.7 Socioeconomic characteristics

In order to analyze the distributional consequences of incomplete regulation and pollution leakage, I use data from the Mexican National Marginalization index constructed by the Mexican government and used to classify the socioeconomic vulnerability of urban and

²¹Throughout this paper, community refers to a *localidad*, which denotes a small administrative unit in Mexico (smaller than a municipality).

²²Studies have found that pollution exposure has negative birth outcomes for the last pregnancy trimester (Currie et al., 2009; Rangel and Vogl, 2019).

rural areas. The index uses several variables to calculate the marginalization level such as the percentage of people older than 15 without education, percentage of households without piped water, bathroom, electricity, and refrigerator, and average number of people living in a household among others. The index uses data at the community level and classifies localities in five levels of marginalization: very low, low, medium, high, and very high. I also use data from the 2010 census to calculate poverty levels at the community level in order to analyze whether poorer communities experienced a higher increase in fires.

3 Empirical Specification

3.1 Impact of incomplete regulation on supply chain leakage

The first objective of this paper is to estimate the impact of regulation on within-supply chain leakage and pollution redistribution. I take advantage of the introduction of the regulation in 2015 to compare regulated facilities (oil burning mills) and unregulated facilities (biofuel burning mills). In order to analyze whether regulated facilities substitute from cleaning sugarcane in the mills using regulated boilers to cleaning in the fields using fires, I use a difference-in-differences approach:

$$SHF_{idmt} = \alpha + \beta_1 D_i \times \mathbf{1}[t \geq 2015] + \gamma_i + \mu_t \times \rho_m + \lambda W_{idmt} + \epsilon_{idmt} \quad (1)$$

Where SHF_{idmt} is the sugarcane harvest fires on day d associated with mill i in month m and year t , D_i equals one if the sugar mill is a non-exempt facility, γ_i are mill fixed effects, $\mu_t \times \rho_m$ are month by year fixed effects to control for year and seasonality in harvesting activities, W_{idmt} are weather controls such as temperature, rainfall and rainfall², and ϵ_{idmt} are standard errors clustered at the mill level. β_1 shows the difference-in-differences estimate of the impact of being regulated by the new emission limits after 2015.

The main identifying assumption of equation (1) is that in the absence of treatment, fires in both regulated and unregulated facilities would have followed the same trend. Parallel trends graphs for the outcomes of interest allow me to test for trend differences in the groups prior to the introduction of the policy. Figure 2 shows that before treat-

ment, both regulated and unregulated facilities follow similar trends in the number of daily fires.²³ One potential concern is the lack of pre-2012 VIIRS fire data given that VIIRS started in 2012 which only allows me to test for parallel trends using three periods before the policy. In order to address this concern, I obtained data from the FIRMS MODIS data product.²⁴ Figure A5 shows the results using MODIS fire product with additional pre-policy years. While these fires are not as precisely defined as the fires used in the main specification, Figure A5 shows a similar pattern as Figure 2, no statistically significant parallel trends pre-policy and positive, though noisy, positive effects after the policy. I perform two falsification tests. First, I replace the dependent variable with $NSHF_{idmt}$ which is the number of agricultural fires in non-sugarcane plots associated to mills. Second, I restrict the timeframe of the fires to the months of June through October, outside of the harvesting season.

In a similar way, I examine whether the changes in the number of fires are associated with the substitution of inputs related to the fire use. Following a similar approach to equation (1), I estimate the following difference-in-differences specification:

$$Y_{ist} = \alpha + \beta_1 D_i \times \mathbf{1}[t \geq 2015] + \gamma_i + \mu_t \times \rho_m + \epsilon_{ist} \quad (2)$$

Where Y_{ist} denotes the variables of interest at the sugar mill level such as number of tons harvested using manual and mechanical cut, total manual workers, total sugarcane harvested, total sugarcane processed, and total sugar. m in this case is the month with respect to the beginning of the harvest,²⁵ and $\mu_t \times \rho_m$ are month by year fixed effects. Figure 3 shows parallel trends for each of the inputs: sugarcane harvested by mechanical and manual cut, total tons harvested, and number of manual workers.²⁶ Figure A7 shows

²³Figure A7 Panel a) shows average values without any fixed effects, showing similar parallel trends between regulated and unregulated facilities before the policy started.

²⁴MODIS reports the location of the fires using a $1\text{km} \times 1\text{km}$ pixel resolution, while the VIIRS product, the main product used in this paper, uses a $375\text{m} \times 375\text{m}$ resolution. However, MODIS data goes back to 2002, which allows me to test for different pre trends over a longer period. One main limitation using MODIS is that CONADESUCÁ does not indicate whether a fire is located inside a sugarcane parcel. To do this, I created 200m buffers surrounding the fires identified as sugarcane fires using VIIRS and intersected these buffers with the MODIS latitude and longitude. Therefore, these fires can be considered “sugarcane” fires but are not as precisely defined as the main fire dataset.

²⁵The administrative data is reported by sugar mills directly in a weekly basis and they start reporting it at the beginning of each harvesting cycle. However, information on the date of the beginning of the harvest for each mill is not available. Therefore, I grouped the weeks in intervals of 4 weeks with respect to the start of the season in order to have a “month” equivalent across regression specifications.

²⁶Figure A7 Panel b)-d) shows average values without any fixed effects, showing similar parallel trends between regulated and unregulated facilities before the policy started. The only figure that has some

parallel trends for outputs such as total sugarcane processed and total sugar produced.²⁷ These two figures show that there are no significant differences in trends between regulated and exempt facilities at the start of the policy in terms of inputs used or total sugarcane harvested or sugar produced.

