

AGRICULTURAL FIRES AND HEALTH AT BIRTH

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Abstract—Fire has long served as a tool in agriculture, but the practice’s link with economic activity has made its health consequences difficult to study. Drawing on data from satellite-based fire detection systems, air monitors, and vital records in Brazil, we study how in utero exposure to smoke from sugarcane harvest fires affects health at birth. Exploiting daily changes in fire location and wind direction for identification, we find that late-pregnancy smoke exposure decreases birthweight, gestational length, and in utero survival. Fires less associated with smoke exposure predict improved health, highlighting the importance of disentangling pollution from its economic correlates.

I. Introduction

ENVIRONMENTAL degradation is often seen as a problem of industrialization, but some forms of anthropogenic pollution precede industry, as in the case of controlled burns, which have played an important role in agriculture throughout its history. Farmers use fire to clear land, control weeds, regenerate nutrients, and dispose of crop residues (Andreae, 1991). In recent years, the last category alone accounts for roughly half as much burned biomass as forest fires (Food and Agriculture Organization, 2017). While emissions from these fires are the subject of an extensive scientific literature (Crutzen & Andreae, 1990), their human capital consequences have proved difficult to study. Burning is associated with economic activity across space and time, and technologies or policies that reduce it may have economic side effects, which may in turn influence health and other forms of human capital. We estimate the effect of smoke from agricultural fires on health at birth, disentangling it from economic activity associated with agriculture.

The health burden of air pollution among children is the topic of a large literature, but this literature tends to focus on pollution from industry, motorized travel, and other modern sources, which differs from agricultural smoke in intensity, frequency, and chemical composition.¹ A separate line of research does consider biomass burning but concentrates either on massive pollution shocks, as in the case of major forest fires (Sastry, 2002; Frankenberg, McKee, & Thomas, 2012;

Jayachandran, 2009; Tan-Soo & Pattanayak, 2019), or on settings with extremely low air quality, as in the case of indoor air pollution from traditional cookstoves (Smith, 2000; Ezzati & Kammen, 2001; Smith et al., 2011; Duflo, Greenstone, & Hanna, 2016). Whether the results extend to routine, moderate with different emission factors (Andreae & Merlet, 2001) is an open question. So too is the generalizability of the developed country finding that air pollution harms health at birth. Research on developing countries mainly estimates health impacts at older ages (from later infancy to childhood and adulthood).²

Estimating the effects of agricultural fires is also difficult because they often coexist with other forms of biomass burning, especially on the rain forest frontier or the grasslands of Africa. We thus focus on a setting where the spatial and temporal distribution of fires has a clearer link with agriculture: the sugar-growing region of the Brazilian state of São Paulo, which is engulfed each year by widespread field burning during harvest. São Paulo is a major producer of sugarcane, accounting for roughly one-fifth of the tonnage produced annually across the globe (FAO, 2017; UNICA, 2016). In Brazil as elsewhere, cultivators burn their fields before harvesting, eliminating debris and creating plumes of smoke that potentially elevate nearby air pollutant concentrations. Controlled fires are an integral part of the traditional harvesting process because they increase the productivity of labor (cane cutters) with minimal loss in the produce’s glucose content. Field burning is continuously paced to optimize processing capacity utilization in sugar mills, with the harvest and milling period lasting up to six months. Though potentially harmful to health, the pollution from these fires does not reach levels considered dangerous by present-day industrial standards. Hence, the setting provides an opportunity to study the health burden of repeated exposure to moderate-scale pollution from traditional sources.³ Sugarcane accounts for a substantial share of global agriculture—ranking eleventh globally in area harvested, seventh in value, and first in weight (FAO, 2017)—and is considered an important driver of trends in land use, energy generation, economic development, and poverty reduction even in regions far away from São Paulo, like the Caribbean and southern Africa (Mitchell, 2005; Souza et al., 2016). Our results may also provide insight into the burning of residues from other common crops, like wheat, maize, and rice.

Our empirical strategy exploits wind direction and fire location at a daily level to resolve the identification challenges posed by the seasonal and economic correlates of field burning. Combining these data with daily measurements of air

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¹See Graff Zivin and Neidell (2013) for a review of the economics literature.

²An exception is Bharadwaj et al. (2017), who analyze birth outcomes to supplement their main test score results.

³Our study region has little forest or savanna cover, leaving little ambiguity that the predominant source of fire is controlled agricultural burning.

pollution, we first show that fires upwind from a pollution monitor raise pollution significantly more than fires at other angles to the wind or fires taking place during periods of calm. Particulate matter (PM_{10}) concentrations increase 25% to 33% (relative to the mean) during weeks in which upwind fire activity within 50 kilometers increases by 1 standard deviation, holding constant total fire activity within that radius. Ozone (O_3) also rises moderately (7% to 8%), but we find no effect on nitrogen oxides (NO_x). We therefore use fires not upwind from a mother's place of residence to control for confounders, under the assumption that upwind and other fires are equally correlated with other determinants of health. In essence, we use the differential association of upwind fires with health, relative to the association of other fires with health, to identify the effect of exposure net of economic impacts.⁴ Our models include location and time fixed effects, so the empirical approach amounts to asking whether, within a locality and during a given week, relocation of fires to upwind positions negatively affects health.

The analysis is made possible by São Paulo's sophisticated, high-frequency monitoring systems for pollution, climate, and wind, which we link with satellite remote-sensing data on fires and vital registration data on infant health. The richness and completeness of São Paulo's birth records allow us to consider outcomes less extreme than death, which is important given the setting's low mortality rates among the very young.⁵ We relate smoke exposure in utero to health at birth (birthweight and prematurity), perinatal morbidity (hospital admission and APGAR scores), and perinatal mortality (stillbirth and death just after birth).

We find that increased in utero exposure to smoke from sugarcane fires reduces birthweight and gestational age at birth, both on average and at the lower tail of the distribution. During the last three months of gestation, a 1 standard deviation increase in fires per week in the upwind direction raises the prevalence of very low birthweight (below 1,500 grams) and very preterm birth (fewer than 32 weeks) by approximately 0.6 of 1 standard deviation for both outcomes. The same increase in upwind fires also reduces birth cohort size (by 12%) and increases reported stillbirths (by 17 per 1,000), indicating effects on in utero survival. We do not detect effects on early-life mortality or measured morbidity outside the womb. Nor do we find effects of exposure in earlier gestational periods, although estimates for these periods may suffer from selection bias due to our retrospective dating of

exposure from the date of birth.⁶ Increased fire activity not upwind from the mother's municipality has a mild but significant positive relationship with health at birth, consistent with confounding from the agricultural business cycle.⁷ Without considering the differential impact of upwind fires, we would have entirely missed the health costs of harvest fire pollution.

Our context and strategy set us apart from previous analyses because both wind and pollution source locations frequently change within an area. This combination is useful for both clearly distinguishing pollution effects from economic effects and avoiding selection concerns that arise in strategies involving fixed pollution sources (e.g., a factory, a road, an airport). While our identification strategy is novel for a developing country, we join a growing literature that exploits pollution variation from wind direction in the United States (Schlenker & Walker, 2016; Anderson, 2016; Deryugina et al., 2016).⁸ Cross-sectional and time-series analyses in Brazil have tended to find negative relationships between sugarcane fires and respiratory health, but the effect of smoke per se has proved elusive.⁹ Concerns about economic confounders may also apply to studies of pollution and child health elsewhere, including Chay and Greenstone's (2003) on recession-induced pollution in the United States, Greenstone and Hanna's (2014) on environmental regulation in India, and Cesur, Tekin, and Ulker's (2017) on natural gas in Turkey.

Our findings suggest that exposure to this common but moderate form of pollution in utero harms health in early life. Given the connection between early-life health and long-term outcomes, our results raise the question of whether governments should encourage adoption of mechanized harvesting methods, which can reduce the productivity benefits of fire. Sugar plantations in Brazil have been adopting these methods, but the evidence suggests that little of this trend is attributable to policy (Davis, 2017), and burned area has not declined (Aguiar et al., 2011). In any case, the infant health effects of mechanization are ambiguous, with positive environmental effects but possibly negative labor market effects.¹⁰ Our estimates are also relevant to the search for sustainable energy (Chu & Majumdar, 2012), which has promoted sugarcane-based ethanol (Goldemberg, 2007). With sugarcane production growing to meet the resulting surge in demand, negative production externalities pose distributional questions, as nonproducing areas benefit from cheaper fuel

⁶The backdating issue arises in many studies of in utero shocks.

