The Distributional Effects of Tighter Regulations: New Evidence from the Sugarcane Burning in Florida

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Abstract

Environmental regulations shape the spatial distribution of pollution, influencing the burden on different communities. In South Florida, wind-based sugarcane burning regulations have historically favored wealthier, densely-populated areas by limiting burning during specific wind conditions. In 2019, additional restrictions were introduced to limit burning on days with low air quality. By using satellite fire data and Aerosol Optical Depth (AOD) data, we assess the impact of these stringent restrictions on burning and air pollution. Results reveal a 41% decrease in burning on restricted days within the main cultivation area, potentially leading to increased burning on days without restrictions. This unintended consequence exacerbates air quality issues for the region's most vulnerable populations. The study reveals regulatory enhancements inadvertently worsen environmental inequities, highlighting the need for environmental justice policies that address historical and systemic discrimination affecting pollution distribution.

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1. Introduction

Decades of interdisciplinary research have established that low-income communities and people of color disproportionately suffer from pollution exposure (Mohai et al., 2009; Banzhaf et al., 2019; Chakraborti and Shimshack, 2022). The primary drivers of this disparity have been identified as income inequality, discrimination, the costs borne by firms for regulatory compliance and inputs, and the lack of reliable information about environmental quality (Hausman and Stolper, 2021). However, the literature has yet to fully explore how the introduction of stricter environmental regulations alongside pre-existing policies, particularly those discriminatory policies. This oversight highlights a critical gap: the potential for new, more stringent regulations to either mitigate or exacerbate environmental injustices remains an open question. Our study seeks to address this gap by examining the implications of tighter burning regulations within the specific context of sugarcane burning in Florida, focusing on communities historically impacted by discriminatory policies associated with this practice.

In Florida, the practice of burning sugarcane fields before harvest is common, aimed at removing the non-sugar-bearing parts of the plant, such as leaves and tops, and leaving only the sugar-rich stalk for collection. Although this method facilitates the harvesting process, it significantly degrades the local and downwind air quality. Research, particularly studies conducted in Brazil—the world's largest producer of sugarcane—has highlighted the environmental and health impacts of the burning practice. These studies have linked emissions from sugarcane burning, especially particulate matter (PM2.5), to an uptick in respiratory health issues. Specifically, there is evidence of increased hospital admissions for asthma (Arbex et al., 2007), as well as for respiratory conditions among children and the elderly (Cançado et al., 2006). Further, research has demonstrated negative neonatal outcomes associated with proximity to sugarcane burning, including reduced birth weights, shorter gestational durations, and lower in-utero survival rates (Rangel and Vogl, 2019). Thus, communities located near sugarcane fields are disproportionately affected by these health risks, compared to those living outside sugarcane-growing regions.

In response to growing concerns over air pollution, the Brazilian sugarcane industry worked with the state government in 2017 to eliminate nearly all pre-harvest sugarcane burning practices. This initiative led sugar producers to transition to mechanized harvesting by investing in harvesting equipment that allowed them to cut the sugarcane without burning (Sussman, 2021). Outside Brazil, alternative strategies have been proposed to mitigate the environmental impact of sugarcane burning. These include adopting smoke management practices and conducting controlled burns when atmospheric conditions are most favorable to minimize the negative effects on surrounding communities (Hiscox et al., 2015). Conversely, Florida authorities have tried to regulate sugarcane burnings in ways that emphasize the protection of wealthier communities by restricting the burning activities in the predominantly sugarcane-growing regions.

This study evaluates the sugarcane burning regulatory frameworks within South Florida's Zone 1 and Zone 4. Zone 1, with higher average incomes and population density, benefits from a regulation established in 1991 that prohibits burning under certain wind conditions (NNW, NW, W, SW, SSW), aimed at protecting its dense population. Conversely, Zone 4, characterized by extensive sugarcane cultivation and lower-income demographics, lacks these protections and experiences the majority of burning activities. In 2019, residents in Zone 4 raised concerns through a lawsuit, alleging that sugarcane burning diminished property values and compromised air quality by emitting toxic carcinogens. The lawsuit was dismissed in 2022, preventing further claims (Morse, 2022). Industry defenders, like U.S. Sugar, have underscored their compliance with the Clean Air Act by sharing data from local air quality monitors (Sussman, 2021). In October 2019, Florida introduced stricter burning regulations, marking the first significant amendment in 30 years. These regulations are aimed at mitigating air quality degradation by restricting burns on days with poor air quality and supplementing wind direction-based restrictions.

This paper evaluates the impacts of the recently tighter burning regulations on sugarcane burning and air quality. In the absence of detailed authorization records, we rely on remote sensing fire data to quantify observed burning activities. We combine the daily fire data with daily pollution and weather information at the census tract level across the sugarcane burning zones, spanning from 2012 to 2021. Using the 2019 policy changes as a natural experiment, our approach leverages temporal variations (pre- and post-policy implementation), spatial disparities (Zone 1 versus Zone 4), and the conditional nature of wind restriction policies (whether wind restrictions bind or not). The empirical strategies in this paper include both difference-in-differences (DD) and triple difference (DDD) estimations.

Our study has three main results. First, we highlight a critical limitation in the burning authorization data provided by the Florida Department of Agricultural and Consumer Service, noting its spatial aggregation at the county level. This aggregation may obscure the true effects of burning regulations on the incidence of authorized fires. To address this issue, we rely on satellite imagery to reconstruct a more precise account of observed fires. Our analysis reveals a general decline in fire occurrences and an improvement in air quality following policy implementation, before differentiating between sugarcane burning zones. When separating the two zones, we find that on days subject to wind restrictions, the enforcement of stricter regulations leads to a significant reduction in the number of daily fires, notably with a 41% decrease in Zone 4 compared to Zone 1. Conversely, on days without these wind restrictions, the recent policy appears to decrease fire occurrences in Zone 1 while inadvertently increasing them in Zone 4. The effectiveness of these tighter regulations, as evidenced by the reduction of fires in Zone 4 on restricted days (when winds favor Zone 1), suggests they are beneficial in further safeguarding Zone 1, aligning with the wind-based regulation's objective. However, the unintended increase in fires in Zone 4 on non-restricted days signals a need for a refined approach that considers the collateral effects of these regulations outside their primary focus area. This calls for a balanced policy framework that maintains the protective measures for Zone 1 while mitigating adverse outcomes in Zone 4.

Second, we further examine the impact of wind-based restrictions in Zone 4 on Zone 1's air quality, in light of the new tighter burning regulations. We observe a significant improvement in air quality in Zone 1, with reductions in pollution levels ranging between 1.9% to 4.8%, following the implementation of these regulations. This improvement is particularly notable when analyzing data outside the harvest season, a period without wind-based regulations, which highlights the significant role of wind direction in transporting smoke and pollutants from Zone 4 (west) to Zone 1 (east). During the non-harvest season, in the absence of wind restrictions, the prevailing westerly winds facilitate the transfer of air pollution from Zone 4 to Zone 1. However, during the harvest season, when wind-based regulations are in effect, we document a clear decrease in pollution exposure in Zone 1, underscoring the efficacy of these regulations in not only reducing fire occurrences but also significantly improving air quality in Zone 1. These findings support the argument that the new burning regulations, by imposing stricter controls on burning activities in Zone 4 during wind-restricted periods, offer air quality benefits to Zone 1, thereby achieving their intended protective effect.

Third, we explore whether the change in pollution levels disproportionately affects highly vulnerable communities within Zone 1 and Zone 4. We use the CDC Social Vulnerability Index to classify whether a census tract is highly vulnerable. Our results indicate that on days with wind restrictions when the wind is directed towards Zone 1, all communities in Zone 1 see improvements in air quality, with the most significant benefits observed among the highly vulnerable populations. This result imply the policy's effectiveness in safeguarding the most susceptible groups in Zone 1 against pollution. However, this protective effect contrasts with the situation in Zone 4 on non-restricted days when the wind is oriented towards Zone 4, where we note an increase in pollution levels. Notably, the highly vulnerable communities in Zone 4 face increased pollution exposure compared to their less vulnerable counterparts, suggesting an unintended redistributive effect of the policy that may exacerbate vulnerabilities in Zone 4. Given Zone 4's much smaller population, this increase in pollution highlights a critical equity issue, as the policy's unintended consequences disproportionately affect a smaller, yet highly vulnerable segment of the population. These findings highlight the necessity for tailored adjustments to mitigate adverse consequences on Zone 4's highly vulnerable populations, despite its smaller population size.

Our paper makes three key contributions. First, to the best of our knowledge, this is the first paper to develop plausibly causal estimates of the impacts of the 2019 Florida burning policy changes on sugarcane burning practices and air quality. Prior studies on Florida's sugarcane burning, primarily grounded in atmospheric science, have focused on mapping the geographic spread and health implications of these fires through atmospheric dispersion modeling and emissions simulations (Nowell et al., 2018, 2022). Notably, Nowell et al. (2022) show that sugarcane burning is associated with 1-5 annual mortalities due to particulate matter exposure, with the highest mortality risk located within the main sugarcane-growing region. This study also highlights the disproportionate effect of burning smoke on lower-income and minority communities, exacerbated by wind direction-based regulations. In contrast, we use a causal inference design to assess the effects of regulatory changes on burning activities. We show the introduction of stricter regulations, enhancing the wind direction criteria, effectively reducing air pollution in the wealthier, densely populated eastern regions (Zone 1) by limiting burning in the primary sugarcane cultivation area (Zone 4). However, this approach inadvertently places a greater pollution burden on the disadvantaged communities within the sugarcane production zones, revealing a paradox where regulatory intentions to protect may accidentally exacerbate existing inequalities.

Second, this paper contributes to the literature about the distributional impacts of environmental policies. The new burning regulations, by imposing stricter controls on burning activities in Zone 4 during wind-restricted periods, offer substantial air quality benefits to Zone 1 but intensify the pollution burdens on the already disadvantaged communities within the sugarcane production areas of Zone 4. These findings are consistent with findings by Mohai et al. (2009), which suggest discriminatory siting by firms or governments, influenced by race or other demographic factors, can create disparities in pollution exposure. Building on this dialogue, Hernandez-Cortes (2023) studies sugarcane burning in Mexico, the world's sixth-largest sugarcane exporter, highlighting that incomplete environmental regulation can increase the number of fires and pollution in disadvantaged areas. Our paper identifies another source of environmental justice: discriminatory wind-based regulations. In the literature on environmental justice, poor places tend to be more polluted. Environmental justice consequences of environmental policies may exacerbate or decrease the pollution in poor communities (Currie et al., 2023; Fullerton and Muehlegger, 2019; Hernandez-Cortes, 2023; Hernandez-Cortes and Meng, 2023; Holland et al., 2019). The findings of this study underscore that uniform tighter regulations may fail to alleviate and even exacerbate the environmental burdens on economically disadvantaged communities. This paradox arises from the regulations' inability to account for the historical and systemic discrimination that predisposes these communities to higher pollution levels. As Hernandez-Cortes and Meng (2023) articulate, solving environmental justice issues necessitates policies crafted to mitigate the specific inequities contributing to disproportionate pollution impacts. In essence, this means that policies must go beyond a one-size-fits-all approach to specifically address the systemic inequities that lead to disproportionate pollution exposure among poor communities. Therefore, regulations may be tailored to correct the historical injustices to achieve improvements in pollution exposure and environmental health outcomes for all communities.