Finally, in order to examine whether there are differences in air pollution concentrations due to changes in the number of fires or production patterns I use a similar specification to equation (1):

$$P_{idmt} = \alpha + \beta_1 D_i \times \mathbf{1}[t \geq 2015] + \gamma_i + \mu_t \times \rho_m + \lambda W_{id} + \epsilon_{idmt} \quad (3)$$

Where P_{idmt} is the ambient pollution concentration of daily PM_{2.5} in $\mu\text{g}/\text{m}^3$. I run two separate versions of equation (3): one for the pollution associated to the fires' locations and another for the pollution associated to the mills' locations.²⁸ Figure 4 Panel a) shows the parallel trends graph for the pollution associated with the fields and Figure 4 Panel b) shows the pollution parallel trends associated with the mills.²⁹

3.2 Distributional effects of incomplete regulation

The second objective of this paper is to analyze the distributional consequences of within supply chain leakage. A large body of literature has documented negative effects of pollution on health outcomes (Rangel and Vogl, 2019; Chay and Greenstone, 2003; Deryugina et al., 2019) and how the damages of pollution can vary across income levels (Arceo et al., 2016). Other studies have analyzed whether the damages from environmental policies are distributed unevenly across populations (Fowlie et al., 2012; Grainger and Ruangmas, 2018). However, studies that document emissions leakage caused by policies

differences pre-policy is Panel c), average mechanical cut. This shows a similar pattern to Figure 3 Panel b), though only one pre-trend coefficients is statistically significant.

²⁷Figure A7 Panel e) and f) shows average values without any fixed effects, showing similar parallel trends between regulated and unregulated facilities before the policy started.

²⁸Important to note, specification (3) differs between mills and fires pollution since the time resolution of the two satellite pollution products is different: pollution associated to fires can be obtained on a daily basis given the larger extent of sugarcane fires while pollution associated to mills can only be obtained on an annual basis given the geographic extent of mills. Therefore, specification (3) in the case of fires would be at the year level instead of the day level. Note that for the mill pollution specification we only have year-level results, month by year fixed effects are thus replaced by year fixed effects.

²⁹Figure A7 Panel g) and h) shows average PM_{2.5} concentrations without any fixed effects, showing similar parallel trends between regulated and unregulated facilities before the policy started.

have not examined how these emissions are distributed across populations.³⁰ Understanding how the damages from environmental policy are distributed across populations and the determinants of the environmental damages is important for welfare analysis (Hsiang et al., 2019) and environmental justice (Banzhaf et al., 2019). Furthermore, analyzing the distributional effects of incomplete regulation in the context of this paper is important because of the characteristics of the underlying population living close to the sugarcane fields. Figure A8 shows the characteristics of the populations exposed to mills and fields. Generally, poorer households tend to live in rural areas that are exposed to sugarcane fires while mills are located in urban and semiurban areas.

In order to explore the distributional consequences of incomplete regulation, I calculate the catchment areas of all localities (either urban or rural) by creating a buffer of 10 km surrounding the centroid of the community.³¹ I then merge these catchment areas to pollution concentrations by predicting the pollution exposure coming from the policy in equation (3), obtaining the annual predicted PM_{2.5} from the policy, \hat{P}_{jt} , and modifying the empirical specification of Hernandez-Cortes and Meng (2023):

$$\hat{P}_{jt} = \gamma_0 + \gamma_1 DAC_j \times \mathbf{1}[t \geq 2015] + \tau_j + \mu_y + \epsilon_{jt} \quad (4)$$

Where \hat{P}_{jt} is the predicted average annual pollution exposure in community j in year t coming from the policy calculated in equation (3) and DAC is an indicator variable that equals one if the community is disadvantaged (high or very high marginalization index), τ_j are community fixed effects, μ_y are year fixed effects.³² Standard errors are clustered at the community level. $\gamma_1 > 0$ would imply that disadvantaged communities have experienced a higher burden of the pollution change due to the incomplete regulation compared to other disadvantaged localities whereas $\gamma_1 < 0$ would imply that disadvantaged communities have experienced a lower burden of the pollution change due to the incomplete regulation. I also divide communities into the marginalization categories to examine heterogeneity across different marginalization levels.

³⁰Many studies that have documented leakage have done it in terms of GHG emissions where emissions occur is not as worrying due to the nature of GHG emissions.

³¹I assigned pollution from fires and mills by calculating a receptor catchment area of 10km from the centroid of the urban or rural community. The total population in the buffer area of fires originated in sugarcane fields is 9,834,436 and the total population in the buffer area of the mills is 5,723,850.

³²Note that the analysis in equation 4 is done at the *year* level. While the pollution from fires can be analyzed at the day level, I performed the analysis at the year level to have consistency with the pollution from mills, which can only be analyzed at the year level due to the spatial resolution of mills.

3.3 Health impacts of incomplete regulation

This section analyzes whether pollution concentration increases caused by incomplete regulation translate into negative outcomes for populations located within the fires catchment areas. In particular, I use the predicted pollution exposure derived in equation (3) to explain changes in birth outcomes:

$$H_{jd} = \alpha + \theta_1 \hat{P}_{j(d-w)m} + \gamma X_{jd} + \lambda_j + \mu_t + \epsilon_{jd} \quad (5)$$

Where H_{jd} denotes average birth outcomes such as birth weight, gestation length, very low birth weight, and very preterm births at the community and day level. $\hat{P}_{j(d-w)m}$ is the predicted exposure coming from the policy calculated in equation (3) associated with the weeks w before the birthdate in the last trimester of the pregnancy, where $w \in \{4, 8, 12\}$. X_{jd} are controls such as average mothers' age and average total doctor visits at the community and day level. μ_t denotes year fixed effects. Standard errors are clustered at the community level. This specification differs from Rangel and Vogl (2019) since the authors explore the differences between upwind and downwind fires from the mother's municipality in order to isolate the impacts of pollution from the economic activity derived from the harvesting season. To the extent that $\hat{P}_{j(d-w)m}$ is obtained using variation that exploits the introduction of regulation to sugarcane mills with a rich set of controls and fixed effects, specification (5) is likely capturing pollution and not economic activity.