⁷The implication that infant health improves during agricultural booms contrasts Miller and Urdinola (2010), who find countercyclical child survival in coffee-growing areas of Colombia.

⁸In a related approach, Knittel, Miller, and Sanders (2016) use pollution variation stemming from the interaction of automobile congestion with weather conditions.

⁹See Arbex et al. (2004, 2007), Cançado et al. (2006), Ribeiro (2008), Uriarte et al. (2009), and Chagas, Almeida, and Azzoni (2014). In a rare panel analysis, Davis and Miller (2017) confirm that place and time fixed effects are insufficient for eliminating bias.

¹⁰Consistent with this view, an extension to our main analysis finds that mechanization is associated with fewer fires, fewer new jobs, and no pronounced change in health at birth.

⁴We implicitly assume that other pollution-causing activity associated with harvest (e.g., processing or transport) is not strongly correlated with the interaction of wind direction and fire location, which is plausible because these alternative sources of pollution (mills and road locations) are fixed across space.

⁵The state of São Paulo has an infant mortality rate of 11 per 1,000 live births, while the municipalities in the study area range from 7 to 12 (SEADE, 2016). The U.S. rate is 6 per 1,000 live births (Kochanek et al., 2016). Our data set and research design lack the statistical power to detect effects for an outcome with such low baseline levels. We do analyze infant death as an extension in section VB, but estimates are imprecise, as expected.

and reduced emissions while individuals in producing areas may suffer.

II. Background: Harvesting and Health

A. *Fire, Croplands, and Sugarcane across the Globe*

Controlled agricultural burns are an important contributor to fire activity globally. Using satellite remote sensing data on fires, Korontzi et al. (2006) estimate that areas that are at least 80% covered by cropland (8% of the global landmass, according to Friedl et al., 2010) account for up to 11% of burned area. Of the three major sources of burning tracked by the FAO (2017)—forest fires, savanna fires, and the burning of crop residues—all are at least partly related to agriculture, with many fires in the first two categories related to land clearance. In the last category, sugarcane accounts for less burning than the other crops tracked (maize, rice, and wheat), roughly in proportion with its contribution to area harvested. Relative to maize, rice, and wheat, sugarcane accounts for 5% of both area harvested and burned residue. The concentration of sugarcane harvesting in our study site makes it an appealing crop to study, however, and its residues produce similar emissions to these other crops (Andreae & Merlet, 2001). Online appendix figure A1 maps fires, croplands, and sugar harvesting around the world, showing that our study site is a hotspot in all three areas.

B. *Sugarcane Harvesting in Brazil*

Brazil is the world's leader in sugarcane production (FAO, 2017), and the state of São Paulo accounts for more than two-thirds of the country's harvest (UNICA, 2016). In recent years, rising demand for biofuels and sugar has led to rapid production growth (McConnell, Dohlman, & Haley, 2010). The share of São Paulo's land area devoted to sugarcane monoculture more than doubled from 2000 to 2014, from 10% to 23%, displacing other crops and cattle production. Sugarcane expanded over the plateau northwest of the Serra do Mar mountain range, with more municipalities planting sugarcane and more area devoted to the crop in municipalities already producing it. These trends are confirmed in online appendix figure A2, which maps the spatial distribution of municipality-level sugarcane land shares in the 1990s and our study period, 2009 to 2014.

From April to November, sugarcane farms and plantations in São Paulo harvest their crop using either traditional manual methods or modern mechanical methods. To carry out a manual harvest, cultivators burn the field before cutting the stalk of the cane with a cane knife or machete. The fire burns off straw and other extraneous materials, leaving only the harvestable part of the cane and its roots. A typical fire lasts approximately five minutes per hectare burned (Le Blond et al., 2017). The use of fires is believed to increase the productivity of laborers by a factor of ten relative to the manual

harvesting of unburned fields (Fernandes, 1988; Marinho & Kirchoff, 1991). While the fire by itself does not lead to significant glucose loss, the crop starts degrading once cut due to evaporation and bacterial growth (Salassi, Garcia, & Breaux, 2004; Saska, Goudeau, & Marquette, 2009; Saxena, Srivastava, & Sharma, 2010). As a result, fires are set throughout the harvesting season, depending on transport logistics and the operational capacity of the mills processing the cane. In fact, Lamsal, Jones, and Thomas (2013) report that a conservative estimate of cut-to-crush time is approximately three hours, with harvest being conducted 24 hours a day during peak season.

With modern methods, a mechanical combine or sugarcane harvester cuts the stalk at the base, removes the straw, and then chops the cane into pieces. Fire becomes less productive. São Paulo's sugarcane industry is undergoing widespread mechanization, in large part due to rising labor costs (Davis, 2017). By state law, preharvest burning will become illegal in most parts of the state in 2021; an industry-state agreement between set nonbinding goals for reductions started in 2007, but the total area undergoing burn harvesting has not appreciably declined (Aguilar et al., 2011).

C. *Potential Environment and Health Impacts*

Observational studies document associations between sugarcane fires and pollution over time and across space (Marinho & Kirchoff, 1991; Cançado et al., 2006; Martinelli & Filoso, 2008; Tsao et al., 2012). In the laboratory, França et al. (2012) find that burning sugarcane straw raises particulate matter concentrations, as well as unburned hydrocarbons and trace gases such as carbon dioxide, carbon monoxide, and nitrogen oxides. Particulate matter emissions may be higher outside the laboratory, where objects larger than straw also burn. Based on field data from harvest fires in Brazil and Ecuador, Le Blond et al. (2017) report that 96% of the PM₁₀ generated by sugarcane burning is respirable (under 4 micrometers). O₃ concentrations are also likely to increase from open-area burning, since they result from the exposure of NO_x to sunlight and hydrocarbons. This process is more rapid under stagnant high pressure, which commonly accompanies the weather conditions that prevail in São Paulo during harvest: low humidity, moderate to high temperature, and sunshine (Vukovich, 1995). Evidence also suggests that some of the larger particulate matter generated during burning can be further broken down and resuspended even weeks after the spread of ashes (Le Blond et al., 2017).

Research on the health impact of this pollution focuses on concurrent respiratory health status (Arbex et al., 2004, 2007; Cançado et al., 2006; Ribeiro, 2008; Uriarte et al., 2009; Chagas et al., 2014). We depart from this tradition by using birthweight and gestational age at birth, which measure the stock of health (at the start of life) more comprehensively and reflect investments and shocks during a well-defined period (gestation). Epidemiological evidence indicates that

particulate matter concentrations correlate with several birth outcomes, and economic research suggests these correlations in part reflect causal effects of pollution.¹¹ The mechanism biologically relating particulate matter to perinatal outcomes is not precisely known, but the respiratory and cardiovascular health of pregnant women likely plays an important role. Particulate matter may contribute to systemic oxidative stress, affecting the embryo in the earliest phases of growth, although this channel is more likely for industrial pollution containing transition metals. More relevant here, particulate matter and ozone may decrease fetal-placental exchange of oxygen and nutrients, and particulate matter may increase pulmonary and placental inflammation in the mother, potentially resulting in premature contractions and membrane rupture. Blood viscosity and coagulability may also change, slowing fetal growth and increasing the risk of maternal cardiovascular events, preeclampsia, and preterm delivery.

III. Fires: Documenting Variation over Time and Space

To motivate our study design, we provide a descriptive analysis of fire variation in São Paulo. We introduce the satellite-based data set that we use to track fires in this section and in the main analysis. With these data, we describe the spatial and temporal distributions of fire and sugarcane harvesting. We then document longitudinal relationships among sugarcane harvesting, local economic activity, and fires.

A. Satellite Remote-Sensing Data

We assemble panel data on fires from a Brazilian space agency (Instituto Nacional de Pesquisas Espaciais, INPE) database based on pictures of the Brazilian territory by U.S.-operated satellites. Data from three satellites—NOAA-15 (orbiting at 800 kilometers and launched by the U.S. National Oceanic and Atmospheric Research Agency), TERRA, and AQUA (both orbiting at 730 kilometers and launched by the U.S. space agency, NASA)—are employed.¹² Each satellite passes over the Brazilian territory twice per day, covering mornings, afternoons, evenings, and late nights.