Third, this paper joins a growing literature that exploits pollution variation from wind patterns within the United States (Anderson, 2020; Deryugina et al., 2019; Rangel and Vogl, 2019; Schlenker and Walker, 2016). These studies use wind direction to model the spatial dispersion of air pollution emissions. Our paper extends this approach by recognizing wind direction as not only a factor influencing the diffusion of pollutants but also as a critical element of regulatory controls over the sugarcane burning practices in Florida. By analyzing wind patterns during both the harvest and non-harvest seasons, this study provides precise causal estimates of regulatory impacts, enriching our understanding of how environmental policies perform in specific agricultural settings.

The rest of the paper is laid out as follows. Section 2 presents the institutional features of Florida's sugar industry and burning regulations in Florida. Section 3 describes the data sources. Section 4 quantifies the effect of policy changes on burnings. Section 5 further demonstrates the impact of upwind restrictions on downwind air pollution. Section 6 examines whether the changes in pollution disproportionately affect highly vulnerable communities. Section 7 concludes and discusses the policy implications of the paper.

2. Background and Study Area

2.1 The big sugar companies

Florida is a national leader in sugarcane-based sugar production, accounting for approximately 50% of the United States' total sugar value in 2021. This sector significantly bolsters the state's economy, employing over 14,000 people and generating more than $800 million in annual income, with its total economic impact exceeding $2 billion (Palm Beach County Cooperative Extension, 2021). The industry's landscape is characterized by key players such as the U.S. Sugar Corporation and Florida Crystals Corporation, collectively responsible for 65% of the state's sugarcane cultivation. Additionally, the Sugarcane Growers Cooperative of Florida, representing local farmers, contributes 25% to the production. The remaining 10% of sugarcane is grown by independent farmers who then sell their sugarcane to these mills.

There have been some environmental justice discussions behind the sugarcane industry in Florida. For instance, residents in the sugarcane growing region have attempted to challenge the burning, and some even launched lawsuits in 2019 alleging that pollution from sugarcane burning damages health, but it has not been easy. The industry argues that air quality data demonstrate compliance with the Clean Air Act, countering claims of harmful pollution levels. However, a joint investigation by ProPublica and The Palm Beach Post in 2021 revealed that within the 400,000 acres of sugarcane fields, only one air quality monitor was installed, and notably it has been broken for eight years. Even assuming the air quality monitor was functional, the state and federal air monitoring surveillance systems failed to capture pollutants released by the smoke from cane burning.[1] Complicating matters, in 2021, the Florida Legislature enacted a bill that specifically inhibits residents from filing lawsuits against farmers for particle emissions, which includes emissions from sugarcane burns.[2] Finally, the lawsuit was dismissed in 2022 with prejudice, closing the door on future claims.

2.2 Why do they burn sugarcane?

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[1] See the investigation by ProPublica and The Palm Beach Post https://projects.propublica.org/black-snow/

[2] See the recent report on sugarcane burning lawsuit dropped by Florida residents https://www.palmbeachpost.com/story/news/local/2022/02/26/glades-residents-drop-sugarcane-burning-lawsuit-against-sugar-growers/6944816001/

In Florida, pre-harvest burning of sugarcane fields is a common practice aimed at removing the leaves and tops, thereby facilitating the harvest of the sugar-dense stalks. Every year from October through April, about 10,000 sugarcane fields of over 440,000 acres are burned around the Everglades Agricultural Area (EAA) to minimize the biomass transported to mills and streamline the sugar extraction process (Baucum and Rice, 2009). Burning sugarcane fields reduces the energy expenditure of the farmers, eliminates unnecessary wear of field and factory machinery, decreases the amount of material that factories process, and shortens the harvest season by 10% (Carney et al., 2000).

An alternative to burning is the green harvest technique, which uses mechanical harvesters to separate the leaves and tops from the stalks without burning. Brazil, as the world's primary sugarcane producer, has adopted this method to alleviate the respiratory health issues caused by pre-harvest burning. The adoption has led to improved air quality and has facilitated the production of renewable energy from biomass, which has generated considerable profits (Gonzalez, 2022).

The decision to burn sugarcane primarily hinges on economic considerations. Leaving the extraneous leafy material on the canes results in the transport of greater quantities to the processing plant, necessitating increased trips and prolonged processing time, which incurs higher costs. Alternative practices, such as green harvesting methods that involve on-site removal of the debris, demand additional machinery and labor, thereby reducing profit margins. Nonetheless, the sugarcane industry in Florida remains averse to adopting measures that would increase production costs, maintaining that such expenses would inevitably be passed on to consumers (Nebeker, 2021).

2.3 Regulatory Framework for Sugarcane Burning in Florida

The Florida Forest Service has pioneered conservation through controlled, prescribed fires. Every pre-harvest burn requires a burn permit for each field where the burn will occur, and permits are granted only on the day of harvest. On the day that farmers want to burn, they must contact the local Florida Forest Service office and request a burn authorization. Its approval depends on a comprehensive review of weather conditions. During harvest season, sugarcane fields are burned in small areas - 40 acres at a time. Geographically, these controlled burns are concentrated around the southern periphery of Lake Okeechobee, particularly near the communities of Belle Glade, Clewiston, and Pahokee. The proximity of these activities ranges from 10 to 40 kilometers from the densely populated coastal cities of South Florida, where the population exceeds 6 million residents (Nowell et al., 2022). For a visual representation of the areas affected by sugarcane burning and the location of controlled burns relative to populated areas, see Figure A1 in the Appendix, adopted from Nowell et al. (2022).

Since 1991, regulatory practices governing sugarcane burning in Florida have been contingent upon wind direction to protect populated areas, particularly in eastern Palm Beach County. The delineation of burning zones, as illustrated in Figure 1[3], reflects a disparity in the stringency of restrictions applied. In Zone 1, located eastward, regulations are most stringent, prohibiting burning when winds blow from the NNW to the SSW. This range of directions, all westwardly oriented, ensures that when winds could carry pollutants toward Zone 1, burning activities are halted, safeguarding these communities from pollution. In contrast, Zone 4, which lies to the west near the bulk of sugarcane fields, is afforded less protection. Notably, when winds from the NW, W, or SW exceed 15 miles per hour, a specialized technique known as a backing fire[4] is mandated in Zone 4. These wind-based regulations, tailored specifically for sugarcane burning, aim to prevent pollutant transport to the east by westerly winds. However, they do not offer equivalent protections when winds could direct pollutants toward Zone 4.

On October 1, 2019, Agriculture Commissioner Nikki Fried introduced comprehensive reforms to Florida's prescribed burning regulations, aimed at enhancing public safety and environmental protection. These modifications include the integration of the Air Quality Index (AQI) into burn authorization decisions, the deployment of advanced software for improved wildfire response and public access to fire maps, and the enhancement of smoke plume prediction with updated weather models. Specifically concerning sugarcane burning, the new regulations introduce several significant changes: an 80-acre buffer zone requirement on dry, windy days to mitigate wildfire risks; a prohibition on nighttime burns without express

Figure 1. The geographic map of the sugarcane burning zones during 1992-2020

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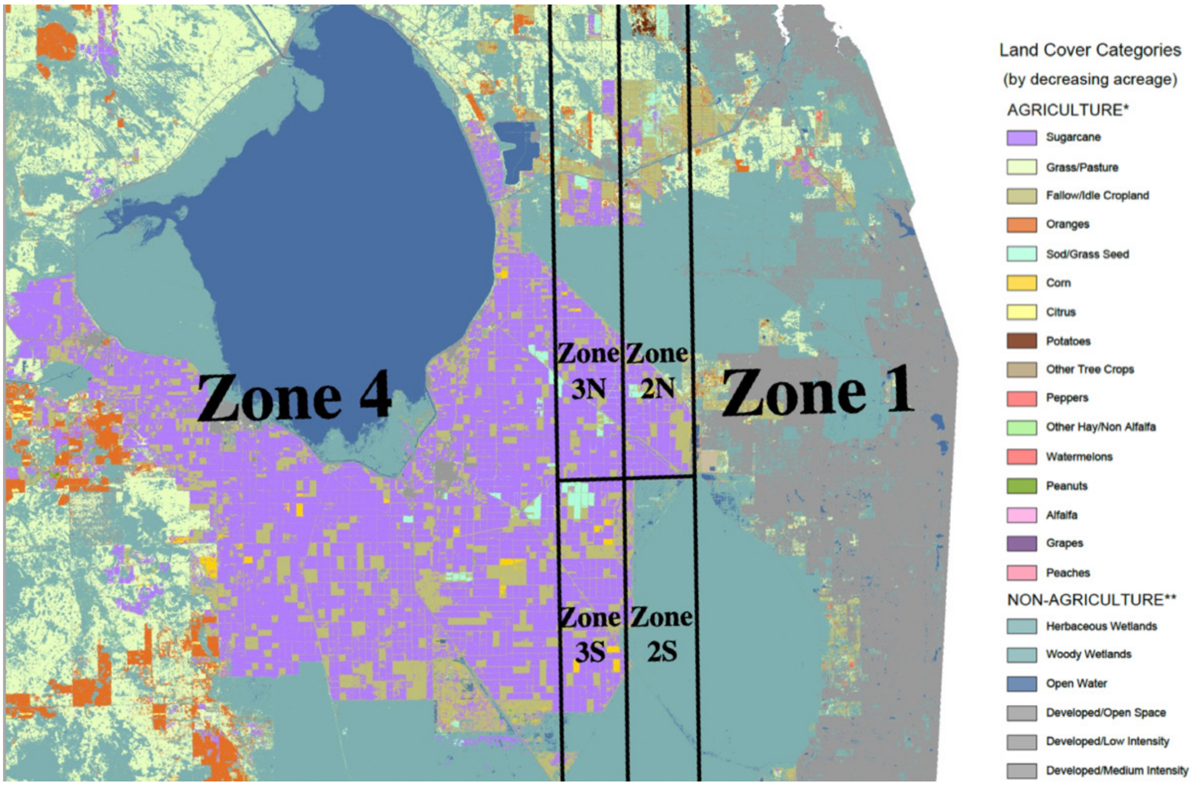
[3] Figure 1 is from the Stop the Burn Campaign website obtained from a U.S. Sugar Handout Circa https://drive.google.com/file/d/0B50HBF5vaoScdHJIWmtUejVOYzVjNEtoSXg4MlJudkRuV1Qw/view?resourcekey=0-CsxLYbavq4eyBh6IY1lfTQ

[4] Backing fire is a fire spreading against the wind. The flames tilt away from the fire's direction of spread.



Notes: There are 358 census tracts in Zone 1, 2 census tracts in Zone 2, 1 census tract in Zone 3, and 33 census tracts in Zone 4. The empirical analysis includes all the census tracts in Zone 1 and Zone 4.

permission; a ban on burning under fog advisories before 11:00 am to facilitate better smoke dispersion; and a reduction in the timeframe for muck fire suppression from 96 to 72 hours. While the geographical boundaries of the burn zones remain unchanged, these rules now incorporate AQI and Dispersion Indices to minimize smoke exposure across all communities. These 2019 updates represent a pivotal shift towards stricter regulation of sugarcane burning practices, maintaining wind-based considerations but prioritizing air quality and public health (The Florida Department of Agriculture and Consumer Services, 2021).

