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Foetal Exposure to Air Pollution and Students' Cognitive Performance: Evidence from Agricultural Fires in Brazil*

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Abstract

This paper examines the impact of foetal exposure to air pollution from agricultural fires on Brazilian students' cognitive performance later in life. We rely on comparisons across children who were upwind and downwind of the fires while *in utero* to address concerns around sorting and temporary income shocks. Our findings show that agricultural fires increase $PM_{2.5}$, resulting in significant negative effects on pupils' scores in Portuguese and Maths in the 5th grade through prenatal exposure. Back-of-the-envelope calculations suggest that a 1% reduction in $PM_{2.5}$ from agricultural burning has the potential to increase later life wages by 2.6%.

I. Introduction

Controlled agricultural burning is a traditional technique commonly used by farmers, particularly in parts of the developing world, to clear fields from previous harvests and to regenerate nutrients in the soil for the next seeding phase. There is growing evidence, however, that the smoke from agricultural fires contributes to increasing levels of fine particulates in the air, causing harmful health outcomes for nearby communities (Andreae and Merlet, 2001; Zhang, Liu, and Hao, 2016; Chen *et al.*, 2017; Lai *et al.*, 2018; Rangel and Vogl, 2019; He, Liu, and Zhou, 2020). Since there is also compelling evidence that exposure to poor air quality can result in cognitive impairment (Currie, Neidell, and Schmieder, 2009b; Sanders, 2012; Bharadwaj *et al.*, 2017; Almond, Currie, and Duque, 2018), the prevalence of agricultural burning in many countries suggests that

cognitive impacts may be widespread in such rural communities. Focusing on Brazil, the purpose of this paper is to estimate the long-run causal effects of foetal exposure to air pollution from agricultural fires on students' academic performance in 5th grade (aged 10) national examinations.

A growing body of research has shown the *contemporaneous* effects of agricultural fires on cognitive outcomes of the elderly (Lai *et al.*, 2018), on mortality rates (He *et al.*, 2020), and on students' scores in university entrance examinations (Graff-Zivin *et al.*, 2020), while Rangel and Vogl (2019) examine the effects of such fires on health at birth. However, to the best of our knowledge the effects of prenatal exposure to air pollution from agricultural burning on pupils' scores *later in life* have yet to be examined.[1] Filling this gap is challenging for several reasons. First, air pollution levels may be correlated with students' performance since parents may choose their residence according to the air quality of the region. Second, seasonal agricultural fires may raise farmers' productivity and incomes, and thus may affect students' cognitive performance by allowing parents to invest more in their children. Finally, sugarcane is harvested in Brazil in the winter, hence seasonality in weather conditions and winter-related diseases could potentially result in a spurious correlation between fires and foetal health.[2]

To address these challenges we follow Rangel and Vogl (2019) and interact fires with wind direction enabling us to predict spatial variation in the dispersion of smoke without being directly related to prenatal health or students' scores. As such, we are capable of causally evaluating the different cognitive outcomes of agricultural burning on pupils born upwind and downwind of the fires. Our study contributes to the literature in three ways. First, while Rangel and Vogl (2019) examine the short-term effects of prenatal exposure to agricultural fires on babies' health, we provide the first analysis of the longer term effects (pupils' scores in the 5th grade). Second, we focus on the effects of fire-induced *air pollution* on human health and hence show the mechanism through which fires affect health. To this end, we utilize an instrumental variable approach using counts of fires upwind from the population centroid of the municipality in which each student attended school, which arguably provides plausibly exogenous shocks to air pollution[3]. Finally, we examine fine particulate matter ($PM_{2.5}$)[4], which is the main by-product of agricultural burning and is recognized as having a stronger negative link with health and human capital than PM_{10} used in previous work (Zanobetti and Schwartz, 2009).

In a similar approach to ours, He *et al.* (2020) use the differences between upwind and downwind fires in China as instruments for air pollution to estimate the effects of straw burning on mortality. Our study is also related to Graff-Zivin *et al.* (2020)

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[1]Other works have investigated the prenatal exposure to air pollution on students' performance but not in the context of agricultural fires. For an extensive literature review (Currie *et al.*, 2014; Almond *et al.*, 2018).

[2]Although a number of studies in the medical literature show a negative effect of biomass burning on health (Arbex *et al.*, 2004; Cançado *et al.*, 2006; Ribeiro, 2008; Uriarte *et al.*, 2009), or its positive impact on asthma hospitalizations (Arbex *et al.*, 2007) in Brazil, these studies still fall short of showing a causal relation by failing to disentangle the confounding effects of other health determinants that are also correlated with controlled fires.

[3]Although we have secondary data on the place of birth, we cannot merge it with our main education data set. Therefore, we use each municipality's population centroid where the student attended school as a plausible proxy for municipality of birth since we calculate that 92% of students interviewed by the *Educational Census* in 2011 lived in the same municipality they were born. Section IV presents more detailed explanation on this migration issue.