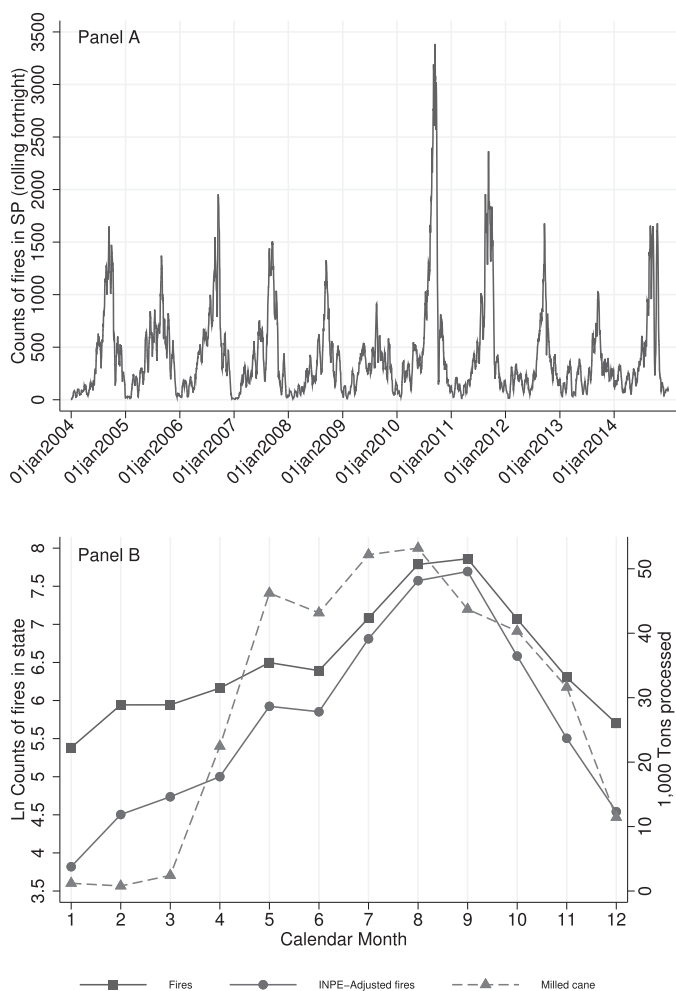
The resulting data consist of binary information about the existence of a potential fire on a given day and in a given location, as a function of pixels within specific thermal ranges (luminosity). The sensors can detect fires as small as 30 m × 1 m, but data output is at the pixel-day level, representing a 1 km × 1 km area for each day.¹³ Each pixel-day is assigned a confidence index reflecting the probability that a fire occurred, varying from 0% to 100%, based on meteorological

¹¹Stieb et al. (2012) review the epidemiology literature. Currie et al. (2014) review the economics literature.

¹²NOAA satellites use advanced very high resolution radiometer (AVHRR) sensors, while TERRA and AQUA use moderate resolution imaging spectroradiometer (MODIS) sensors. For descriptive analyses, we extend the data using NOAA-12, the predecessor of NOAA-15.

¹³We geocode the centroid of each pixel. INPE reports location errors of 400 meters on average, with a 3 kilometer standard deviation; 80% of the fires are correctly placed within the pixel.

FIGURE 1.—TIME AND SEASONAL EVOLUTION OF FIRES AND SUGARCANE PRODUCTION



(A) Trends of satellite-based fire counts within the state of São Paulo per moving fortnight (2004–2014). (B) Seasonality in satellite-based fire counts and in milled sugarcane tonnage within the state of São Paulo (2009–2014). INPE-adjusted counts are weighted by the probability of occurrence.

logical conditions and vegetation at the time of potential fire detection (Setzer & Sismanoglu, 2007). Most of our empirical investigation, in this section and after, weights fires by their probability, so that a fire that occurred with 25% probability is given half the weight of a fire that occurred with 50% probability. Since preharvest burns take place at all times of day, we sum the three data series into daily counts. We do not measure the duration of fires, apart from the fact that longer-burning fires are more likely to be detected by multiple satellites.

B. Time Series and Spatial Patterns

We report temporal and seasonal patterns of fires and production in figure 1. Panel A presents the rolling cumulative count of fires within the state of São Paulo across all three satellite series for every fortnight between January 2004 and December 2014, revealing no obvious time trend in the occurrence of fires but a clear seasonal pattern. Panel B details this

seasonal pattern further by plotting the log of average monthly counts over our main study period, which runs from 2009 to 2014. Starting from their trough in January, fires climb through the year until peaking in August or September. The peak-to-trough difference in monthly fires is approximately 2.5 log points, corresponding to a 35% increase. This pattern is even more dramatic if we focus on probability-weighted counts, yielding a 73% increase in fire activity between January and September. To illustrate the link to sugarcane harvesting, panel B reports seasonal patterns in the tonnage of cane processed monthly by São Paulo mills from the National Union of Sugarcane Producers (UNICA) during our main study period (2009–2014). As with fires, milling activity is lowest in the summer months, from December to March, and highest in the winter months, peaking in August.¹⁴

C. Sugarcane, Fires, and the Local Economy

The prevalence of field fires depends on both the extent of sugarcane production and the choice of harvesting method, both of which change over time in ways that may be closely linked to the local economy. For motivating evidence on this point, we assemble an annual panel of all 645 São Paulo municipalities covering 2004 to 2014, with data on fires, sugarcane production, and municipal GDP per capita.¹⁵ We use these data to regress probability-weighted fire intensity on measures of sugarcane harvesting and the local economy, controlling for municipality and year fixed effects.

Table 1 presents the results, showing clear links among harvest area, GDP per capita, and fires. Columns 1 to 4 provide evidence on annual relationships. An expansion of harvesting from none to at least three-quarters of the municipal territory is associated with two more fires per 100 km², more than two-thirds of mean fire intensity. Controlling for log GDP per capita negligibly alters the coefficients on harvest area, but a doubling of GDP per capita is associated with one extra fire per 100 km². Fires are related to economic activity within the year as well, as shown using monthly jobs data in columns 5 and 6.¹⁶ Here, we regress the change in fires from the previous month on jobs created and destroyed, controlling for month-year fixed effects. One job created per inhabitant is associated with one extra fire per 100 km²; one job destroyed per inhabitant is associated with 1.7 fewer. Similar results obtain if we study the wage bill changes associated with these jobs.¹⁷

¹⁴Online appendix figure A3 maps the intensity of probability-weighted fires, revealing a similar spatial distribution to that of sugarcane production in online appendix figure A2.

¹⁵We sum probability-weighted fires within a municipality over the year and divide by the municipality's land area. Agricultural and economic data are from the Brazilian statistical agency IBGE (Instituto Brasileiro de Geografia e Estatística).

¹⁶Jobs data are from Cadastro Geral de Emprego e Desemprego (CAGED) by the labor ministry MTPS (Ministério do Trabalho e Previdência Social).

¹⁷See additional analyses in tables A1 and A2 in the online appendix.

IV. Pollution and Health: Data and Methods

In light of the association of economic activity with fire, we use high-frequency changes in wind direction and fire location and timing to isolate exogenous variation in smoke exposure.

A. Data

In addition to the remote-sensing data introduced in section 3, two other data sets are key for our analysis: one containing pollution and weather data from state-run air quality monitoring stations and the other containing birth and death certificate information from the national vital statistics system.