3. Data

To assess the impact of the recently enhanced burning regulations on fire incidence and air quality, I construct a daily panel dataset at the census tract level, covering the period from October 2012 to September 2021. This dataset combines remote sensing data on fire counts and air pollution with weather metrics from multiple sources.

3.1 Fires data

The primary data source for daily fire occurrences is the Active Fire Product from NASA’s Visible Infrared Imaging Radiometer Suite (VIIRS) with a 375 m resolution. This product records all fires starting in 2012, detects fires in a 375m x 375m grid, and provides the centroid of the pixel with a fire event. The VIIRS product is notable for its hotspot detection capabilities and enhanced spatial resolution, which is particularly effective in identifying fires in smaller areas. Given that pre-harvest sugarcane burns are controlled to cover roughly 40 acres each time, one VIIRS pixel can represent around one burn event. Additionally, I restrict the fires from October to April to cover the entire sugarcane burning season.

The burning authorization data, sourced from the Florida Forest Service Reporting System, provides daily summaries of the number and total acres of authorized open burns by burn type for each county in Florida, starting from January 20, 2012. A critical limitation in our analysis is the lack of spatially disaggregated burning authorization data, which prevents a direct evaluation of the stringent regulation's impact on the number of authorized fires. Consequently, to approximate the scale and distribution of burning events, this study employs NASA's VIIRS 375 m resolution fire data. By leveraging the VIIRS dataset, we reconstruct a proxy for the observed burning activities, representing the most comprehensive approach feasible given the data limitations. This methodological choice underscores the innovative use of remote sensing data to infer patterns of sugarcane burning in the absence of more granular authorization records.[5]

3.2 Sugarcane coverage data

Except for focusing on the harvest period, to identify the sugarcane fires, I use the Cropland Data Layer, which is a crop-specific land cover data layer created annually for continental States by the U.S. Department of Agriculture. It provides annual crop acreage at every 30-by-30 meter pixel in the U.S. So, I can classify sugarcane fires by identifying whether a fire event happens inside a sugarcane field.

3.3 Weather data

The issuance of permits for sugarcane burning in Florida is contingent upon specific weather conditions on the day of the burn, which include wind direction and speed, as well as the broader atmospheric conditions. To capture the effect of these weather conditions, I collect

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[5] We compiled daily summaries of authorized burns from the Florida Forest Service Reporting System, detailing the number and acres of burns by type across Florida counties since January 20, 2012. Figure A2 shows the trend of these authorizations over time. Data on authorized fires are aggregated at the county-date level, spanning seven counties over 1,910 days. There is no striking discontinuity in authorized fires before and after Oct 1, 2019, as shown in Figure A2.

comprehensive daily weather data, including temperature, precipitation, wind direction and speed, humidity, and visibility, from Visual Crossing Weather Data.[6]

The acquired weather data is matched to the fire occurrence data at the census tract level for each day. This matching process involves aligning each fire event recorded in the study period with corresponding weather conditions specific to the location and day of the fire. By using the TIGER census tract boundary files in Visual Crossing's Query Builder, the study ensures that the interpolated weather data is accurately localized to the precise census tract of each fire event.

3.4 Pollution data

While using data from pollution monitors would ideally provide a precise spatial and temporal analysis of air quality, the distribution of these monitors is notably sparse, particularly in South Florida. In this region, there is only one air quality monitor in proximity to the sugarcane fields, as depicted in Figure A1.[7] Consequently, this study draws upon the methodology of the remote sensing literature, which offers alternative approaches for assessing air quality in areas with limited monitor coverage (Gendron-Carrier et al., 2022; Gupta et al., 2006; Hernandez-Cortes, 2023; Kumar et al., 2011; Van Donkelaar et al., 2010). Specifically, we use aerosol optical depth (AOD) data as a measure of air quality, leveraging its capability to provide a quantitative estimation of atmospheric aerosol concentrations and serving as an indirect indicator for surface PM2.5 levels. This AOD information, sourced from Google Earth Engine, is available at a 1 km grid resolution starting from 2012.

The daily AOD data is then aggregated to the census tract level, using raw averages. This approach, while straightforward, acknowledges the limitation that AOD values represent aerosol concentrations resulting from both anthropogenic activities and natural events, not solely attributable to sugarcane burning. Despite these constraints, AOD data represents the

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[6] Visual Crossing employs a sophisticated interpolation technique to amalgamate multiple proximate weather reports into a singular, hourly dataset. This method is particularly advantageous for areas that are distant from major reporting stations or possess unique geographical features that induce microclimatic variations within short distances. The interpolation process ensures the generation of weather observations that accurately reflect the conditions of each requested location, especially beneficial for areas better served by the integration of data from several weather stations. See more descriptions here:
https://www.visualcrossing.com/resources/documentation/weather-data/how- historical-weather-data-is-updated/

[7] In Figure A1, the U.S. EPA monitoring sites are indicated in yellow boxes with dots in the center. Belle Glade is the only location within the sugarcane growing region that has a PM2.5 monitor.

most feasible option for this study, given the limited availability of ground-level pollution monitors.[8]

3.5 Socioeconomic characteristics

To see whether highly vulnerable communities experience higher pollution levels, I use the census tract-level data on the Social Vulnerability Index developed by the Centers for Disease Control and Prevention. Social vulnerability is a factor that affects a community's ability to prevent human suffering and financial loss in a disaster. The index ranks the census tracts on 15 social factors, including poverty, employment, minority status, and disability, and further groups them into four related themes: Socioeconomic, Household Composition & Disability, Minority Status & Language, and Housing Type & Transportation. Then, each census tract receives a separate ranking for each of the four themes and an overall ranking. In this study, we consider the overall tract ranking.[9] The tract rankings are based on percentiles, and percentile ranking values range from 0 to 1, with higher values indicating greater vulnerability. The Census Tracts in the top 10%, i.e., at the 90th percentile of values, are given a value of 1 to indicate high vulnerability. Tracts below the 90th percentile are given a value of 0 (Centers for Disease Control and Prevention, 2018). Figure 2 shows the spatial distribution of overall vulnerability across census tracts, presented as percentile rankings. It reveals that census tracts located near the sugarcane fields, which are primarily located in Zone 4, exhibit significantly higher levels of vulnerability compared to those located farther away.

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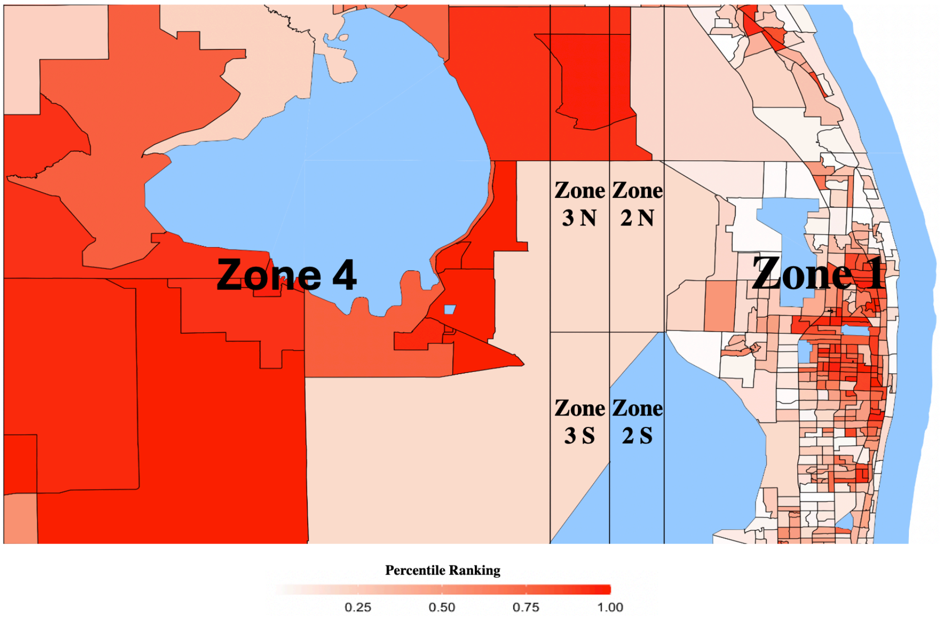
[8] Nowell et al. (2022) use the HYSPLIT atmospheric dispersion model, satellites, and surface measurements to simulate PM2.5 concentrations directly associated with sugarcane burning events.

[9] To get the overall tract rankings, they sum the sums for each theme, order the tracts, and then calculate overall percentile rankings.

Figure 2. Spatial distribution of overall tract rankings



3.6 Summary statistics

Table 1 presents summary statistics for the characteristics of Zones 1 and 4 in the period leading up to the imposition of stringent burning regulations in 2019. The population size, as evidenced by 2014-2018 ACS estimates, is much greater in Zone 1. In stark contrast, Zone 4 surpasses Zone 1 in terms of sugarcane acreage and the frequency of fires. The greater number of burning events in Zone 4 does not translate to a significant disparity in daily AOD levels between the two zones.[10] However, the AOD levels during the sugarcane harvesting season are greater than 200, surpassing the mean AOD reported for most U.S. cities as shown in Figure A3. Furthermore, Zone 4 exhibits higher levels of vulnerability across all measures of the social vulnerability index. These disparities underscore the targeted nature of wind-based burning regulations that historically have favored Zone 1, where the population is denser. Such regulatory focus highlights the unequal distribution of environmental safeguards between the more populous Zone 1 and the agriculturally intensive yet more vulnerable Zone 4.

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[10] High AOD values indicated a relatively hazy atmosphere, while low values of AOD indicate a relatively clear atmosphere.

Table 1: Summary Statistics

Variable	Zone 4	Zone 1	Difference
Population size	149,899	1,564,249	-1,414,350
Acreage of sugarcane	205,077	3613	201,464***
	(18837)	(2852)	(0.000)
Share of sugarcane area in	0.302	0.064	0.238***
total area of agriculture	(0.031)	(0.053)	(0.000)
Daily total fires	0.181	0.001	0.180***
	(1.208)	(0.127)	(0.000)
Daily AOD level	205.067	206.183	-1.116*
	(122.171)	(114.312)	(0.091)
SV overall ranking	0.747	0.409	0.338***
	(0.275)	(0.304)	(0.000)
SV Socioeconomic ranking	0.802	0.395	0.407***
	(0.191)	(0.297)	(0.000)
SV Household Composition &	0.663	0.422	0.241***
Disability ranking	(0.228)	(0.243)	(0.000)
SV Minority Status &	0.627	0.489	0.138***
Language ranking	(0.305)	(0.279)	(0.000)
SV Housing Type &	0.684	0.433	0.251***
Transportation ranking	(0.315)	(0.296)	(0.000)

Notes: This table reports the mean of variables in pretreatment periods (2012-2018). For columns 1 and 2, standard deviations are in brackets. For column 3, the p-value for the t-test of equal means of two groups is in parentheses. Gendron-Carrier et al. (2022) report the nominal scale of AOD reported by MODIS is 0-5,000, and they rescale to 0-5 for legibility, as is common in the literature. In the table, AOD is not rescaled. The last five rows are the mean of the CDC Social Vulnerability Index for the four themes and its overall position in 2018. The rankings are based on percentiles and range from 0 to 1, with higher values indicating greater vulnerability. *** $p<0.01$; ** $p<0.05$; * $p<0.10$.