4 Results

4.1 Effects on sugarcane fires

This section discusses the effects of incomplete regulation on within-supply chain leakage. Given that fires are a production substitute for more cleaning in the mills, we would expect the amount of fires to increase after the boiler regulation in regulated facilities. Column (1) of Table 1 shows the difference-in-differences estimator, β_1 , of interest. This shows that there is an approximately 15% increase in the number of daily fires after the policy began. Column (2) shows the impact on the number of fires using a Poisson model and the results are similar to column (1), the increase in the count of fires is around 13.8%

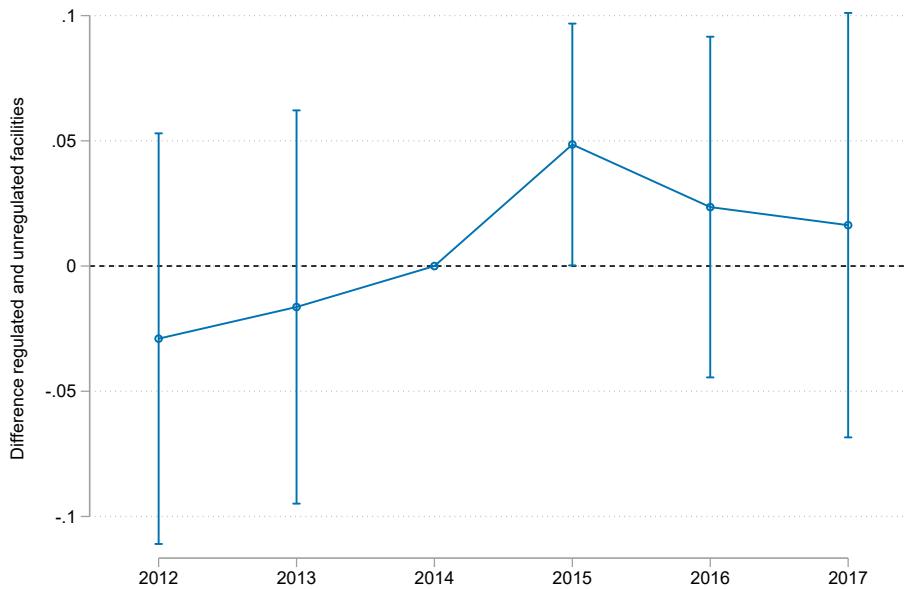
after the policy began with respect to the baseline number of fires.

Table 1: Effects of incomplete regulation on daily fires

	(1)	(2)
	Total SHFs	Total SHFs
After 2015 × Regulated	0.044** (0.022)	0.139** (0.065)
Pre 2015 mean	0.297	0.302
Obs.	67,770	66,515
Month by Year FE	Yes	Yes
Mill FE	Yes	Yes
Weather controls	Yes	Yes
Cluster level	Mill	Mill
Poisson	No	Yes

Notes: Regulated is an indicator variable that equals one if the mill is regulated by the policy. Column (1) shows the difference-in-differences estimator of the impact of being regulated by the emission limits after the policy started on the number of fires using equation 1. Column (2) estimates the same specification in equation 1 using a Poisson model. Standard errors clustered at the mill level in parenthesis. Weather controls include temperature, rain, and rain².

Figure 2: Event study for total daily fires



Notes: This figure shows the difference-in-differences year specific coefficients for the total number of daily fires following Equation (1). Regulated facilities are defined as facilities using oil as the main fuel. Unregulated facilities are defined as facilities using biofuels as main fuel. The regulation started in 2015. 95% confidence intervals calculated using cluster standard errors at the mill level. Weather controls include temperature, rain, and rain².

Robustness: Table 2 Column (2) shows the results from equation 1, analogous to column (1) of Table 1 with bootstrapped standard errors. Table 2 Column (3) shows a stronger effect when restricting the dataset to the fires inside of the mills' distribution

areas using the sampling points of several mills in the state of Veracruz, the state with the highest number of mills. Table 2 Column (4) and Column (5) show the results doing two sample restrictions. First, I estimate the results without the only mill that invested in a biofuel-powered boiler in 2016 who could have changed fuel use as a response to the policy. Second, I estimate the results without the mill that shows a higher rate of mismatched fields based on the minimum distance definition according to Figure A3. The coefficients remain unchanged but are less precise compared to the benchmark specification. Table 2 Column (6) shows the results using the monthly number of fires at the mill level. The effect is similar in magnitude considering the number of monthly fires. Table A2 shows the results of two falsification tests with other types of fires.³³

Table 2: Robustness checks

	(1) Benchmark	(2) Bootstrap	(3) Distribution areas	(4) Sample rest. 1	(5) Sample rest. 2	(6) Monthly fires
After 2015 × Regulated	0.044** (0.022)	0.044*** (0.014)	0.023** (0.010)	0.042* (0.022)	0.044* (0.023)	1.135* (0.667)
Pre 2015 mean	0.297	0.297	0.066	0.296	0.300	8.734
Obs.	67,770	67,770	25,000	66,515	66,515	2,268
R-squared	0.102	0.102	0.035	0.104	0.102	0.568
Month by year FE	Yes	Yes	Yes	Yes	Yes	Yes
Mill FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes	Yes	Yes	Yes
Cluster level	Mill	Bootstrap	Mill	Mill	Mill	Mill