Air monitoring station data. Data on pollution concentrations and atmospheric conditions come from air monitoring stations operated by the São Paulo's environmental agency, CETESB (Companhia Ambiental do Estado de São Paulo). Thirteen stations started collecting data in sugar-growing areas between January 2008 and April 2009, with all but one in operation at least through the end of 2014. Our study period thus runs from 2009 through 2014.¹⁸

At hourly intervals, all stations measure temperature, relative humidity, wind direction, particulate matter (under 10 μm, PM₁₀), and ozone (O₃) concentrations, while twelve also measure the concentration of nitrogen oxides (NO_x). Particulate and ozone concentrations are measured in micrograms per cubic meter (μg/m³), while nitrogen oxide concentrations are measured in parts per billion (ppb).¹⁹ PM₁₀ and NO_x are primary pollutants, directly generated by burning, while O₃ is secondary, a by-product of primary pollutants interacting with the environment. For all variables except wind direction (discussed below), we convert hourly observations into a daily mean for every day with at least eight hours of raw data. We then compute rolling week averages, so that for each day t , we average daily readings between $t - 6$ and t if daily means were available for at least three days. Depending on the outcome, our data contain approximately 26,000 location-dates.²⁰

For winds, we similarly aggregate hourly measurements into the daily prevailing wind because we lack precise information on the start and end of each fire. To find the daily prevailing wind, we search for the sector of the wind rose that contains the most frequent occurrences, starting from the sector centered at due north and then increasing in intervals of 10 degrees.²¹ In our analysis of the pollution effects

¹⁸Like most other environmental agencies, CETESB targets population centers for monitoring, so our sample municipalities are more urban than the typical municipality in the sugar-growing region.

¹⁹Other commonly studied pollutants (e.g., PM_{2.5} and CO) are not available.

²⁰As reported in online appendix table A3, missing data are rare, and average pollution readings are far below current regulatory limits in the United States (<http://www.epa.gov/>) and São Paulo (<http://ar.cetesb.sp.gov.br/>).

²¹In cases of ties (mostly between overlapping sectors), we choose the lowest angle. To reduce noise, we assign no prevailing wind if the modal

TABLE 1.—SUGARCANE PRODUCTION, LABOR MARKETS, AND FIRES
DEPENDENT VARIABLE: MUNICIPALITY-LEVEL YEARLY/MONTHLY PROBABILITY-WEIGHTED COUNT OF FIRES PER 100 KM²

	Municipality-Year Panel (Fixed-Effects Estimations)				Municipality-Month Panel (First-Difference Estimations)	
	(1)	(2)	(3)	(4)	(5)	(6)
1 {Harvesting sugarcane in year}	0.37 (0.15)	0.13 (0.15)	0.18 (0.15)	0.16 (0.15)		
Share of area harvested (reference areas, <.05)						
.05 to 0.15		0.57 (0.16)	0.58 (0.17)	0.53 (0.16)		
.15 to 0.25		1.13 (0.20)	1.06 (0.22)	0.95 (0.21)		
.25 to 0.35		1.78 (0.27)	1.95 (0.28)	1.82 (0.28)		
.35 to 0.50		1.61 (0.33)	1.70 (0.37)	1.54 (0.37)		
.50 to 0.75		1.53 (0.44)	1.73 (0.51)	1.54 (0.50)		
.75 to 1		1.96 (0.79)	2.27 (1.12)	2.07 (1.12)		
ln municipal GDP per capita				0.98 (0.35)		
Job creation (per resident in 2010)					1.03 (0.23)	
Job destruction (per resident in 2010)					-1.70 (0.45)	
Wage bill increase with hires (in R\$1,000 per resident in 2010)						1.29 (0.38)
Wage bill reduction with destruction (in R\$1,000 per resident in 2010)						-1.50 (0.61)
Observations	7,095	7,095	5,805	5,805	45,795	45,795
Municipalities	645	645	645	645	645	645
Years covered	2004–2014	2004–2014	2004–2012	2004–2012	2009–2014	2009–2014

Standard errors clustered at the municipality level. All estimations include appropriate time fixed effects. INPE-probability-adjusted count of fires in a given municipality-year/month is used to construct dependent variables (summed across three satellites) and land area (excluding water bodies) for municipality used as the denominator. INPE probability adjustment of fires takes into consideration vegetation and weather conditions in the area of the captured pixel, assigning a value [0,1] for the likelihood of actual fire occurrence in a given location (see http://sigma.cptec.inpe.br/queimadas/documentos/doc_RF_2007.pdf). Agricultural production data from IBGE, GDP per capita from IPEA, and jobs data are from the Ministry of Labor (CAGED). Mean/SD value for probability-weighted count of fires is 2.8/3.8 (per year) and 0.41/1.1 (per month). Further estimations are presented in tables A1 and A2 in the online appendix.

of fires, which is akin to a first-stage relationship, we experiment with different central angles for this sector—30, 45, and 90 degrees—searching for the angle that best trades off the benefits of wider angles (more fires) and narrower angles (more precision in wind direction). We find that the octant (45 degrees) best captures pollution dispersion, so we use octants throughout our analysis of health outcomes.²²

Counting fires by wind direction is key to our research design. We count the the daily number of 1 km-by-1 km grid cells containing a fire within a 50 km radius of a municipality’s population centroid (averaged across the three satellites), omitting those within 5 km because they are unlikely to be related to agriculture. Fires occurring within the modal wind octant in a given day (and within 5 km to 50 km of the air quality station) are defined as upwind. From these daily measures, we compute rolling week counts.²³

sector accounts for fewer than eight hours or if the opposing sector accounts for more than two. Results are not sensitive to these choices.

²²As reported in online appendix table A4, winds are dispersed, with each octant typically accounting for 5% to 20% of a station’s hourly measurements. Stations record no wind in 5% to 20% of hours, leading to no prevailing wind on one-quarter to one-half of days for each station.

²³As reported in online appendix table A5, on average, 2.93 fires are detected near each monitoring station per week, or 1.86 when weighted by the probability of occurrence. Of these 1.86, 0.13 occur upwind on days with a prevailing wind.

Vital and hospital records. Data on birth and perinatal outcomes are drawn from individual-level vital records and hospitalization records in DATASUS, the Brazilian Ministry of Health’s Usage Information System.²⁴ To ensure correct wind measurement, we restrict our study to mothers residing in the thirteen sugar-growing municipalities with air monitoring stations, leading to a sample of 287,506 live singleton births.²⁵

Our primary outcomes are birthweight and gestational age at birth, drawn from the birth registry. Birthweight is measured continuously in grams or as an indicator for low (below 2,500 grams) or very low (below 1,500 grams) birthweight. Brazilian birth records code gestational age at birth in coarse categories, limiting our ability to analyze it as a continuous dependent variable and to estimate the date of conception. We define indicators for preterm (below 37 weeks) and very preterm (below 32 weeks) births, and we also impute weeks of gestation, using the weekly gestational age distribution in the United States to estimate the average gestational age

²⁴According to estimates from 2010, at least 99% of births and infant deaths were registered in the administrative areas containing the study sample (IBGE, 2011).

²⁵As reported in online appendix table A6, our sample accounts for a small share of São Paulo’s population, GDP, land area, sugarcane planting area, and fire activity, but average socioeconomic outcomes are broadly similar.

at birth within each category.²⁶ Secondary outcomes from the vital records data include one- and five-minute APGAR scores, reported stillbirths, the number of births, and mortality in the first full day (the day following the birthdate) and first week of life. We complement these data with the Ministry of Health's Hospitalization Records (SIH-DATASUS), which record hospital admissions charged to the public health care system.²⁷ To reduce computational demands and to link the birth, death, and hospitalization data without individual identifiers, we collapse individual records by location and date of birth, leading to a data set of average birth outcomes in 26,100 location-dates.²⁸ We weight all analyses by the number of observations within the location-date.

B. Estimation

We carry out two estimations—one linking fires to air pollution and the other to health outcomes. In all estimations, we cluster standard errors at the monitor (or municipality) level. Because our data have few clusters, we report *p*-values based on a wild cluster-bootstrap percentile-*t* procedure, following recommendations by Cameron, Gelbach, and Miller (2008).