4. Effects of policy changes on sugarcane burning practices

This study evaluates the impact of stringent burning regulations introduced in October 2019 on burning behaviors within sugarcane-growing regions of Florida. The key research question is to what extent the updated regulations, which complement existing wind-based restrictions, influence burning practices. Given the absence of detailed authorized fire data, we rely on satellite-derived fire observations as a proxy to examine farmers' adaptation to the new regulations. The identification strategy involves a difference-in-differences (DD) framework to assess the aggregate-level policy impact, followed by a triple difference (DDD) estimation to capture the differential effects across sugarcane burning zones.

The DD model serves as a preliminary analysis, quantifying the average effect of policy changes on the number of observed fires before proceeding to a zone-specific analysis. The estimation equation is:

$$\begin{aligned} Y_{idmt} = {} & \alpha_0 + \alpha_1 \times WindRestrict_{idmt} + \alpha_2 \times Post_{idmt} \\ & + \alpha_3 \times WindRestrict_{idmt} \times Post_{idmt} + \lambda W_{idmt} + \gamma_i + \rho_m + \mu_t + \epsilon_{idmt} \end{aligned} \tag{1}$$

where Y_{idmt} represents the number of observed fires in census tract i on date d, month m, year t during the harvest season. $WindRestrict_{idmt}$ is a binary variable that equals 1 if the daily wind direction in census tract i falls within the NNW to SSW range. The wind direction, measured in degrees from north, is categorized from 0° (north) to 360° (north again), with $WindRestrict_{idmt}$ set to 1 for angles between 202.5° and 337.5°, aligning with the wind direction constraints. $Post_{idmt}$ is a dummy equals 1, representing the period following October 1, 2019. To capture the potential influence of weather on both burning permits and measured pollution levels, the model incorporates a matrix of weather controls W_{idmt}, including daily temperature, precipitation, wind speed, humidity, and visibility in each census tract. The vector γ_i contains census tract fixed effects to control for any time-invariant characteristics in a census tract. The vector μ_t are year-fixed effects and ρ_m are month-of-year fixed effects to control for seasonality in harvesting activities. The coefficient of interest is α_3 , which shows the difference-in-differences estimate of the additional impact of the stringent regulations on burning behavior when wind restrictions are in place.

Table 2 shows the DD estimates. Columns (1)-(3) indicate a significant 29%-35% reduction in daily observed fires following the implementation of the 2019 regulations, particularly on days with wind restrictions. This effect is robust despite the known challenges of satellite detection of sugarcane fires, as documented by Nowell et al. (2018). Additionally, Columns (4)-(6) reveal a modest but consistent 3.3%-6.4% decrease in AOD levels, aligning with the observed reduction in fire events and suggesting an improvement in air quality attributable to the policy changes. Collectively, these results, before distinguishing the effects by zone, support the policy's objective to tighten burning restrictions and enhance overall air quality.

Table 2: Policy effect on fires and AOD levels (DD) at the aggregate level

	TF	TF	TF	logAOD	logAOD	logAOD
Wind Restriction	-0.002	-0.001	-0.001	-0.087***	-0.087***	-0.079***
	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)	(0.003)
Post	0.002	0.002	-0.006*	-0.045***	0.044***	0.223***
	(0.003)	(0.003)	(0.004)	(0.005)	(0.003)	(0.007)
Wind Restriction x Post	-0.006***	-0.006***	-0.005**	-0.064***	-0.033***	-0.045***
	(0.003)	(0.002)	(0.002)	(0.004)	(0.004)	(0.004)
Adj. R^2	0.094	0.094	0.094	0.322	0.364	0.371
Pre dep mean	0.017	0.017	0.017	5.152	5.152	5.152
Census FE	Yes	Yes	Yes	Yes	Yes	Yes
Month FE		Yes	Yes		Yes	Yes
Year FE			Yes			Yes

Notes: TF denotes the number of daily observed total fires. The entries in columns (1) to (3) in Table 2 are coefficient estimates from the DD estimator in equation (1), where the dependent variable is the number of daily observed total fires in each census tract x day x year. The number of observed fires is reconstructed by combining Satellite remote sensing data (VIIRS 375m and Cropland Data Layer) and census tract boundaries. Columns (4) to (6) are coefficient estimates from the DD estimator in equation (1), where the dependent variables are daily AOD levels, measured in log. The regression includes detailed weather controls: daily temperature, precipitation, wind speed, wind gust, humidity, and visibility. Additional controls are listed at the bottom of Table 2. The number of observations is 599,697 in columns (1)-(3) and 345,058 in columns (4)-(6). Standard errors, clustered at the census tract level, are in parentheses. *** p<0.01; ** p<0.05; * p<0.10.

Having established the average effects of the policy changes using the DD framework, I use the DDD estimator to address potential confounders that may vary over time and differ between Zones 1 and 4. The DDD estimator enhances the robustness of our findings by incorporating an additional layer of comparison. It controls for time-variant factors that could differentially influence the outcomes between the more protected Zone 1, comprising 358 census tracts, and the less protected Zone 4, with 33 tracts. The DDD estimator takes advantage of three sources of variation: the temporal changes before and after the policy implementation in October 2019, the differential levels of protection across zones, and the conditional effects of wind restrictions based on specific wind directions. I proceed with the following DDD regression:

$$\begin{aligned} Y_{idmt} = {} & \beta_0 + \beta_1 \times WindRestrict_{idmt} + \beta_2 \times Post_{idmt} \\ & + \beta_3 \times WindRestrict_{idmt} \times Post_{idmt} + \beta_4 \times WindRestrict_{idmt} \times Zone4_i \\ & + \beta_5 \times Zone4_i \times Post_{idmt} + \beta_6 \times WindRestrict_{idmt} \times Zone4_i \times Post_{idmt} \\ & + \lambda W_{idmt} + \gamma_i + \rho_m + \mu_t + \epsilon_{idmt} \qquad (2) \end{aligned}$$

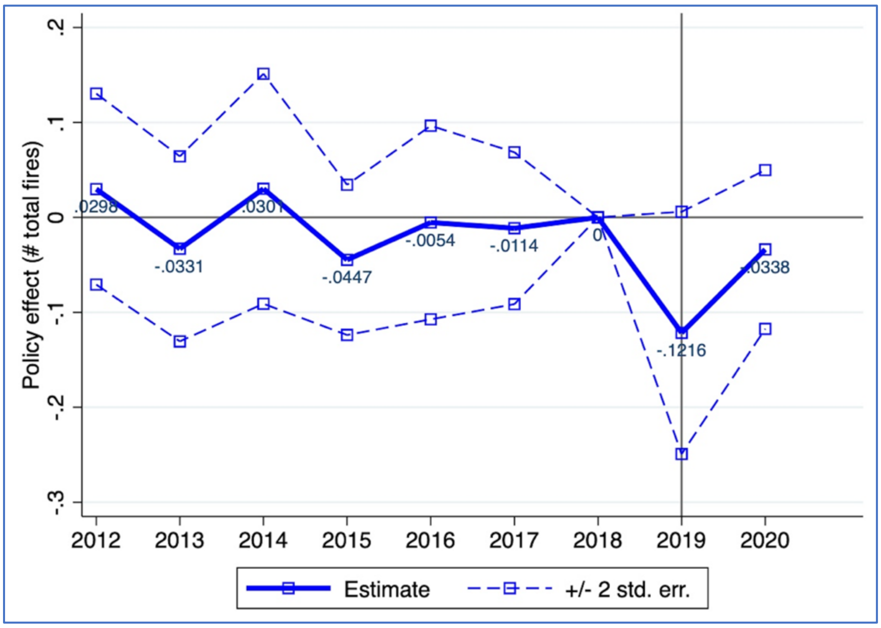
The notations are the same as before. The variable Y_{idmt} denotes the number of observed fires within census tract i on date d, month m, year t during the harvest season. The variable $WindRestrict_{idmt}$ is defined as a binary variable that equals 1 if the daily wind direction in census tract i ranges between 202.5° and 337.5°, thus spanning from SSW to NNW. $Post_{idmt}$ is a dummy variable that indicates the post-policy period, equals 1 for dates following October 1, 2019. The weather-related controls W_{idmt}, include daily temperature, precipitation, wind speed, humidity, and visibility in each census tract. The vector γ_i contains census tract fixed effects to control for any time-invariant characteristics in a census tract. The vector μ_t are year-fixed effects and ρ_m are month-of-year fixed effects to control for seasonality in harvesting activities. Our analysis uses a balanced panel of census tract-day-month-year. The standard errors are clustered at the census tract level to account for serial correlation. The parameter of interest is β_6, associated with the triple interaction term, which captures the differential impact of the policy within Zone 4 compared to Zone 1, specifically on days affected by wind restrictions versus those without, and in the context of the post-policy era versus the pre-policy period.

To have a causal interpretation, the triple difference estimator requires the assumption that Zone 1 and Zone 4 exhibit similar outcome trends in the absence of the 2019 policy changes. To test the validity of the common trend assumption, the separate measures of the policy's effects in each year provide additional information. Hence, I report the parameters γ_{6t} from the following model in the event study style graph in Figure 3:

$$\begin{aligned} Y_{idmt} = {} & \gamma_0 + \gamma_1 WindRestrict_{idmt} + \sum_{t=2012}^{t=2020} \gamma_{2t}\, Year_t \\ & + \sum_{t=2012}^{t=2020} \gamma_{3t} WindRestrict_{idmt} \times Year_t + \gamma_4 WindRestrict_{idmt} \times Zone4_i \\ & + \sum_{t=2012}^{t=2020} \gamma_{5t} Zone4_i \times Year_t + \sum_{t=2012}^{t=2020} \gamma_{6t} WindRestrict_{idmt} \times Zone4_i \times Year_t \\ & + \lambda W_{idmt} + \gamma_i + \rho_m + \mu_t + \epsilon_{idmt} \end{aligned} \tag{3}$$

where $Year_t$ indicates a set of year dummies for 2012-2020. To be consistent with the definition of $Post_{idmt}$, $Year_t$ is redefined to accommodate the sugarcane harvest period: for

Figure 3. DDD dynamic policy effect on # fires



Notes: The estimates in Figure 3 are from the event study regressions for the daily total number of fires (measured in the count and observed at census tract x day x year) in equation (3) where the estimates for the year 2018 are restricted to have a value of 0. The regression includes detailed weather controls, census tract fixed effects, and month-of-year fixed effects. The standard errors underlying the confidence intervals (dashed lines) are clustered at the census tract level. The p-value of the F-test for testing the joint significance of the pre-trend coefficients is 0.3475, which indicates a lack of pre-trend.

months from October to December, $Year_t$ is the actual calendar year of the given date d; for months from January to April, $Year$ is assigned to the preceding year, reflecting the continuation of the harvest season that began in the previous October.