Notes: Column (1) shows the baseline identification, difference-in-differences estimator of the impact of being regulated by the emission limits after the policy started on the number of fires using Equation (1). Column (2) shows the baseline specification using bootstrapped standard errors. Column (3) shows the baseline specification restricted to the plots that are located in the parcels linked to the distribution network based on 2009 sampling data. Column (4) shows the baseline specification without one mill that invested on a biofuel boiler. Column (5) shows the baseline specification without one mill that had the lowest number of matches of parcels. Column (6) shows the baseline specification aggregating at the month level instead of day level. All columns use cluster standard errors at the mill level except column (2). Weather controls include temperature, rain, and rain².

4.2 Effects on input substitution

Next, I analyze whether the change in the number of fires is reflected in input substitution across firms. Consistent with the finding of an increase in the number of fires used during the harvest, Column (1) of Table 3 shows that there is an increase of 8% in the total sugarcane harvested using manual cut. Since fires are mainly used with manual cut, we might expect a decrease in mechanical cut. I find that the amount of sugarcane harvested using mechanical cut decreases although this result is not statistically significant. Given

³³Table A2 Column (1) shows that there is no difference in the number of non-sugarcane agricultural daily fires. Column (2) no significant difference in the number of sugarcane fires outside of the sugarcane harvest season (June-October).

that the use of fires is consistent with an increase in manual cut, I also find that the number of field workers increases by 5%, as Column (3) of Table 3 shows. The results of Table 1 and 3 show that incomplete regulation generates within supply chain leakage and changes in the inputs used. I do not find a discernable impact on wages³⁴ and I do not find evidence of an increase in total sugar produced³⁵. I find suggestive evidence that the non-increase in total sugar produced is due to changes in production efficiency.³⁶

Table 3: Effects of incomplete regulation on weekly input use

	(1) Manual cut (tons)	(2) Mechanical cut (tons)	(3) Total field workers
After 2015 × Regulated	2,655.145** (1,165.398)	-359.836 (780.138)	79.923** (34.803)
Pre 2015 Mean	32,140.435	6,810.680	1,491.401
Obs.	5,887	5,894	5,420
R-squared	0.742	0.739	0.908
Month by Year FE	Yes	Yes	Yes
Mill FE	Yes	Yes	Yes
Cluster level	Mill	Mill	Mill

Notes: Column (1) shows the difference-in-differences estimator of the impact of being regulated by the emission limits after the policy started on the amount of sugarcane harvested using manual cut (tons) following Equation (2). Column (2) shows the difference-in-differences estimator of the impact of being regulated by the emission limits after the policy started on the amount of sugarcane harvested using mechanical cut (tons) following specification 2. Column (3) shows the difference-in-differences estimator of the impact of being regulated by the emission limits after the policy started on the number of manual labor workers following Equiation (2). Standard errors clustered at the mill level in parenthesis.

4.3 Effects on ambient pollution

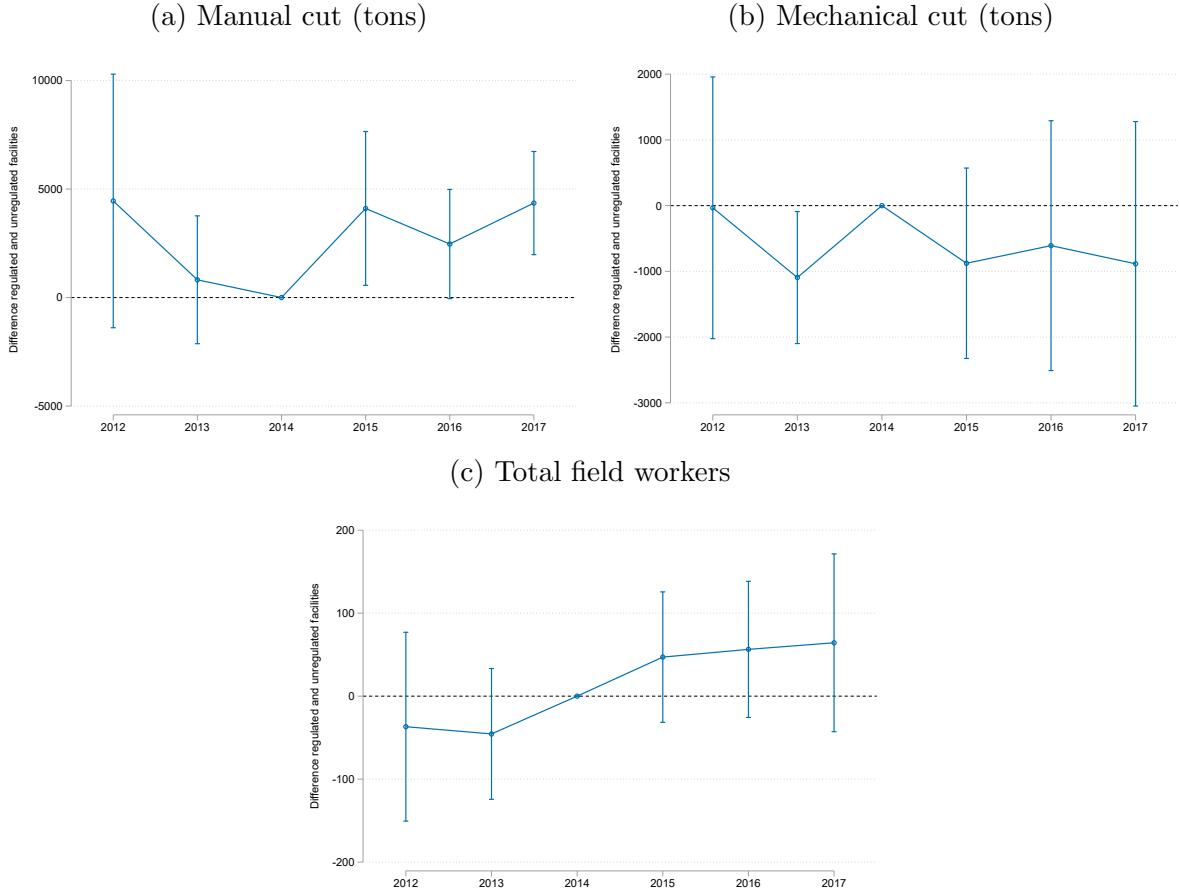
What is the effect of supply chain leakage on total pollution concentrations? Table 4 shows the implications of an increase of fires in terms of local ambient pollution levels around the sugarcane fields (column 1) and mills (columns 2). Columns (1) and (2) are estimated using different datasets, given the spatial resolution of the data: column (1) is estimated using data from MERRA 2.0 with calculations following Buchard et al. (2016) and column (2) is estimated using the data from Hammer et al. (2020). I find