To test our research design's assumption that upwind fires raise pollution more than downwind fires do, we first analyze air monitoring station data on pollutant concentrations. Our primary focus is particulate matter, a by-product of sugarcane burning with well-known health effects, but we also examine the other pollutants (NO_x and O₃) tracked by the stations to shed light on the composition of pollution from sugarcane burning. For the air monitoring station in municipality *j* on date *t*, we run the contemporaneous model:

$$y_{jt} = \alpha^U \text{upfires}_{jt} + \alpha^N \text{nonupfires}_{jt} + X'_{jt} \beta + \mu_j + \tau_t + \varepsilon_{jt}. \quad (1)$$

μ_j and τ_t are station and date fixed effects, respectively, so we only leverage within-station, within-time (rolling-week) variation. The dependent variable y_{jt} is the average pollution concentration from date $t - 6$ to t . The central covariates for our research design are upfires_{jt} and nonupfires_{jt} , which reflect upwind and other fires during the same week-long period. To ease interpretation, we transform the probability-weighted counts of fires into *z*-scores based on the average and standard deviation of total probability-weighted weekly counts of fires in the pooled sample. The vector X_{jt} includes weekly average temperature, weekly average relative humidity, the share of hours with no wind, the share of hours with winds blowing from each fixed octant of the wind rose, and the share of days with no prevailing wind. In this setup, $\alpha^U - \alpha^N$ cap-

tures the differential impact of upwind fires, relative to the overall association between fires and pollution.

Our infant health regression specification is similar to equation (1), except that the analysis of in utero exposure requires many lags. We set the number of lags to 38 weeks, allowing for week-specific effects of fires over the course of the potential pregnancy. However, backdating exposure in this way presents an estimation hurdle because the timing and length of pregnancy are endogenous.²⁹ Because selection biases estimates of the effects of exposure to fires occurring long before birth, we emphasize estimates pertaining to the last three months of pregnancy.

We thus employ a distributed lag model on grouped data, with births aggregated into municipality-birthdates. For births in municipality *j* on date *t*, we run

$$\bar{y}_{jt} = \sum_{s=0}^{38} \alpha_s^U \text{upfires}_{j,t-7s} + \sum_{s=0}^{38} \alpha_s^N \text{nonupfires}_{j,t-7s} + \sum_{s=0}^{38} X'_{j,t-7s} \beta_s + \mu_j + \tau_t + \varepsilon_{jt}, \quad (2)$$

where \bar{y}_{jt} is an average birth outcome for births occurring in location *j* on date *t*; μ_j and τ_t are municipality and date fixed effects; and α_s^U , α_s^N , and β_s are the distributed-lag versions of the coefficients from equation (1). Each independent variable is an average or count for the week leading up to date $t - 7s$, where *s* is multiplied by 7 because *t* is measured in days, while *s* is measured in weeks.

The differential impact of an upwind fire occurring *s* weeks before birth is $\alpha_s^U - \alpha_s^N$. Equation (2) yields many week-specific estimates. To reduce noise, we report sums of the coefficients for blocks of thirteen weeks, corresponding to the last, second-to-last, and third-to-last periods before birth,

$$\alpha_{\{\underline{T}, \bar{T}\}} \equiv \sum_{s=\underline{T}}^{\bar{T}} \alpha_s^U - \alpha_s^N,$$

where the periods $\{\underline{T}, \bar{T}\}$ are $\{0, 12\}$, $\{13, 25\}$, and $\{26, 38\}$. These sums represent the impact of increasing fires by one occurrence per week during periods of approximately three months.³⁰ Despite the similarity between these periods and pregnancy trimesters, we refrain from referring to them as such because we count backward from the date of birth rather than forward from the date of conception. Given the selection biases due to backdating, we view our estimate of $\alpha_{\{0,12\}}$, relative to the period closest to birth, as being more interpretable

²⁶Births are distributed similarly across categories (17–21, 22–27, 28–31, 32–36, 37–41, and 42–47 weeks) in São Paulo and the United States.

²⁷A newborn is admitted to the hospital separately from the mother in cases of pronounced vulnerability, such as admission to a neonatal intensive care unit.

²⁸Online appendix table A7 presents summary statistics for the births data set.

²⁹Brazilian birth records code gestational age coarsely, so we cannot backdate conception.

³⁰Existing research typically uses trimester-averaged covariates, which in our model would correspond to imposing that the weekly coefficients are identical within each block of thirteen weeks.

TABLE 2.—EFFECTS OF FIRES ON AVERAGE WEEKLY AIR POLLUTION
PROBABILITY-WEIGHTED COUNTS OF FIRES WITHIN 50 KM OF STATIONS (*z*-SCORES)

	Particulate Matter (PM ₁₀)		Nitrogen Oxides (NO _x)		Ozone (O ₃)
	(1)	(2)	(3)	(4)	(5)
Fires during week ending in <i>t</i>	2.68 (0.61) [<.001]	2.47 (0.58) [<.001]			
Upwind fires during week ending in <i>t</i>			9.87 (2.44) [<.001]	-0.86 (0.94) [.784]	2.13 (1.43) [.200]
Nonupwind fires during week ending in <i>t</i>			2.05 (0.55) [<.001]	0.35 (0.27) [.216]	-0.30 (0.61) [.720]
Upwind versus nonupwind			7.83 (2.43) [<.001]	-0.61 (0.75) [.408]	2.43 (1.16) [.048]
Upwind versus nonupwind (weighted by birth cohorts in week-location)			10.47 (2.60) [<.001]	0.05 (1.30) [.968]	3.10 (1.41) [.064]
Controls					
Date FE	Yes	Yes	Yes	Yes	Yes
Location FE	Yes	Yes	Yes	Yes	Yes
Weather	No	Yes	Yes	Yes	Yes
Mean of dependent variable		31.4		15.3	39.5
SD of dependent variable (total/between/within)		16.1 / 5.3 / 15.2		9.1 / 4.9 / 7.7	13.3 / 4.5 / 12.6
Observations		26,342		23,448	27,159

Observations are at the station-date level. Robust standard errors in parentheses are clustered at the station level. The *p*-values reported in brackets under standard errors are based on wild bootstrap (249 replications). There are twelve stations observed between 2009 and 2014 and one station observed between 2009 and 2013. Weather controls include average temperature, relative humidity and their interactions, share of hours with a given direction of wind (fixed octants), and periods of calm and nonmeasured winds.

than our estimates of $\alpha_{\{13,25\}}$ and $\alpha_{\{26,38\}}$, which would reflect earlier stages of the pregnancy.

By interpreting the differential association of upwind fires with health as a causal effect, we assume that the interaction of fire locations and wind direction is exogenous to the causal system. Identification comes from comparing different types of fires within the same area, not from comparing different areas. If we were comparing upwind and other fires in the cross section, then sorting would be a concern, but our inclusion of municipality fixed effects eliminates most of this concern. One could also worry that mothers time their pregnancies to exposure, but we show that our results are robust to municipality-by-week-of-year fixed effects. A final concern is that harvesters avoid burning on windy days, but we control flexibly for the presence and direction of wind.

V. Pollution and Health: Results

A. Effects of Fires on Air Pollution

Table 2 reports estimations of equation (1), revealing that upwind fires differentially increase PM₁₀ and O₃ but not NO_x. We first focus on our main choices for the central angle of the upwind sector, 45 degrees, and the radius of the catchment area, 50 km, and then discuss online appendix results on alternative angles and radii.

To build intuition, we start with an unsophisticated specification for PM₁₀ and then gradually refine it. Columns 1 and 2 report results for unweighted counts of fires, disregarding their orientation to the wind. In column 1, which does

not control for atmospheric conditions, a *z*-score increase in probability-weighted fire activity in a given week raises contemporaneous PM₁₀ concentrations by 2.7 units, or 9% of the average weekly PM₁₀ concentration in the sample. Controlling for atmospheric conditions in column 2 does little to change this estimated effect.