Figure 3 shows an event study graph measuring the difference between the daily count of observed fires in Zone 4 and Zone 1 on days with wind restrictions and without wind restrictions separately by year, with the year 2018 normalized to take the value zero. Based on Figure 3, the coefficient for the interaction term between $Year_t$, $WindRestrict_{idmt}$, and $Zone4_i$ prior to 2019 are not statistically significant, which indicates a lack of pre-trends, and may suggest parallel trends hold. Thus, Figure 3 supports the validity of DDD estimation.

Table 3 presents the impacts of the 2019 burning regulations through a DDD estimation as shown in equation (2). The results reveal a significant reduction in the daily number of observed fires in Zone 4 by approximately 0.075 on average on days when wind restrictions are active, relative to Zone 1. This reduction corresponds to a 41% decrease in the daily observed fires in Zone 4. Figure 3 underscores that the policy's dampening effect on fire occurrences was particularly pronounced in 2019. The subsequent year, marked by the onset of the COVID-19 pandemic, shows a diminished policy effect, which remains difficult to interpret within the limited post-policy period available for analysis. A notable pattern emerges

Table 3: Impact of policy change on daily observed fires (DDD)

	TF	TF	TF
Wind Restriction	-5.4**	-4.3**	-4.1*
	(2.4)	(2.2)	(2.1)
Post	-3.9***	-3.6**	-13.1***
	(1.3)	(1.4)	(4.2)
Wind Restriction X Post	0.01	0.05	0.26
	(0.57)	(0.63)	(0.71)
Wind Restriction X Zone4	39.6***	39.3***	39.2***
	(12.0)	(12.0)	(12.0)
Zone4 X Post	44.6**	43.7**	44.9**
	(21.4)	(21.5)	(21.6)
Wind Restriction X Zone4 X Post	-75.0**	-75.1**	-75.1**
	(31.6)	(31.6)	(31.6)
Adj. R^2	0.094	0.094	0.095
Pre dep mean	0.181	0.181	0.181
Census FE	Yes	Yes	Yes
Month FE		Yes	Yes
Year FE			Yes

Notes: TF denotes the number of daily observed total fires. The coefficient estimates in all entries are multiplied by 1000 for readability. The entries in Table 3 are coefficient estimates from the DDD estimator in equation (2), where the dependent variables are the number of daily observed total fires in each census tract x day x year. The regression includes detailed weather controls: daily temperature, precipitation, wind speed, wind gust, humidity, and visibility. Additional controls are listed at the bottom of Table 3. The number of observations is 599, 697. Standard errors, clustered at the census tract level, are in parentheses. *** p<0.01; ** p<0.05; * p<0.10.

where fire occurrences in Zone 4 decline on days with wind restrictions but exhibit an increase on days without such restrictions (i.e. the estimated coefficients for $Zone4_i \times Post_{idmt}$ are positive and statistically significant). This pattern could suggest a strategic response from farmers, adjusting their burning practices to days exempt from regulatory constraints. In contrast, Zone 1 experiences a consistent reduction in fire events, irrespective of wind conditions. These results imply that the updated regulations do not extend additional protective measures to Zone 4. Moreover, the findings raise concerns about the directional focus of smoke dispersal resulting from the wind-based regulations. Specifically, it appears that the augmented regulations may inadvertently exacerbate exposure for Zone 4, a region already disadvantaged by historical policy decisions. The results are consistent with the patterns identified by Nowell et al. (2022), where preferential smoke direction due to wind-based regulations disproportionately affected less affluent, smaller inland communities. Table A1 presents the results of the falsification test where we restrict the sample to months outside the sugarcane harvest season (May-September) from 2013 to 2021. There is no significant difference in the number of fires between Zone 4 and Zone 1 during the non-harvest season following the implementation of the policy changes.

5. Assessing air quality in Zone 1: downwind impacts of new burning regulations

The wind-based regulations for sugarcane burning are strategically designed to protect the more densely populated communities in Zone 1, especially on days when the wind carries the potential for smoke and particulates from Zone 4 directly toward them. Intriguingly, our previous results reveal a decrease in the number of fires in Zone 4 on wind-restricted days, which are the days when Zone 1 is downwind and most vulnerable to the effects of burning. Given Zone 1's position as the downwind recipient of air pollution on such days, it is crucial to investigate the air quality impacts in this region following the introduction of the new regulations. To answer this question, we first calculate the proportion of census tracts in Zone 4, that is, $\frac{\sum_{i\in Zone4}\text{WindRestrict}_{idmt}}{33}$, where 33 is the number of census tracts in Zone 4. Then I estimate the following equation:

$$\begin{aligned} Y_{idmt}^{Zone1} = \delta_0 + \delta_1 \times \overline{WR_{idmt}^{Zone4}} + \ \delta_2 \times Post_{idmt} + \delta_3 \times \overline{WR_{idmt}^{Zone4}} \times Post_{idmt} \\ + \lambda W_{idmt} + \gamma_i + \rho_m + \mu_t + \epsilon_{idmt} \end{aligned} \tag{4}$$

where Y_{idmt}^{Zone1} is the daily AOD level in census tract i in Zone 1 on date d, month m, year t. $\overline{WR_{idmt}^{Zone4}}$ is the proportion of census tract in Zone 4 that have wind restrictions on date d.[11] $Post_{idmt}$ is a dummy variable that indicates the post-policy period, equals 1 for dates following October 1, 2019. The weather-related controls W_{idmt}, include daily temperature, precipitation, wind speed, humidity, and visibility in each census tract. The vector γ_i contains census tract fixed effects to control for any time-invariant characteristics in a census tract. The vector μ_t are year-fixed effects and ρ_m are month-of-year fixed effects to control for seasonality in pollution levels. The parameter of interest is δ_3, which describes the marginal effect of policy changes on the daily AOD levels in Zone 1.

Table 4 reveals a reduction in daily Aerosol Optical Depth (AOD) levels ranging from 1.9% to 4.8% relative to pre-policy levels. Notably, the estimated coefficients for $\overline{WR_{idmt}^{Zone4}}$ are negative and statistically significant, suggesting that on days when wind restrictions are

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[11] The equation does not include the wind direction in census tract i because it is highly correlated with $\overline{WR_{idmt}^{Zone4}}$.

Table 4: DD policy effect on downwind pollution

	logAOD	logAOD	logAOD
Post	-0.062***	0.043***	0.235***
	(0.007)	(0.004)	(0.007)
$\overline{WR^{Zone4}_{idmt}}$	-0.085***	-0.097***	-0.083***
	(0.003)	(0.003)	(0.003)
$\overline{WR^{Zone4}_{idmt}}$ X Post	-0.048***	-0.019***	-0.042***
	(0.006)	(0.006)	(0.006)
N	311,718	311,718	311,718
Adj. R^2	0.309	0.349	0.547
Census FE	Yes	Yes	Yes
Month FE		Yes	Yes
Year FE			Yes

Notes: The entries in Table 4 are coefficient estimates from the DD estimator in equation (4), where the dependent variable is the number of daily AOD levels in each census tract x day x year measured in log in Zone 1. The regression includes detailed weather controls: daily temperature, precipitation, wind speed, wind gust, humidity, and visibility. Standard errors, clustered at the census tract level, are in parentheses. *** p<0.01; ** p<0.05; * p<0.10.

enforced in Zone 4, there is a decrease in the average AOD levels in Zone 1 compared to the baseline. These findings underscore the effectiveness of wind-based restrictions in mitigating air pollution in Zone 1. However, the observed decrease in pollution on restricted days may be accompanied by a potential increase on days without restrictions. This pattern may reflect a strategic response from farmers in Zone 4, who adjust their burning practices to circumvent the regulatory constraints, potentially leading to higher pollution levels in Zone 1 on these unrestricted days. Such a phenomenon would constitute a violation of the Stable Unit Treatment Value Assumption (SUTVA), indicating that the intervention's effects might be indirectly influencing untreated units through behavioral changes among the regulated units.

To address the SUTVA concerns, some institutional knowledge might prove helpful. Sugarcane deteriorates at a quick rate, just like other perishable crops. The sugarcane must be processed into sugar in mills before trading and storing it. The unreasonable delays in cane transportation from the fields to the mill are frequently linked to several problems related to sucrose losses (Misra et al., 2022). Given the present milling capacity in South Florida, a full five months (October to March) are required to process approximately 400,000 acres planted to sugarcane. Some sugarcane must be harvested before achieving maximum sucrose levels to sustain early-season (October-November) milling operations (Gilbert et al., 2004). So each cane field is tied into an integrated harvesting schedule. If a sugarcane field does not get a burn permit approved on the day it is scheduled to be harvested, it is green-harvested so that the overall harvesting schedule is not interrupted (Ferguson, 2022).[12] The informal institutional knowledge may lessen the concerns of strategic shifting in response to wind restrictions. Despite the possibility that farmers may attempt to align burning practices with favorable wind directions, the complex rules of the new regulations, the capacity of mills, and the integrated harvesting schedule make strategic time shifting less possible.

Table A2 shows the results of the falsification test where I restrict the sample to the months outside the sugarcane harvest season (May-September), a period not subject to wind-based burning regulations. In such scenarios, one would expect pollution from upwind sugarcane burning in Zone 4 to drift and accumulate in Zone 1. This analysis aims to explore air quality dynamics in the absence of wind-based regulations specific to the harvest period. Remarkably, Table A2 indicates a modest decrease in Aerosol Optical Depth (AOD) levels downwind following the policy implementation. Not surprisingly, the coefficients associated with the average wind restriction variable in Zone 4 ($\overline{WR_{idmt}^{Zone4}}$) are positive and statistically significant, underscoring the inherent relationship between wind direction and subsequent air pollution concentrations in downwind regions. The findings in this section provide evidence that the stringent burning policy further reduces pollution downwind during the sugarcane harvesting season. Moreover, the results here complement the recent findings that PM2.5 from sugarcane fires dropped abruptly to the east and more slowly to the west and south because Forest Forest Service denies burning permit requests under brisk westerly winds (Nowell et al., 2022).

6. Distributional effects of the stringent regulations

Understanding the distributional impacts of the stringent regulations is crucial, given the historical use of wind-based regulations to shield populous areas at the expense of nearer, often economically disadvantaged and minority communities. I use the CDC vulnerability index to identify highly vulnerable communities, defined as those with an overall ranking above the 90th percentile. In Zone 4, 19 out of 33 (58%) census tracts are classified as highly vulnerable, starkly contrasting with Zone 1, where only 35 out of 358 (10%) census tracts fall into this category.

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[12] Patrick Ferguson is leading the Stop Sugar Field Burning Campaign for the Sierra Club. He learned this from conversations with farmers and former employees of the sugarcane industry. Moreover, he mentioned that the sugar industry does not share such internal documents publicly.