³⁴Using data on payroll for formal sugarcane agricultural workers at the municipality level, Table A3 shows that there is no change in wages for agricultural workers throughout the period of study, even dividing by different age categories.

³⁵Table A4 shows that there is no increase in the total amount of sugarcane processed in the mill and no increase in the total amount of sugar produced in the mill.

³⁶I estimate changes in production efficiency by using three indicators: (1) the total kilograms of sugar obtained by ton of harvested sugarcane, (2) total kilograms of sugar obtained by ton of processed sugarcane, and (3) sugar extraction efficiency. Table A5 shows these results which suggest that there is a non-significant decrease in overall sugar production efficiency.

Figure 3: Event study for weekly input use

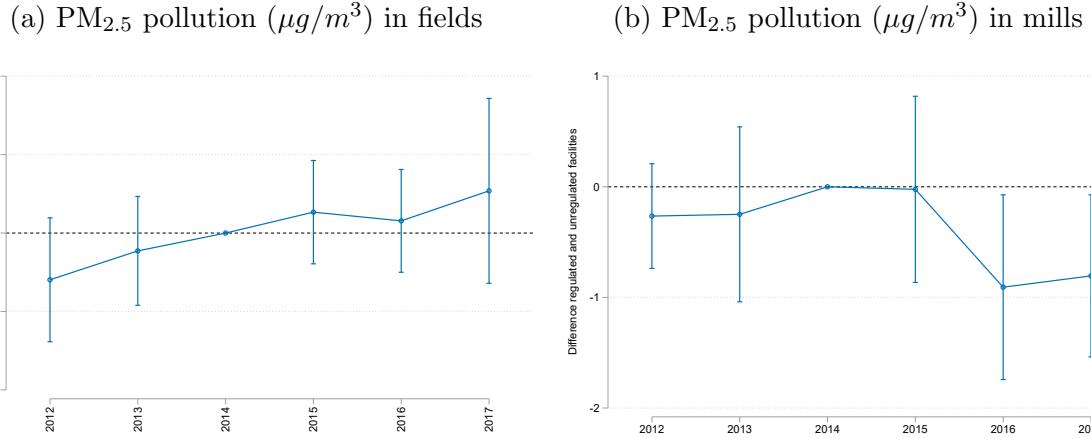


Notes: Panel a) shows the difference-in-differences year specific coefficients for the total sugarcane in tons using manual cut following Equation (2). Panel b) shows the difference-in-differences year specific coefficients for the total sugarcane in tons using mechanical cut following equation Equation (2). Panel c) shows the difference-in-differences year specific coefficients for the harvested hectares following equation Equation (2). Panel d) shows the difference-in-differences year specific coefficients for the total number of manual workers following Equation (2). 95% confidence intervals calculated using cluster standard errors at the mill level.

that there is an increase of $1.18 \mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$ or a 7% increase in pollution coming from the fields associated to the 2015 regulation. Column (2) of Table 4 shows the results of pollution from the mills, suggesting a decrease of pollution near the mills. These magnitudes suggest that concentrations in areas close to mills decreased, while areas close to fields increased, which suggests a total net increase in pollution concentrations due to the policy.

Magnitudes comparison: The magnitudes of my results are consistent with existing studies. I find that in response to the regulation, regulated mills increased fires by 14%. Gibson (2018) finds that regulated facilities under the Clean Air Act increased their production in unregulated facilities by 11% and Hanna (2010) finds that regulated

Figure 4: Event study for pollution concentrations



Notes: Panel a) shows the difference-in-differences year specific coefficients for pollution from PM_{2.5} in the fields following Equation (3). Panel b) shows the differences in differences-year specific coefficients for pollution from PM_{2.5} in the mills following Equation (3) using Hammer et al. (2020). 95% confidence intervals calculated using cluster standard errors at the mill level.