In column 3, we decompose probability-weighted fire counts into upwind fires, which are located in the prevailing wind octant, and nonupwind fires, which are located at other angles to the prevailing wind or take place on days without a prevailing wind. Coefficient estimates now indicate that the equivalent increase in upwind and nonupwind fire activity has a very different impact on pollution readings. A *z*-score increase in upwind fires raises PM₁₀ by 9.9 units (30% of the average), but the same increase in nonupwind fires raises PM₁₀ by only 2.0 units. Our identifying variation for the rest of the analysis comes from the difference between these effects, which at 7.8 is highly statistically significant based on both asymptotic and bootstrap inference. Relative to nonupwind fires, a *z*-score increase in upwind fires raises PM₁₀ concentrations by half of a standard deviation. We apply the same model to measures of NO_x and O₃ in columns 4 and 5, respectively. These pollutants are primary and secondary by-products of biomass burning, respectively. They may appear at different stages of the burning process because they have different dispersion properties and because sunlight interacts with some nitrogen oxides to produce ozone. Column 5 reveals a significant differential upwind-fire impact on O₃ of 2.4 units, or one-fifth of a standard deviation. Meanwhile, column 4 shows no evidence of a differential impact on NO_x by wind direction. These results are internally consistent; the

TABLE 3.—EFFECTS OF FIRES ON BIRTHWEIGHT AND GESTATIONAL AGE AT BIRTH
PROBABILITY-WEIGHTED COUNTS OF FIRES WITHIN 50 KM OF STATIONS (z -SCORES)

	All Fires (1)	All Fires (2)	Upwind Fires (3)	Nonupwind Fires (4)	Upwind versus Nonupwind		
					Difference (5)	Difference (6)	Difference (7)
Birthweight (in Grams)							
Fires/week in weeks 0–12 before birth	5.66 (3.37) [.080]	8.11 (4.31) [.136]	−83.42 (23.31) [.024]	14.21 (3.89) [<.001]	−97.63 (23.52) [.008]	35.03 (12.58) [.020]	21.63 (7.38) [.056]
Fires/week in weeks 13–25 before birth	4.81 (2.72) [.144]	9.23 (3.32) [.040]	44.81 (32.44) [.232]	9.01 (3.09) [.056]	35.80 (32.68) [.328]	2.32 (17.85) [.832]	−6.54 (9.68) [.552]
Fires/week in weeks 26–38 before birth	2.55 (3.83) [.600]	−4.04 (6.00) [.568]	−40.46 (37.63) [.312]	−1.09 (5.72) [.800]	−39.36 (36.95) [.280]	−15.03 (17.94) [.644]	6.58 (9.37) [.452]
Mean/SD dependent variables	3,159.3 / 161.8					80.7 / 83.7	12.4 / 34.2
Gestational Age (in Weeks)							
Fires/week in weeks 0–12 before birth	0.006 (0.013) [.792]	0.022 (0.015) [.280]	−0.309 (0.092) [.032]	0.044 (0.014) [.024]	−0.353 (0.093) [.024]	18.56 (23.81) [.544]	23.06 (4.72) [<.001]
Fires/week in weeks 13–25 before birth	0.023 (0.006) [.024]	0.024 (0.015) [.232]	0.028 (0.129) [.904]	0.030 (0.013) [.096]	−0.001 (0.129) [.956]	−22.54 (16.44) [.140]	−2.62 (9.38) [.796]
Fires/week in weeks 26–38 before birth	0.010 (0.010) [.272]	0.009 (0.018) [.744]	−0.117 (0.107) [.312]	0.020 (0.017) [.344]	−0.137 (0.106) [.228]	16.22 (17.94) [.392]	6.99 (8.36) [.468]
Mean/SD dependent variables	38.6 / 0.5					96.9 / 93.6	12.4 / 34.4
Controls							
Date FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather	No	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors in parentheses are clustered at the station level. The p -values reported in brackets under standard errors are based on wild bootstrap (249 replications). Observations are at the municipality-day level and they are weighted by the size of local birth cohort in that location-day. There are twelve stations observed between 2009 and 2014 and one station observed between 2009 and 2013. Weather controls include average temperature and relative humidity and their interactions, direction of wind (fixed octants), periods of calm, and periods of nonmeasured winds.

exposure of NO_x to sunlight leads to a chemical reaction that produces O_3 in less than one week, so NO_x is not expected to travel with the wind for long distances. The results are stronger when we weight location-dates by the number of births to match the analysis of health outcomes.

Online appendix table A8 further explores these results. First, we confirm that the results are the same when we restrict to location-dates with measurements of all three pollutants. Next, we consider the presence of nonlinearities in the impact of fire activity, which we capture by additionally including an indicator for weeks of any upwind fire activity. We find similar impacts on the intensive margin for PM_{10} and O_3 . When we apply a stricter definition of the prevailing wind, requiring twelve hours of wind (rather than eight) from the same octant, we find stronger effects. When we consider alternative central angles of 30 and 90 degrees for the upwind sector, we find coefficients of the same sign but with coefficients and t -statistics smaller than those in table 2. Because the 45-degree definition appears to best capture pollution dispersion, we use it henceforth. When we assess alternatives to the 50 km radius we use for our catchment area, we find larger standard errors with smaller radii but similar conclusions. We then investigate robustness to alternative specifications of time effects and local-level seasonality by including station-by-

year fixed effects and station-by-week-of-year fixed effects. Even these more demanding specifications, which account for station-specific annual and seasonal trends, do not alter the magnitudes or significance levels of the estimated pollution effects. Finally, we reestimate the models employing log transformations of the dependent variables in columns. Our results remain statistically significant and somewhat similar in magnitude to the level estimates, relative to the outcome means, with implied upwind fire impacts of 17% for PM_{10} and 4% for O_3 .

B. Effects of Fires on Health at Birth

Birthweight and gestational age at birth. Table 3 reports estimates of the thirteen-week sums of coefficients for our primary birth outcomes, birthweight, and gestational age at birth. Columns 1 to 5 build up the full model for birthweight and imputed gestational age across three regressions, first disregarding wind and leaving out the atmospheric condition covariates X_{jt} , then adding X_{jt} , and finally differentiating by wind direction. Columns 6 and 7 then apply the full model to indicators for low and very low birthweight and indicators for preterm and very preterm.

TABLE 4.—DIFFERENTIAL EFFECTS OF IN UTERO UPWIND FIRES ON FETAL MORTALITY, NEONATAL MORTALITY, AND MORBIDITY
PROBABILITY-WEIGHTED COUNTS OF FIRES WITHIN 50 KM OF STATIONS (z-SCORES)

	Fetal Mortality		Neonatal Mortality (per 1,000)		Hospitalizations in First Full Day of Life (per 1,000)		APGAR Score	
	Fetal Death per 1,000 (1)	In Live Births × 100 (2)	First Day (3)	First Week (4)	All Causes (5)	Fetal Growth Causes (6)	1-Minute (7)	5-Minute (8)
Fires/week in weeks 0–12 before birth	16.59 (4.26) [<.001]	−11.67 (4.03) [.008]	1.79 (5.64) [.848]	2.49 (7.79) [.896]	6.07 (15.80) [.696]	6.35 (3.66) [.072]	0.06 (0.13) [.592]	−0.06 (0.15) [.856]
Fires/week in weeks 13–25 before birth	−6.91 (6.39) [.328]	−0.46 (4.52) [.944]	−0.86 (3.18) [.816]	7.65 (6.78) [.208]	22.73 (21.47) [.256]	5.64 (2.15) [.064]	0.21 (0.14) [.168]	0.06 (0.09) [.520]
Fires/week in weeks 26–38 before birth	8.81 (3.40) [.064]	1.80 (8.18) [.816]	6.35 (4.39) [.120]	13.94 (6.07) [.040]	−9.34 (17.31) [.536]	2.52 (2.91) [.352]	−0.18 (0.13) [.152]	−0.07 (0.11) [.520]
Controls								
Date FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Municipality FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Mean of dependent Variable	7.7	260.2	2.6	5.7	49.2	1.5	8.5	9.5
SD of dependent Variable	26.3	59.8	18.0	26.8	74.1	11.1	0.5	0.3
Observations	26,198	26,190	26,190	26,190	26,190	26,190	26,189	26,189

Robust standard errors in parentheses are clustered at the station level. The *p*-values reported in brackets under standard errors are based on wild bootstrap (249 replications). All regressions are weighted by the number of observations in each date-location.

In columns 1 and 2, the results for all fires within 5 and 50 km is positive and, in some cases, even significant. For example, an additional *z*-score of fire activity per week occurring in the last 13 weeks of gestation is associated with a 5.7 to 8.1 gram increase in birthweight, with *p*-values of roughly 0.1. Similar associations are evident for 13 to 25 weeks before birth but not for 26 to 38 weeks before birth. By the same token, some positive associations are observed for gestational age despite wider confidence intervals. Therefore, a naive panel data analysis with location and time fixed effects leads to the conclusion that in utero exposure to fires has marginally significant, positive effects on birth outcomes.