Table 5: Distributional effects in Zone 1

	Highly vulnerable			Non-highly vulnerable		
	logAOD	logAOD	logAOD	logAOD	logAOD	logAOD
Post	-0.062***	0.051***	0.207***	-0.062***	0.042***	0.239***
	(0.021)	(0.013)	(0.023)	(0.007)	(0.004)	(0.007)
$\overline{WR_{idmt}^{Zone4}}$	0.072***	-0.084***	-0.066***	-0.087***	-0.099***	-0.085***
	(0.013)	(0.013)	(0.013)	(0.003)	(0.003)	(0.003)
$\overline{WR_{idmt}^{Zone4}}$ X Post	-0.069***	-0.040**	-0.066***	-0.046***	-0.017***	-0.039***
	(0.017)	(0.017)	(0.017)	(0.006)	(0.006)	(0.006)
N	30,944	30,944	30,944	280,744	280,744	280,744
Adj. R^2	0.316	0.348	0.356	0.308	0.349	0.358
Census FE	Yes	Yes	Yes	Yes	Yes	Yes
Month FE		Yes	Yes		Yes	Yes
Year FE			Yes			Yes

Notes: The entries in Table 5 are coefficient estimates from the DD estimator in equation (4). For columns (1)-(3), the dependent variable is the daily AOD levels measured in log in the highly vulnerable census tracts in Zone 1. In columns (4)-(6), the outcome is the daily AOD measured in log in the non-highly vulnerable census tracts in Zone 1. The regression includes detailed weather controls: daily temperature, precipitation, wind speed, wind gust, humidity, and visibility. Standard errors, clustered at the census tract level, are in parentheses. *** p<0.01; ** p<0.05; * p<0.10.

Section 5 shows that the air quality in Zone 1 improves following the implementation of stringent burning regulations. To assess the differential impacts on highly vulnerable versus less vulnerable communities within Zone 1, I estimate equation (4) again separately for each group, distinguishing between highly vulnerable and non-highly vulnerable communities. Table 5 shows the results and indicates a reduction in daily Aerosol Optical Depth (AOD) levels ranging from 1.7% to 6.9% across all communities in Zone 1 on days with wind restrictions in Zone 4. By comparing the coefficients of $\overline{WR_{idmt}^{Zone4}} \times Post_{idmt}$ from columns (1)-(3) to columns (4)-(6) of Table 5, it seems highly vulnerable communities in Zone 1 experience a more pronounced improvement in air quality post-policy, compared to their less vulnerable counterparts. This indicates a distributional benefit of the new regulations, with the greatest air quality improvements observed in areas of higher vulnerability.

Having examined the distributional impacts of the stringent burning regulations on air quality in Zone 1, our attention now shifts to Zone 4. Section 4 reveals that an unintended consequence of the new policy is an increase in the number of fires in Zone 4 on days not subject to wind restrictions. To understand the air quality implications of this increase, equation

(5) is estimated to determine air quality changes in Zone 4 communities during non-restricted days:

$$Y_{idmt}^{Zone4} = \varphi_0 + \varphi_1 \times \overline{NWR_{idmt}^{Zone4}} + \varphi_2 \times Post_{idmt} + \varphi_3 \times \overline{NWR_{idmt}^{Zone4}} \times Post_{idmt} + \lambda W_{idmt} + \gamma_i + \rho_m + \mu_t + \epsilon_{idmt} \quad (5)$$

where Y_{idmt}^{Zone4} is the daily AOD level in census tract i in Zone 4 on date d, month m, year t. $\overline{NWR_{idmt}^{Zone4}} = 1 - \frac{\sum_{i \in Zone4} \text{WindRestrict}_{idmt}}{33}$, so $\overline{NWR_{idmt}^{Zone4}}$ is the proportion of census tract in Zone 4 that do not have wind restrictions on date d. This adjustment reflects the scenario when winds are more likely to direct pollution toward Zone 4 itself. $Post_{idmt}$ is a dummy variable that indicates the post-policy period, equals 1 for dates following October 1, 2019. The parameter of interest is φ_3, which captures the extent to which Zone 4 experiences higher pollution levels on non-restricted days as a consequence of the new burning regulations.

Table 6 shows the results and reveals a notable increase in daily Aerosol Optical Depth (AOD) levels, ranging from 4% to 7%, in Zone 4 on days when wind patterns are expected to direct pollution towards Zone 4. Table A3 shows the results of the falsification test where we restrict the sample to the months outside the sugarcane harvest season (May-September). Table A3 indicates that the air quality improves on non-restricted days. The increase in AOD levels in Zone 4, particularly on days when the wind directs pollution towards this area, suggests that current stringent burning regulations may not be fully effective in protecting all communities from the adverse effects of sugarcane burning. This necessitates a reevaluation of the policies to ensure they are comprehensive and adequately safeguard all affected regions, especially those downwind of burning activities.

To see whether highly vulnerable communities in Zone 4 suffer from higher levels of pollution, I estimate equation (5) separately for both highly vulnerable and non-highly vulnerable communities. Table 7 shows the results and suggests on days with winds directed toward Zone 4, highly vulnerable communities in Zone 4 experience an increase in daily AOD levels ranging from 4.4% to 7.4%. In contrast, non-highly vulnerable communities in Zone 4 experience a slightly smaller increase of 3.5% to 6.0%, with these effects being less significant. A comparison of the policy's impact on air quality, as depicted in Table 6 for Zone 4 as a whole, to the specific effects on highly vulnerable communities detailed in Table 7, suggests a slightly greater increase in AOD levels for the latter group. It is noteworthy that most of the harvest season occurs without wind restrictions, implying that on such days, prevailing winds carry

Table 6: DD policy effect on pollution in Zone 4

	logAOD	logAOD	logAOD
Post	-0.025*	-0.114***	0.129***
	(0.013)	(0.024)	(0.030)
$\overline{NWR_{idmt}^{Zone4}}$	0.205***	0.205***	0.189***
	(0.003)	(0.015)	(0.014)
$\overline{NWR_{idmt}^{Zone4}}$ X Post	0.040**	0.056***	0.070***
	(0.017)	(0.018)	(0.018)
Adj. R^2	33,340	33,340	33,340
Pre dep mean	0.442	0.524	0.536
Census FE	Yes	Yes	Yes
Month FE		Yes	Yes
Year FE			Yes

Notes: The entries in Table 6 are coefficient estimates from the DD estimator in equation (5), where the dependent variable is the daily AOD levels in each census tract x day x year measured in log in Zone 4. The regression includes detailed weather controls: daily temperature, precipitation, wind speed, wind gust, humidity, and visibility. Standard errors, clustered at the census tract level, are in parentheses. *** p<0.01; ** p<0.05; * p<0.10.

emissions directly toward Zone 4, impacting these communities. Over 75% of the harvest season days fall into this category, resulting in higher exposure for these areas. Additionally, given the proximity of over half of Zone 4's communities to the sugarcane fields, and their classification as highly vulnerable, the regulations introduced in 2019 seem to have an unequal impact, exacerbating pollution for those already at a disadvantage. This suggests that while the regulations were aimed at reducing overall pollution, they inadvertently contribute to environmental injustice, necessitating a policy reevaluation to address these disparities and protect the most vulnerable groups.

7. Conclusion

The recent tightening of burning regulations in South Florida, while intending to curb pollution from sugarcane burning, has inadvertently amplified environmental inequities. This study demonstrates that such measures reinforce a pre-existing discriminatory wind-based framework, failing to provide additional protections to the marginalized communities in Zone 4. In contrast, these regulations benefit the traditionally protected Zone 1, manifesting in improved air quality at the expense of heightened pollution in the more vulnerable regions. Significantly, the findings of this paper add a data-driven perspective to ongoing policy debates, aligning with the American Lung Association's 2023 stance against agricultural burning due to its adverse health and air quality impacts. Katherine Pruitt, the national senior director of

Table 7: Distributional effects in Zone 4

	Highly vulnerable			Non-highly vulnerable		
	logAOD	logAOD	logAOD	logAOD	logAOD	logAOD
Post	-0.034*	-0.133***	0.117***	-0.007	-0.081**	0.144**
	(0.019)	(0.031)	(0.038)	(0.016)	(0.036)	(0.049)
$\overline{NWR}_{idmt}^{Zone4}$	0.197***	0.194***	0.181***	0.216***	0.218***	0.199***
	(0.018)	(0.019)	(0.019)	(0.022)	(0.023)	(0.021)
$\overline{NWR}_{idmt}^{Zone4}$ X Post	0.044*	0.064**	0.074**	0.035	0.043	0.060**
	(0.024)	(0.026)	(0.027)	(0.022)	(0.024)	(0.024)
N	19,164	19,164	19,164	14,176	14,176	14,176
Adj. R^2	0.439	0.518	0.531	0.450	0.537	0.547
Census FE	Yes	Yes	Yes	Yes	Yes	Yes
Month FE		Yes	Yes		Yes	Yes
Year FE			Yes			Yes

Notes: The entries in Table 7 are coefficient estimates from the DD estimator in equation (5). For columns (1)-(3), the dependent variable is the daily AOD levels in the highly vulnerable census tracts in Zone 4. In columns (4)-(6), the outcome is the daily AOD in the non-highly vulnerable census tracts in Zone 4. The outcome is measured in log and observed at the census tract x day x year. The regression includes detailed weather controls: daily temperature, precip- itation, wind speed, wind gust, humidity, and visibility. Standard errors, clustered at the census tract level, are in parentheses. *** p<0.01; ** p<0.05; * p<0.10.

policy at the association, emphasizes the challenges communities face when contesting industry practices, noting the critical need for more data to support health-related claims (Gaines, 2023). This study presents evidence of the consequences of regulatory changes, highlighting the necessity for data-inclusive policymaking to address and rectify environmental and health disparities.

The study indicates that while uniform regulations have improved air quality in regions affected by wind-based controls, such measures also impose economic and demographic considerations. Policymakers are thus tasked with balancing the need to reduce pollution against the economic vitality of sugarcane burning. These regulations often shift the environmental burden to those living near the fields, especially when protections favor downwind regions. This poses the question of equity: which communities should bear the cost—those in the east, traditionally protected, or those in the west, where sugarcane thrives? For farmers, the freedom to burn is economically crucial. While the research acknowledges the benefits of strict regulations, it is the sugarcane communities that pay the price for cleaner air elsewhere. This underscores the need for policy refinements that equitably distribute both the environmental benefits and the economic costs of pollution control.

There are several limitations of the study. Firstly, the absence of direct pollution data from sugarcane burning necessitates the use of AOD as a proxy for surface PM2.5. And the AOD may not precisely capture the pollution from sugarcane burning. Despite this limitation, AOD stands as the most viable proxy currently available, and its use is substantiated by a falsification test during non-harvest periods. This test enhances the credibility of our findings by validating the interplay between wind direction and policy effect. Secondly, our analysis may seem to oversimplify the policy by demarcating wind restriction days based on a specific wind direction range from SSW to NNW. While wind direction is merely one criterion for burning permits, it is readily quantifiable. The more complex components of the new burning rules, including AQI considerations and smoke prediction tools, fall outside the scope of our regression analysis. Consequently, our results primarily address the wind restriction mechanism, which could lead to conservative estimates of the policy's full impact. Nonetheless, the relevance of wind-based regulations, deeply embedded in discriminatory policies over the past three decades, presents a novel and insightful angle to study the distributional impacts of environmental regulations.

References:

Anderson, M. L. (2020). As the wind blows: The effects of long-term exposure to air pollution on mortality. *Journal of the European Economic Association*, 18(4), 1886-1927.