Table 4: Effects of incomplete regulation on pollution concentrations to nearby communities

	(1)	(2)
	Pollution in fields	Pollution in mills
PM _{2.5}		
After 2015 × Regulated	1.185** (0.580)	-0.397* (0.205)
Pre 2015 Mean	17.765	13.820
Obs.	20,127	324
R-squared	0.508	0.929
Year FE	No	Yes
Month by Year FE	Yes	No
Mill FE	Yes	Yes
Weather controls	Yes	Yes
Cluster level	Mill	Mill

Notes: Column (1) shows changes in PM_{2.5} pollution concentrations in the sugarcane fields using the difference-in-differences estimator of the impact of the regulation after the policy started following Equation (3) using Buchard et al. (2016). Column (2) shows changes in PM_{2.5} pollution concentrations in the area where mills are located using the difference-in-differences estimator of the impact of the regulation after the policy started following Equation (3) using Hammer et al. (2020). Standard errors clustered at the mill level in parenthesis. Weather controls include temperature, rain, and rain².

facilities under the Clean Air Act increased foreign output by 9%. In terms of pollution, I find that incomplete regulation increased pollution exposure by 6% in rural areas located near the agricultural fields. This increase in pollution is higher than that documented by Garg et al. (2024), who find an increase of 1.25% in PM_{2.5} exposure as a result of increasing agricultural fires due to labor exits in India.

4.4 Who experiences the increases in pollution?

This section analyzes whether vulnerable communities experienced a larger increase in pollution coming from sugarcane fires after the policy. I classify vulnerable communities using the marginalization index provided by the Mexican government. This section uses the official index that classifies communities from “very low” to “very high” marginalization and I define a community as “disadvantaged” if it has a “very high” or a “high” marginalization level. Table 5 shows that the annual pollution concentrations in disadvantaged communities increased after the policy compared to non-disadvantaged communities. Column (1) shows the average annual predicted concentrations in communities exposed to fires and Column (2) shows the average annual predicted concentrations in communities exposed to mills. A higher amount of communities are exposed to fires and they have higher levels of pollution before the policy. I estimate that by the end of my sample period, disadvantaged localities in the fires catchment area experienced 2% more pollution exposure than non-disadvantaged localities relative to the no policy counterfactual. While disadvantaged communities in the mills’ catchment area also experienced a significant increase in pollution concentrations due to the policy, the effect is very low, a 0.25% increase relative to the no policy counterfactual.

Table 5: Distributional impacts of incomplete regulation on vulnerable populations

	(1)	(2)
	$\widehat{PM}_{2.5}$	$\widehat{PM}_{2.5}$
DAC × After 2015	0.280*** (0.026)	0.035*** (0.007)
Pre 2015 mean	15.779	13.898
Obs.	92,892	20,262
R-squared	0.854	0.971
Year FE	Yes	Yes
Locality FE	Yes	Yes
Cluster level	Locality	Locality

Notes: Columns (1) and (2) show the predicted difference in pollution exposure for disadvantaged communities after the policy. Community exposure was calculated using catchment areas: 10km radii surrounding the community centroid. Disadvantaged communities were classified using the 2010 Marginalization Index calculated by CONAPO.

The pollution redistribution impacts are heterogenous with respect to different levels of marginalization: the highest level of marginalization experienced a higher burden of pollution exposure than communities with low or very low marginalization indices. This means that more socioeconomically disadvantaged areas experienced a higher increase in

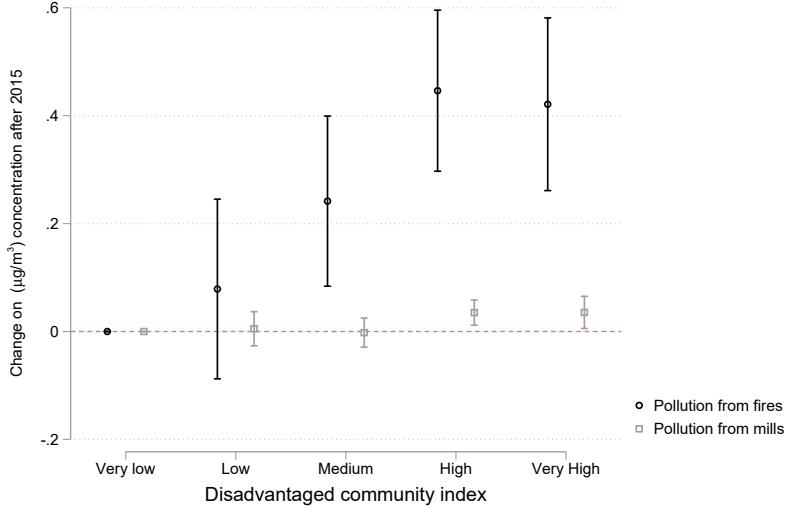
pollution driven by the policy than other non-disadvantaged areas. Panel a) of Figure 5 shows these results. I also show the robustness of these results using another social vulnerability index, the “Social Lag Index”³⁷. This figure shows that the exposure from mills did not change for communities with higher levels of vulnerability, except for the “Very High” category of the social lag index. However, it is smaller than the magnitudes from fires. The heterogeneity in pollution exposure after the policy could have occurred for a variety of reasons such as ex-ante vulnerability or because mills with fields closer to disadvantaged communities could strategically pollute more near these areas without facing opposition to pollute. Chakraborti and Shimshack (2020) show that in the case of Mexico, pollution disparities could be explained by community pressure and collective action responses. However, additional work can be done to analyze whether this is the case in the sugarcane sector. These results are relevant given that previous research shows that pollution damages are not linear with income (Arceo et al., 2016). Moreover, given that defensive investments are an important part of the willingness to pay for pollution reduction (Deschênes et al., 2017) and they could be correlated with income, poorer households might not be as able to cope with changes in pollution exposure.