However, these positive associations appear to mostly reflect the child health benefits of increased economic activity, which can be seen by contrasting the sums of coefficients for upwind (column 3) and nonupwind fires (column 4), estimated in the a single regression. Here, a 1 *z*-score increase in upwind fire activity per week during the last 13 weeks of gestation is associated with significant decreases in birthweight and gestational age, by 83.4 grams and 0.31 weeks, respectively, consistent with a dominant negative effect of fire-related air pollution. Meanwhile, all other fires during this final period of gestation are associated with significant increases in these outcomes, by 14.2 grams and 0.04 weeks. When fire activity does not put mothers at extreme risk for pollution exposure, it correlates with improvements in the in utero environment. But when wind carries the smoke toward mothers, the detrimental effects of pollution outweigh these benefits.

Column 5 reports the difference between the upwind and nonupwind coefficients, revealing that in the last gestational period, the pollution differentially generated by an additional

z-score of upwind fire activity significantly reduces birthweight by 98 grams and gestational length by 0.35 weeks. The other two gestational periods exhibit no significant effects, although they are more prone to concerns about selection from prematurity.

The remainder of table 3 reports differential effects of upwind fires on binary indicators for adverse birth outcomes. In the top panel, columns 6 and 7 show that the birthweight effects are detectable at the lower tail of the birthweight distribution. An additional *z*-score of fire activity per week in the last gestational period raises the incidence of low birthweight by 35 per 1,000 (on a base risk of 81 per 1,000) and the incidence of very low birthweight by 22 per 1,000 (on a base of 12 per 1,000). Some part of these reductions in birthweight may be attributable to earlier birth. Rates of preterm birth rise insignificantly, while rates of very preterm births rise significantly, by 23 per 1,000 (on a base of 12 per 1,000). Across all these outcomes, we again find no evidence of detrimental effects of upwind fires during earlier gestational periods.

Perinatal morbidity and mortality. Besides birthweight and gestational age at birth, vital statistics and hospitalization data provide other useful measures of health in the period immediately surrounding birth—the perinatal period. Using the same approach as table 3, table 4 analyzes these data, focusing on fetal mortality first, early neonatal mortality (in the first week of life) next, and morbidity among the living last.

Table 4 presents estimates of the differential effects of upwind fires on the reported stillbirth rate and the number of births. Because stillbirths may be underreported, we use the number of births as a broader proxy for in utero survival, a

TABLE 5.—ROBUSTNESS AND FALSIFICATION CHECKS FOR DIFFERENTIAL EFFECTS OF UPWIND FIRES IN THE FINAL GESTATIONAL PERIOD
PROBABILITY-WEIGHTED COUNTS OF FIRES WITHIN 50 KM OF STATIONS (z-SCORES)

	Robustness				Falsifications		
	Base Model (1)	Base Model + Covariates (2)	Station-Year FE (3)	Station-Week FE (4)	Out-of-Sample Births (5-Year Lag) (5)	In-Sample Random Year (6)	In-Sample Random Location (7)
Birthweight (grams)	−97.63 (23.52) [.008]	−95.63 (28.80) [.008]	−127.20 (26.20) [.008]	−110.80 (30.83) [.016]	8.43 (14.52) [.432]	[0.984]	[0.996]
LBW (per 1,000)	35.03 (12.58) [.020]	34.14 (13.84) [.016]	42.36 (14.14) [.016]	34.64 (14.63) [.016]	−18.60 (13.29) [.216]	[0.848]	[0.984]
VLBW (per 1,000)	21.63 (7.38) [.056]	21.96 (7.50) [.024]	20.30 (5.30) [.008]	14.87 (6.34) [.048]	−0.88 (5.95) [.888]	[0.952]	[0.996]
Gestational age (weeks)	−0.353 (0.093) [.024]	−0.349 (0.099) [.016]	−0.270 (0.083) [.008]	−0.345 (0.097) [.008]	−0.02 (0.17) [.896]	[0.975]	[>.999]
Premature (per 1,000)	18.56 (23.81) [.544]	16.64 (23.43) [.472]	19.00 (17.26) [.272]	17.05 (32.78) [.664]	−21.49 (22.21) [.384]	[0.650]	[0.811]
Very premature (per 1,000)	23.06 (4.72) [<.001]	23.29 (4.70) [<.001]	17.53 (5.07) [<.001]	19.00 (3.50) [<.001]	22.65 (14.88) [.136]	[0.980]	[>.999]
Controls							
Date FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Station FE	Yes	Yes	No	No	Yes	Yes	Yes
Weather	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Maternal-child demographics	No	Yes	No	No	No	No	No
Station × Year FE	No	No	Yes	No	No	No	No
Station × Week-of-Year FE	No	No	No	Yes	No	No	No
Observations	26,190	26,190	26,190	26,190	25,896		
In-sample falsification draws						249	249

Robust standard errors in parentheses are clustered at the station level. The p -values reported in brackets under standard errors are based on wild bootstrap (249 replications). In columns (7) and (8), numbers in brackets indicate percent of draws in which the estimate was smaller than the full model estimate in column (1). All regressions are weighted by number of observations in each data–location.

strategy similar to Jayachandran (2009). Column 1 considers reported stillbirths, finding that an additional z -score of upwind fire activity over the final gestational period differentially increases the stillbirth rate by 17 per 1,000 births, more than half of a standard deviation. Column 2 looks at the logarithm of the daily number of live births.³¹ The same rise in upwind fire activity during the final gestational period differentially decreases the number of live births by 12%, providing further evidence of fetal death.

For postnatal mortality, we use the share of live infants in a municipality–birthdate who died within a day or a week of birth. As displayed in columns (3) and (4), neither measure of newborn death shows a significant effect from fire exposure late in gestation, although the point estimates are positive.³² However, standard errors are large, and we lack the power to detect meaningful effects. Prenatal mortality may also select out the infants at highest risk for postnatal mortality. For morbidity, we consider rates of hospital admissions (for all causes and for causes related to fetal growth faltering and prematurity) charged to the public health care system by the end of the first full day of life, as well as average 1- and 5-minute APGAR scores, which reflect how well the new-

born tolerates delivery and conditions outside the womb, respectively. While we do not observe APGAR impacts, we find a marginally significant uptick in fetal growth-related hospitalizations.

Robustness and heterogeneity. While equation 2 is exacting, one may still be concerned about confounding maternal characteristics, location-specific time trends, and location-specific seasonality. These factors should not be differentially associated with fire location interacted with daily wind direction, so they should not bias our estimates, but we can confirm empirically. For our primary birth outcomes in the final gestational period, table 5 takes two approaches to addressing these concerns, assessing robustness to additional covariates and fixed effects and carrying out falsification checks.

After column 1 reprints the baseline estimate, the next three columns explore alternative specifications. Column 2 adds municipality–birthdate averages of maternal and infant characteristics as covariates, column 3 introduces station-by-year fixed effects, and column 4 introduces station-by-week-of-year fixed effects.³³ Our results are broadly robust across these alternatives.

³¹Less than 1% of municipality birthdates have no births.

³²One-week mortality significantly increases with upwind fire exposure in the earliest period, but we do not emphasize this result because of concerns about selection and endogenous fertility.

³³Online appendix table A9 uses maternal and infant characteristics as outcomes, confirming that they are not differentially associated with fires by wind direction in the final gestational period.

The remaining columns of table 5 implement falsification checks. Column 5 estimates the original model with dependent variables measured at a five-year lag, finding no significant effects. Columns 6 and 7 reassign fire counts from either a random year (for the same municipality and day of the year) or random location (for the same birthdate). We perform each randomization 249 times and report the proportion of placebo samples with point estimates less extreme than our baseline estimates. In all cases except preterm birth (for which table 3 did not show a statistically significant effect), our baseline estimate is more extreme than 95% of the placebo estimates.³⁴

A possible critique is that we test many hypotheses, so standard p -value thresholds may be inappropriate. Following the existing literature on fetal exposure and health at birth (Currie, Neidell, & Schmieder, 2009), our primary outcomes are birthweight and gestational age (and transformations thereof); other outcomes are reported for additional insight. Choosing the continuous measure of each primary outcome, we have two tests for the final gestational period, which we view as most credible due to reduced risk of bias, and six tests across all gestational periods. At the 5% level, a Bonferroni correction leads to a p -value threshold of 0.025 when focusing just on the final gestational period and 0.008 when including all gestational periods. Our p -values for late-pregnancy effects on birthweight and gestational age meet the first criterion, and the birthweight result meets the second. If we treat all outcomes as equally important and choose the most general measure of each outcome, then we have six tests for the final gestational period and eighteen tests across all periods. With six tests, the p -value threshold is 0.008, which is met for birthweight and stillbirths; with eighteen, the threshold becomes 0.003, which is met only for stillbirths. Due to correlation across outcomes and bias in estimates for earlier gestational periods, we believe these thresholds are too conservative.