Arbex, M. A., Martins, L. C., de Oliveira, R. C., Pereira, L. A. A., Arbex, F. F., Cançado, J. E. D., ... & Braga, A. L. F. (2007). Air pollution from biomass burning and asthma hospital admissions in a sugar cane plantation area in Brazil. *Journal of Epidemiology & Community Health*, *61*(5), 395-400.

Banzhaf, S., Ma, L., & Timmins, C. (2019). Environmental justice: The economics of race, place, and pollution. *Journal of Economic Perspectives*, *33*(1), 185-208.

Baucum, L. E., Rice, R. W., & Schueneman, T. J. (2009). An overview of Florida sugarcane. *University of Florida IFAS Extension document SS-AGR-232*.

Cançado, J. E., Saldiva, P. H., Pereira, L. A., Lara, L. B., Artaxo, P., Martinelli, L. A., ... & Braga, A. L. (2006). The impact of sugar cane–burning emissions on the respiratory system of children and the elderly. *Environmental health perspectives*, *114*(5), 725-729.

Carney, W., Spicer, B., Stegall, B., & Borel, C. (2000). Louisiana Smoke Management Guidelines for Sugarcane Harvesting. *Baton Rouge, LA: LSU AgCenter*.

Centers for Disease Control and Prevention. (2018). CDC/ATSDR Social Vulnerability Index 2018 Database. https://www.atsdr.cdc.gov/placeandhealth/svi/documentation/SVI_documentation_2018.html/.

Chakraborti, L., & Shimshack, J. P. (2022). Environmental disparities in urban Mexico: Evidence from toxic water pollution. *Resource and Energy Economics*, *67*, 101281.

Currie, J., Voorheis, J., & Walker, R. (2023). What caused racial disparities in particulate exposure to fall? New evidence from the Clean Air Act and satellite-based measures of air quality. *American Economic Review*, *113*(1), 71-97.

Deryugina, T., Heutel, G., Miller, N. H., Molitor, D., & Reif, J. (2019). The mortality and medical costs of air pollution: Evidence from changes in wind direction. *American Economic Review*, *109*(12), 4178-4219.

Ferguson, P. (2022). private communication.

Fullerton, D., & Muehlegger, E. (2019). Who bears the economic burdens of environmental regulations?. *Review of Environmental Economics and Policy*.

Gaines, P. (2023). Sugar burning season in South Florida. *NBC News*. Updated May 16, 2023. https://www.nbcnews.com/news/nbcblk/sugar-burning-season-south-florida-rcna82479

Gendron-Carrier, N., Gonzalez-Navarro, M., Polloni, S., & Turner, M. A. (2022). Subways and urban air pollution. *American economic journal: Applied economics*, *14*(1), 164-196.

Gilbert, R. A., Shine, J. M., Miller, J. D., Rice, R. W., & Odero, D. C. (2004). Maturity curves and harvest schedule recommendations for CP sugarcane varieties. *SS-AGR-221 document of the Institute of Food and Agricultural Sciences (IFAS), University of Florida. Belle Glade.*

Gonzalez, R. (2022). Tell me about sugarcane burning in Florida. Thompson Earth Systems Institute. https://www.floridamuseum.ufl.edu/earth-systems/blog/tell-me-about-sugarcane-burning-in-florida/

Gupta, P., Christopher, S. A., Wang, J., Gehrig, R., Lee, Y. C., & Kumar, N. (2006). Satellite remote sensing of particulate matter and air quality assessment over global cities. *Atmospheric Environment*, *40*(30), 5880-5892.

Hausman, C., & Stolper, S. (2021). Inequality, information failures, and air pollution. *Journal of Environmental Economics and Management*, *110*, 102552.

Hernandez-Cortes, D. (2023). The Distributional Consequences of Incomplete Regulation.

Hernandez-Cortes, D., & Meng, K. C. (2023). Do environmental markets cause environmental injustice? Evidence from California's carbon market. *Journal of Public Economics*, *217*, 104786.

Hiscox, A. L., Flecher, S., Wang, J. J., & Viator, H. P. (2015). A comparative analysis of potential impact area of common sugar cane burning methods. *Atmospheric Environment*, *106*, 154-164.

Holland, S. P., Mansur, E. T., Muller, N. Z., & Yates, A. J. (2019). Distributional effects of air pollution from electric vehicle adoption. *Journal of the Association of Environmental and Resource Economists*, *6*(S1), S65-S94.

Kumar, N., Chu, A. D., Foster, A. D., Peters, T., & Willis, R. (2011). Satellite remote sensing for developing time and space resolved estimates of ambient particulate in Cleveland, OH. *Aerosol Science and Technology*, *45*(9), 1090-1108.

Misra, V., Mall, A. K., Solomon, S., & Ansari, M. I. (2022). Post-harvest biology and recent advances of storage technologies in sugarcane. *Biotechnology Reports*, *33*, e00705.

Mohai, P., Pellow, D., & Roberts, J. T. (2009). Environmental justice. *Annual review of environment and resources*, *34*, 405-430.

Morse, H. (2022). Glades residents drop cane burning lawsuit against sugar growers. *The Palm Beach Post*. https://www.palmbeachpost.com/story/news/local/2022/02/26/glades-residents-drop-sugarcane-burning-lawsuit-against-sugar-growers/6944816001/

Nebeker, R. (2021). What You Need to Know About Sugarcane Burning. *FoodPrint*. https://foodprint.org/blog/sugarcane-burning/

Nowell, H. K., Holmes, C. D., Robertson, K., Teske, C., & Hiers, J. K. (2018). A new picture of fire extent, variability, and drought interaction in prescribed fire landscapes: Insights from Florida government records. *Geophysical research letters*, *45*(15), 7874-7884.

Nowell, H. K., Wirks, C., Val Martin, M., van Donkelaar, A., Martin, R. V., Uejio, C. K., & Holmes, C. D. (2022). Impacts of sugarcane fires on air quality and public health in South Florida. *Environmental health perspectives*, *130*(8), 087004.

Palm Beach County Cooperative Extension. (2021). Sugar cane, rice and sod. https://discover.pbcgov.org/coextension/agriculture/pages/sugarcane.aspx/.

Provençal, S., Kishcha, P., Da Silva, A. M., Elhacham, E., & Alpert, P. (2017). AOD distributions and trends of major aerosol species over a selection of the world's most populated cities based on the 1st version of NASA's MERRA Aerosol Reanalysis. *Urban Climate*, *20*, 168-191.

Rangel, M. A., & Vogl, T. S. (2019). Agricultural fires and health at birth. *Review of Economics and Statistics*, *101*(4), 616-630.

Schlenker, W., & Walker, W. R. (2016). Airports, air pollution, and contemporaneous health. *The Review of Economic Studies*, *83*(2), 768-809.

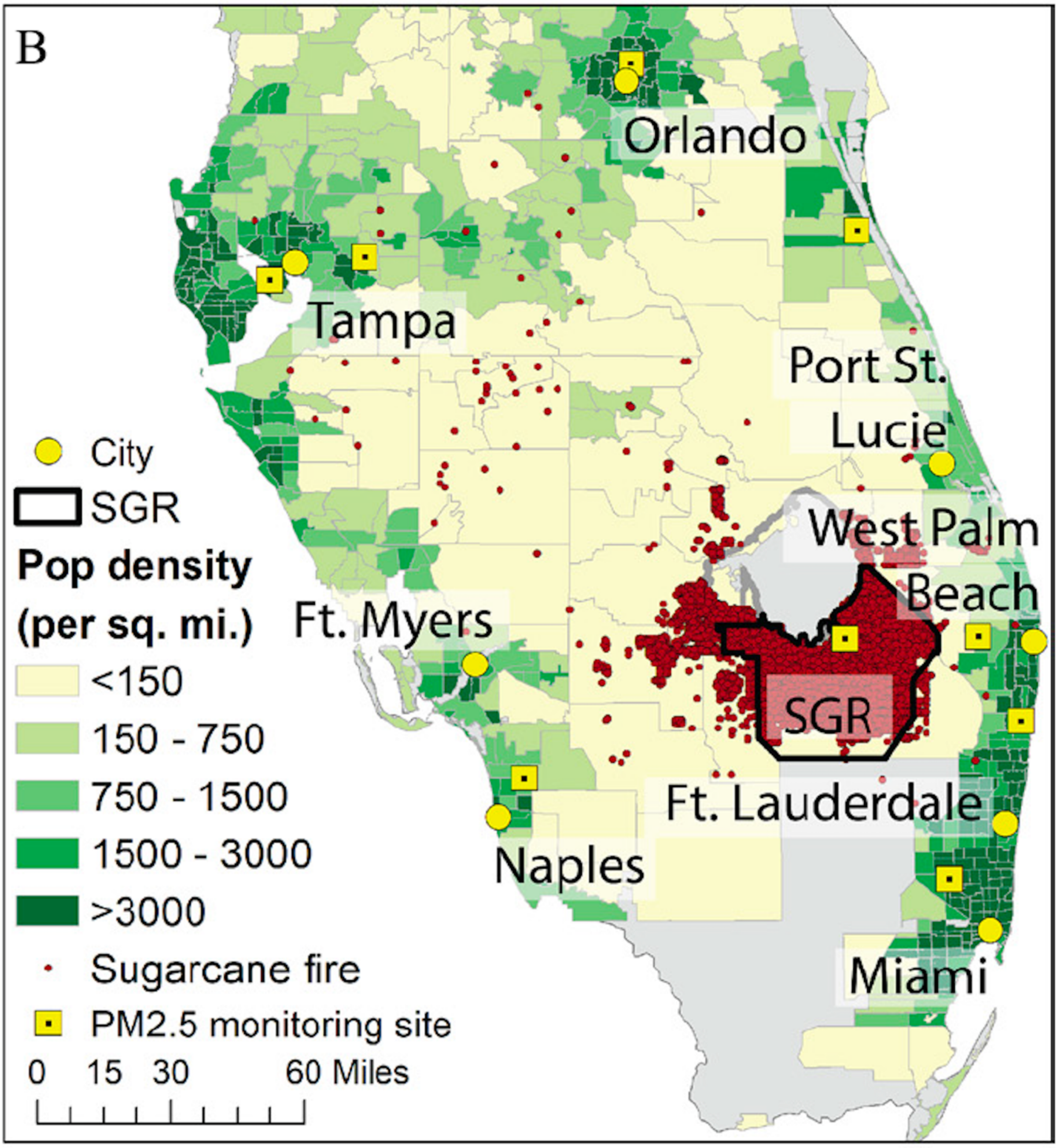
Sussman, N. (2021). Burning sugar cane pollutes communities of color in Florida. Brazil shows there’s another way. *ProPublica*. https://www.propublica.org/article/burning-sugar-cane-pollutes-communities-of-color-in-florida-brazil-shows-theres-another-way

The Florida Department of Agriculture and Consumer Services. (2021). Commissioner Nikki Fried announces major changes to prescribed burning. https://www.fdacs.gov/News-Events/Press-Releases/2019-Press-Releases/Commissioner-Nikki-Fried-Announces-Major-Changes-to-Prescribed-Burning

Van Donkelaar, A., Martin, R. V., Brauer, M., Kahn, R., Levy, R., Verduzco, C., & Villeneuve, P. J. (2010). Global estimates of ambient fine particulate matter concentrations from satellite-based aerosol optical depth: development and application. *Environmental health perspectives*, *118*(6), 847-855.