Besides showing that the policy generated a relatively higher pollution exposure for the most vulnerable communities, I test whether locations with higher poverty levels are the most affected by the fires. Table A6 shows that the increase in fires is higher in localities that have poverty levels above the state median. This is consistent with Chakraborti and Shimshack (2020) who found that pollution releases is higher in marginalized communities in the case of Mexico. This is another indicator that the most vulnerable communities were affected by incomplete regulation.

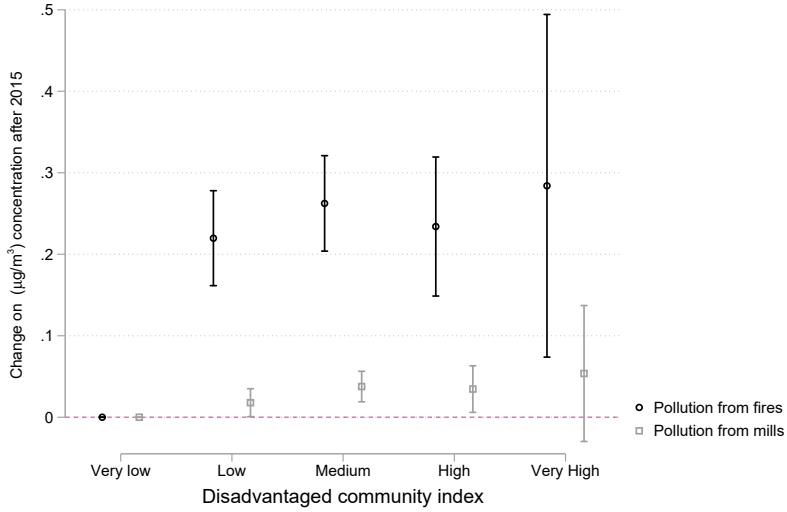
³⁷This index considers data from the 2010 data and is based on different variables than the Marginalization Index calculated by CONAPO. The index considers indicators of infrastructure at the community level and asset holding characteristics for the localities’ households.

Figure 5: Distributional impacts of incomplete regulation by level of vulnerability

Panel a) Social Vulnerability Index



Panel b) Social Lag Index



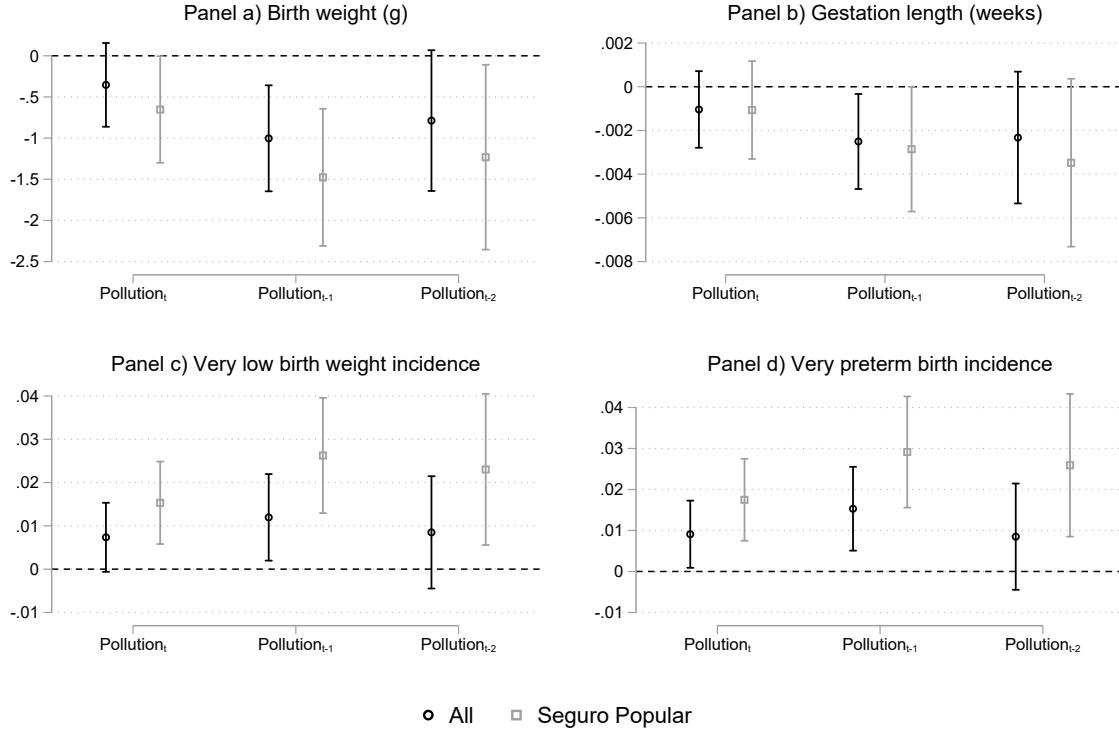
Notes: Panel a) shows the results of pollution associated to fires by level of marginalization according to the marginalization index and the social lag index. Panel b) shows the results of pollution associated to mills by level of marginalization according to the marginalization index and the social lag index. Coefficients show the interaction between the marginalization level and an indicator after the policy. Regressions include community and year fixed effects. Confidence intervals calculated using clustered standard errors at the community level.

4.5 The impacts of incomplete regulation on health outcomes

Do changes in pollution caused by incomplete regulation affect health outcomes? I examine this by analyzing whether predicted pollution obtained in Section 4.3 changes birth weight, gestation length, very low birth weight incidence, and very preterm birth incidence for populations located in the fires' catchment area. Figure 6 shows the main health results for pollution exposure in the last pregnancy trimester on birth outcomes

for all mothers and mothers in Seguro Popular averaged at the community-day level.³⁸ I find that pollution exposure in the last trimester of pregnancy significantly lowers birth weight and increases the incidence of very low birth, and very preterm birth. These effects are larger in the last gestation period.