Which infants are most affected by fires? Two features of the data are relevant: which infants are born following peak periods of exposure and which infants are more susceptible to pollution. Online appendix figures A4 and A5 show that late in the harvest season, the number of births falls, while average health at birth and average maternal characteristics improve. These patterns suggest that infants at risk for this particular health shock have better-off parents and greater health endowments than the average infant. At the same time, online appendix table A11 estimates separate effects by child sex, maternal age, and maternal education, finding no significant heterogeneity.

Extensions

Does prematurity explain the birthweight results? Low birthweight has two proximate determinants: intrauterine

growth restriction and preterm delivery. The theory involving maternal inflammation and preterm labor predicts an important role for the latter. Online appendix table A12 finds that including gestational age as a covariate reduces the main birthweight result by half and renders the low and very low birthweight results insignificant. Shorter gestation can account for much of the birthweight effect, particularly in the lower tail of the distribution.

Maternal health. An effect of environmental conditions during gestation presumes a mechanism involving the mother's body—for instance, infection and related inflammation. To investigate this issue, we draw on SIH-DATASUS data on hospital admissions charged to the public health care system, focusing on women of childbearing age (15–45).³⁵ Online appendix table A13 estimates equation (1) using the inverse hyperbolic sine of the weekly hospitalization rate as the dependent variable, finding a significant positive differential effect of upwind fires on hospitalization of reproductive-age women.

Postnatal fire exposure and infant mortality. We prioritize prenatal exposure and health at birth over postnatal exposure and infant health because infant mortality is rare in our setting, and our small number of clusters leaves us underpowered to detect effects on it. For completeness, we apply the approach from the “Robustness and Heterogeneity” section to infant hospitalizations and deaths in online appendix table A13 (panels B and C), finding positive point estimates for infant hospitalizations but no significant effect on either outcome.

VI. Interpretation

A. Comparison with Existing Literature

To compare our results with the existing literature, it is useful to convert them to health effects per unit of pollutant. A straightforward approach is to divide health effects by pollution effects, akin to a Wald estimator. Due to the resuspension of ashes, however, we need to incorporate the lag structure of the fire-pollution relationship. In a distributed lag version of equation (1), an additional z -score of upwind fire activity over thirteen weeks leads to a population-weighted increase in PM_{10} of $18.7 \mu\text{g}/\text{m}^3$ ($SE = 4.5$), roughly 75% larger than the contemporaneous effect in table 2. The Wald calculation implies a 5.2 gram reduction in birthweight per unit ($\mu\text{g}/\text{m}^3$) of PM_{10} averaged over the final three months of gestation. Because PM_{10} is correlated with other pollutants, this quantity should not be interpreted as the causal effect of PM_{10} , but it can serve as a benchmark.

The literature on pollution and infant health offers few estimates of the effect of in utero PM_{10} exposure on birth outcomes. In a meta-analysis, Stieb et al. (2012) find a wide range of positive to negative associations between PM_{10} exposure

³⁴Online appendix table A10 reports results for larger samples that include municipalities within 10 to 20 km of the air monitoring stations. Consistent with increased measurement error in wind, estimated effects shrink as we include municipalities farther from the stations.

³⁵We lack power to detect effects by specific causes. We have verified that overnight stays after delivery do not account for our results.

and birthweight, with a significantly negative but moderate pooled estimate for exposure over the entire pregnancy, about 1 gram per unit of PM_{10} . The wide variation in effect sizes across studies reinforces the motivation for our research: that standard epidemiological approaches to studying the infant health effects of air pollution are confounded. The study that goes furthest in addressing this concern is by Currie et al. (2009), who use data from New Jersey to study the association of PM_{10} with birthweight by trimester, controlling for place-by-season and mother fixed effects. This design eliminates confounding from composition and seasonality but not economic activity. Imprecise estimates imply that a unit increase in final-trimester PM_{10} exposure is associated with a 0.4 (95% CI: -0.3 – 1.1) gram reduction in birthweight for all mothers and a 2.4 (95% CI: -0.3 – 5.1) gram reduction for smoking mothers.³⁶

On net, our estimates are large relative to the literature, but our confidence intervals overlap those for high-risk populations in other settings. The differences may be due to impact heterogeneity or economic confounding in the other research designs.

B. Implications for Mechanization

The governments of São Paulo and other sugar-growing states have been encouraging sugarcane producers to adopt mechanized harvesting, with the goal of reducing air pollution and improving health. Given our results on fires, is mechanization likely to improve newborn health? Because mechanization represents an equilibrium response to changing market and regulatory conditions, its pollution-related health effects are difficult to separate from any health effects due to its economic causes and consequences. Unfortunately, we are unaware of compelling instruments to separate these mechanisms. But to shed partial light on this question, we analyze how environmental, economic, and health outcomes change with the adoption of mechanized methods over time and across municipalities. To measure mechanization, we draw on municipality-year data from the CANASAT project (Aguiar et al., 2011), which uses satellite remote-sensing techniques to detect (traditional) burn harvesting and (mechanized) green harvesting.

Conditional on total area harvested, municipality fixed effects, and year fixed effects, online appendix table A14 finds that the green harvested area is negatively associated with fires, GDP per capita, total job creation, and sugarcane job creation. These results are consistent with the labor-saving properties of mechanization, which may offset any environmental health benefits to infants. Indeed, green harvesting is not significantly associated with birthweight. While this result does not necessarily reflect the causal effect of mechanization, it reinforces the importance of separately understanding the health costs of pollution and the health benefits of local economic activity.

VII. Conclusion

Farmers have used fire as a tool in agriculture for thousands of years, but the health effects of this pollution source are not fully understood. We use data from a major sugar-producing area in Brazil to study the health effects of pollution from fires used during harvest. Using changes in wind direction and fire location to untangle health effects from confounding local business cycle variation, we find a causal pathway running from smoke exposure to reduced birthweight, shorter gestation, and increased risk of stillbirth. Our reliance on high-frequency changes in wind direction and fire location is key; by itself, panel variation in fires leads to misleading results, most likely because harvest activities are so deeply intertwined with improved economic conditions.

One implication of our findings is that the dose response relationship is steep even at low pollution levels, so concerns about the health effects of air pollution should not stop at the periphery of cities or industrial centers. The pollution levels in our study are virtually ignored by environmental agencies across the globe, yet they appear to be a significant health threat.

How helpful are our estimates for thinking about the infant health impacts of agricultural fires globally? Sugarcane is cultivated on five continents, and harvesting methods in most contexts involve at least some fire. Moreover, wheat, maize, and rice residues are burned in greater quantities than sugarcane residues (FAO, 2017), in similarly scaled, controlled fires with similar emissions (Andreae & Merlet, 2001). Increases in population density and market integration may intensify the use of fire in rural areas, with urban spillovers. Examples can be found in India, where field fires in rural Punjab send a cloud of particulate matter to nearby Delhi every November (Pande & Sugathan, 2015); in Indonesia, where land-clearing fires in the country's peatlands export haze to various Southeast Asian metropolises (Tacconi, 2016); and even in the United States (McCarty, Justice, & Korontzi, 2007), where sugarcane farms in the South light fires similar to those in Brazil.

Modern agricultural technology offers potential ways to mitigate the intensification of fire activity, but with complicated economic consequences. For many crops, combines, mechanical harvesters, and ploughs reduce the need for fire, but possibly with offsetting health costs due to labor displacement. While some settings are rapidly mechanizing, others are not. Smallholder sugar farms in Brazil are one example, as are smallholder farms across sub-Saharan Africa, where slash-and-burn agriculture remains prevalent (Andreae, 1991). Results like ours should attract more attention to the trade-offs involved with the elimination of agricultural air pollution.

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³⁶Brazilian natality data lack information on smoking.

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