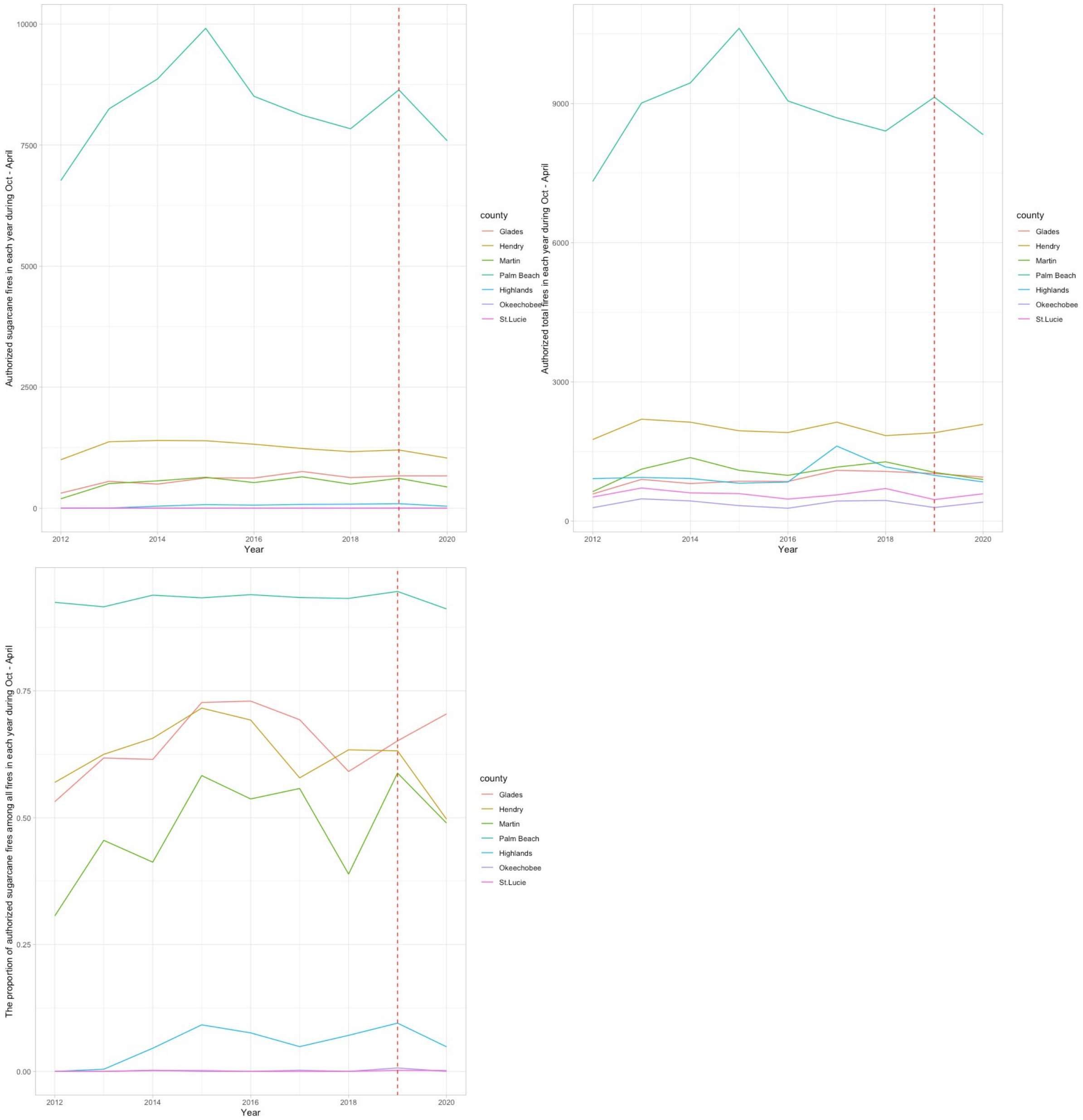
Appendices for "The Distributional Effects of Tighter Regulations: New Evidence from the Sugarcane Burning in Florida"

Figure A1. Locations of sugarcane fires and major cities



Notes: Locations of sugarcane fires and major cities (yellow circles). The sugarcane-growing region (SGR) is shown in black, and colors show population density by Zip code. The U.S. EPA monitoring sites are indicated by yellow boxes with dots in the center (Nowell et al., 2022).

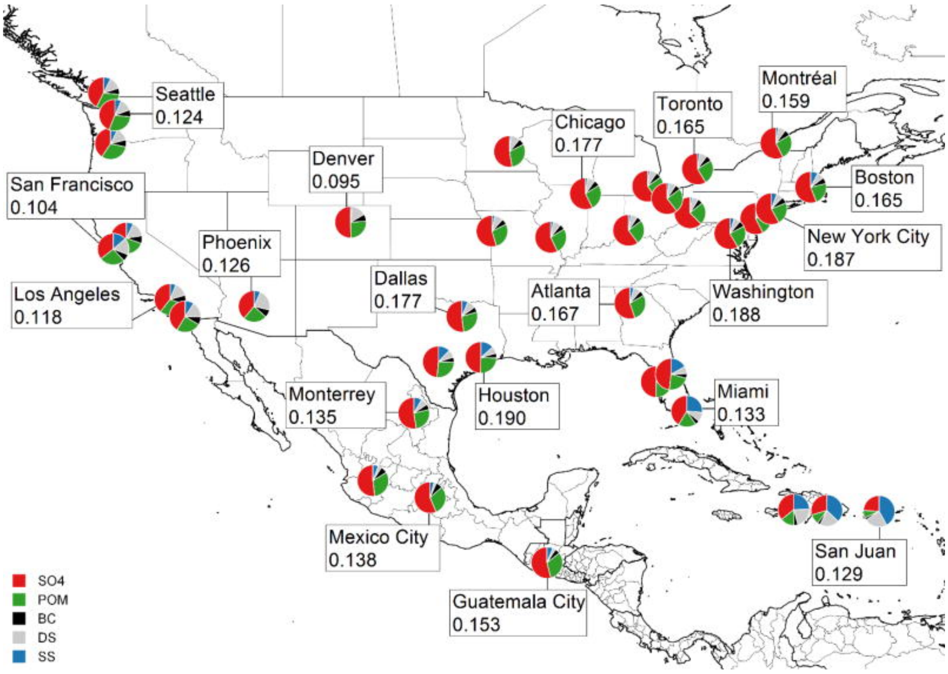
Figure A2. Trend of the annual authorized fires by county



Notes: The counts in Figure A2 are from the burning authorization summary in the Florida Forest Service Reporting System. The original authorized fire data is measured in the count and observed at county x day x year). The number in Figure A2 is the sum of the daily authorized fires/sugarcane fires in each county from October to April next year. Data on authorized fires are aggregated at the county-date level, spanning seven counties over 1,910 days. Among these, four counties are designated as sugarcane-growing areas, while the remaining three are adjacent counties located within the sugarcane-burning regulation zones.

Figure A2 does not provide evidence that the policy changes reduce the number of authorized total fires and sugarcane fires across the sugarcane-growing counties. There are some potential explanations for this finding. First, the air quality monitors are not evenly distributed around the sugarcane growing zones, and only one monitor exists, as shown in Figure A1. So incorporating AQI into burn authorizations may not show the air quality in those seven counties. Second, the quality of the reported fire data may be low. The authorized fire data are spatially aggregated at the county level, making it problematic to model how the permit for burning is approved precisely.

Figure A3. Mean AOD for a few cities



Note: Provençal et al. (2017) point out the highest urban AOD values are observed in Central and Eastern United States and Canada, ranging from 0.133 in Miami to 0.190 in Houston. The Northeastern United States is highly populated and industrialized, which explains the higher AOD values in Philadelphia (0.190), Cincinnati (0.189), Washington (0.188), New York City (0.187), Pittsburgh (0.184), Cleveland (0.181) and St. Louis (0.180).

Table A1: Falsification tests (DDD) during the non-harvest season

	TF	TF
Wind Restriction	-0.861	-0.341
	(0.658)	(0.918)
Post	-1.06	-1.38*
	(0.715)	(0.787)
Wind Restriction X Post	2.02***	1.54***
	(0.755)	(0.516)
Wind Restriction X Zone4	3.34	2.85
	(9.25)	(9.43)
Zone4 X Post	36.7	36.8
	(28.2)	(28.2)
Wind Restriction X Zone4 X Post	-41.0	-41.2
	(47.4)	(47.5)
Adj. R^2	0.017	0.017
Pre dep mean	0.044	0.044
Census FE	Yes	Yes
Month FE		Yes

Notes: TF denotes the number of daily observed total fires. The coefficient estimates in all entries are multiplied by 1000 for readability. The entries in Table A1 are coefficient estimates from the DDD estimator in equation (2), where the dependent variables are the number of daily observed total fires in each census tract x day x year, restricting the sample to be the months outside of sugarcane harvesting season. The regression includes detailed weather controls: daily temperature, precipitation, wind speed, wind gust, humidity, and visibility. Additional controls are listed at the bottom of Table 3. The number of observations is 438, 724. Standard errors, clustered at the census tract level, are in parentheses. *** p<0.01; ** p<0.05; * p<0.10.

Table A2: Falsification tests (DD) during the non-harvest season in Zone 1

	logAOD	logAOD
Post	0.014***	0.010***
	(0.003)	(0.003)
$\overline{WR_{idmt}^{Zone4}}$	0.056***	0.063***
	(0.004)	(0.004)
$\overline{WR_{idmt}^{Zone4}}$ X Post	-0.010	-0.019**
	(0.008)	(0.008)
N	207,071	207,071
Adj. R^2	0.176	0.186
Census FE	Yes	Yes
Month FE		Yes

Notes: The entries in Table A2 are coefficient estimates from the DD estimator in equation (4), where the dependent variable is the number of daily AOD levels in each census tract x day x year measured in log in Zone 1, restricting the sample to be the months outside of sugarcane harvesting season. The regression includes detailed weather controls: daily temperature, precipitation, wind speed, wind gust, humidity, and visibility. Standard errors, clustered at the census tract level, are in parentheses. *** p<0.01; ** p<0.05; * p<0.10.

Table A3: Falsification tests (DD) during the non-harvest season in Zone 4

	logAOD	logAOD
Post	0.068***	0.039***
	(0.017)	(0.019)
$\overline{NWR}_{idmt}^{Zone4}$	0.024	0.015
	(0.019)	(0.020)
$\overline{NWR}_{idmt}^{Zone4}$ X Post	-0.128***	-0.096**
	(0.022)	(0.022)
N	22,609	22,609
Adj. R^2	0.299	0.320
Census FE	Yes	Yes
Month FE		Yes

Notes: The entries in Table A3 are coefficient estimates from the DD estimator in equation (5), where the dependent variable is the number of daily AOD levels in each census tract x day x year measured in log in Zone 4, restricting the sample to be the months outside of sugarcane harvesting season. The regression includes detailed weather controls: daily temperature, precipitation, wind speed, wind gust, humidity, and visibility. Standard errors, clustered at the census tract level, are in parentheses. *** p<0.01; ** p<0.05; * p<0.1