Figure 6: Effects of incomplete regulation on birth outcomes



Notes: Panels a)-d) show changes in birth outcomes associated with predicted pollution exposure with 4, 8 or 12 weeks from birthdate for "all" and "Seguro Popular" covered-mothers. Each estimate is obtained from separate regressions. "Very low birth weigh" is defined if weight < 1,500g, "Very preterm birth" is defined if birth length < 32 weeks. All regressions control for average mothers' age and total of doctor visits during pregnancy and year and community fixed effects. "All" includes all mothers, regardless of health care coverage. "Seguro Popular" includes mothers covered by *Seguro Popular*. Confidence intervals calculated using standard error at the community level.

The results in Figure 6 imply that an additional $\mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$ in weeks 1-8 of the last trimester of pregnancy is associated with a birth weight decrease about 1 grams in average birth weight across all populations. Rangel and Vogl (2019) estimate that a unit increase of PM_{10} (in $\mu\text{g}/\text{m}^3$) caused by sugarcane fires decreases birth weight by 5.2 grams. Other estimates on the impacts of pollution on birth weight find that a unit increase in PM_{10} exposure during the last trimester is associated with a 0.4 gram decrease in birth weight (Currie et al., 2009; Rangel and Vogl, 2019). My estimates are smaller

³⁸Table A7 and Table A8 show the coefficients associated to this figure.

in magnitude than Rangel and Vogl (2019) which could be due to existing differences in fire activity intensity in Brazil, as well as differences in the studied pollutants and identification strategies.³⁹

For the other variables analyzed, I find that a unit increase in PM_{2.5} is associated with a 2.4% increase in very low birth weight prevalence (< 1,500g) and a 3% increase in the probability of very preterm birth (< 32 weeks). These results are consistent with other studies which find that fires increase the likelihood of very low birth weight and very preterm birth in exposed populations (Rangel and Vogl, 2019).⁴⁰ Worse birth outcomes are found for mothers affiliated with *Seguro Popular*, which is the health system covering the most vulnerable populations in Mexico that are uninsured through the traditional social security networks for formal sector workers (IMSS or ISSSTE). Results in Figure 6 and Table A8 shows that the mothers affiliated to Seguro Popular experience a higher impact of pollution increases: an increase in pollution linked to incomplete regulation increases the very low birth weight incidence by 5.75% and the probability of very preterm birth by 7.25%, double as much as the overall effect for all mothers. These results suggest that increases in pollution due to input substitution are linked to worse health outcomes for populations located in the fires catchment area and these effects are higher for the most socioeconomically vulnerable mothers.

5 Conclusion

Many environmental policies are incomplete, covering some sectors or facilities, and not others. This paper shows that under incomplete regulation, regulated facilities can cause increases in pollution in already disadvantaged areas. I find that following the introduction of a regulation aimed at decreasing industrial pollution, regulated sugar mills increased sugarcane harvest fires and complementary inputs (i.e. manual labor) in their fields. This increase in fires caused an increase in pollution near sugarcane fields. The increase in pollution as a response to the regulation is concerning due to poverty level differences between the populations close to the mills and fields. I find that the pollution

³⁹Rangel and Vogl (2019) estimate this by comparing upwind and downwind fires which likely provide a more precise estimate of the impacts of pollution exposure.

⁴⁰Rangel and Vogl (2019) find that an additional z-score of fire activity per week in the last trimester of pregnancy increases the incidence of very low birth weight by 22 per 1000 and an increase in the incidence of preterm birth by 23 per 1000, although the later results is not significant.

increase was higher for disadvantaged communities and translated into worse neonatal outcomes, especially for low-income households. This result contributes to the current discussions on the determinants of environmental justice by examining a previously overlooked mechanism: incomplete regulation.

The results of the paper are relevant for current policy debates in Mexico on whether to regulate agricultural burning from sugarcane. In 2017, the Mexican environmental agency proposed amendments to the existing regulation to include facilities that use biofuels as main fuel (PROY-NOM-170-SEMARNAT-2017). The results of this paper show that if facilities are able to substitute production processes with fires, incomplete regulation might backfire. Therefore, considering these possible adjustment margins is important.

This paper also finds that despite increasing pollution in rural areas, input reallocation can have positive employment benefits. Studies have documented the tradeoff between health and local economic outcomes in developing countries (von der Goltz and Barnwal, 2019; Rangel and Vogl, 2019). By showing that manual work increases together with increases in pollution, this paper adds to the literature examining this health-local economic outcomes tradeoff. However, other studies have shown that regulation of polluting technologies might not need to be accompanied by labor losses. In the case of sugarcane production, Costa and Lima (2020) show that harvest mechanization in Brazil decreased employment in the agricultural sector but increased employment in the manufacturing and services sectors.

There are several limitations to this study. First, the pollution level estimates should be interpreted with caution given the geographic extent of pollution measures. However, I present consistent evidence that manual cut increased together with fires, which suggests that populations located near fields were exposed to more pollution. To the extent that crop burning increases pollution levels, which has been shown by other studies, populations near sugarcane fields are likely to experience higher pollution. Second, despite the efforts to link mills to their respective fields, the possibility of misassignment remains. However, I show that restricting fires to the official distribution areas increases the estimated coefficients. Finally, there is still need to characterize other mechanisms driving distributional concerns of environmental policy and their environmental justice implications. However, by documenting a previously overlooked mechanism, this paper

contributes to the literature on disparities in environmental impacts and their implications for environmental justice.

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