[4]$PM_{2.5}$ refers to fine aerosol particles with a diameter of less than or equal to 2.5 micrometres (μm) near the surface.

who investigate the effects of smoke from fires on the day of the Chinese university entrance examinations on candidates' performance, but their study is unable to establish the causal relation between air pollution and students' cognitive outcomes due to a lack of pollution data at the exact moment of the exams. Finally, we complement Bharadwaj *et al.* (2017) and Isen, Rossin-Slater, and Walker (2014) by calculating the returns to cleaner air quality in terms of examination scores and, in turn, wages in Brazil.

More generally, this paper contributes to an extensive body of literature that relates the impact of air pollution to negative health outcomes (Seaton *et al.*, 1995; Chay and Greenstone, 2003; Currie and Neidell, 2005; Ebenstein *et al.*, 2017); to a decrease in the productivity of low- and high-skilled workers' (Chang *et al.*, 2016; Heyes, Neidell, and Saberian, 2016; Archsmith, Heyes, and Saberian, 2018; Chang *et al.*, 2019; Kahn and Li, 2019); to an increase in school absenteeism (Currie *et al.*, 2009a; Ransom and Pope, 2013; Chen, Guo, and Huang, 2018; Liu and Salvo, 2018); and to a decrease in cognitive performance (Zweig, Ham, and Avol, 2009; Currie *et al.*, 2009a; Reyes, 2011; Ebenstein, Lavy, and Roth, 2016) due to its harmful effects on the respiratory and cardiovascular systems (Dockery *et al.*, 1993; Seaton *et al.*, 1995). Our work also adds to the foetal origins hypothesis literature (Currie *et al.*, 2009b, 2014; Sanders, 2012; Bharadwaj *et al.*, 2017; Almond *et al.*, 2018) insofar as we aim to demonstrate the long-run damages caused by air pollution derived from agricultural fires during pregnancy in locations where concentrations of $PM_{2.5}$ would not traditionally have been considered to be high. Indeed, our data from the Brazilian Institute of Geography and Statistics (IBGE), indicates that around 61% of fires take place on agricultural land.[5]

For our analysis we build an individual-level pooled cross-sectional data set with infants born between 2001 and 2008 in São Paulo state, Brazil which we merge by month, year of birth and municipality of residence with the location of the active fires. To control for atmospheric conditions that could also affect intrauterine health, we use satellite re-analysis data, with which we also construct our air pollution measures and main variables of interest. These consist of the counts of fires by upwind and downwind direction. In our setting and consistent with existing research, we find an impact of agricultural fires on students' performance, where an increase of 1SD of fires occurring during the prenatal phase decreases students' scores by 0.0339SD in Portuguese and 0.0317SD in Maths, with boys more negatively impacted than girls. We also find evidence that weaker pupils are significantly more sensitive to prenatal burning exposure in terms of both subjects. In addition, we show the impact of agricultural burning on higher levels of $PM_{2.5}$ and of this on reduced scores later in life. One can observe that an increase of 1 μg/m^3 of $PM_{2.5}$ during the first trimester of pregnancy causes a reduction in Portuguese and Maths scores by 0.021SD and 0.0167SD; the rise in the exposure to particulate matter during the third gestational period appears to decrease scores in Portuguese by 0.0266 and Maths by 0.0274SD. Back-of-the-envelope calculations indicate that a reduction of 10% of $PM_{2.5}$ during the whole gestational period would increase test scores by

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[5]The rest is spread across urban areas (3.2%), grazing (15%), forestry (15.3%), with the remaining fires being spotted in forests and other fields. To make these calculations, we overlay our fires data from NASA/FIRMS with land coverage data from the agricultural census from 2010 available at the IBGE website.

in Portuguese 1.3% and by 0.9% in Maths. Using previous estimates on returns to schooling this suggests a 2.6% increase in wages later in life. These findings are in line with the economics and medical literature on the harmful effects of foetal exposure to air pollution to the foetus' brain development, particularly during the first and third trimester (Rice and Barone Jr., 2000; Sunyer and Dadvand, 2019; McGuinn *et al.*, 2020).

The remainder of this paper is organized as follows. In the next section we present a scientific background on foetal exposure to air pollution and agricultural fires in Brazil. In section III we describe the data, while section IV details the empirical strategy. Results are presented in section V, and subjected to sensitivity analysis in section VI. We provide heterogeneity and economic significance analysis in sections VII and VIII. The final section concludes.

II. Background

Agricultural burning and air pollution in Brazil

In response to a national and international rise in demand for bio-fuel and sugar, São Paulo state more than doubled its share of area designated to sugarcane production from 10% to 23% during the past two decades, accounting for two thirds of all Brazilian production (McConnell, Dohlman, and Haley, 2010; Rangel and Vogl, 2019). Figure 1 illustrates the rate of fire burning during the period of births that we consider in this paper (2001–08).[6] The harvesting season for sugarcane starts in April until November, when the farmers set controlled fire to the fields to crop the cane (Fernandes, 1988; Kirchhoff *et al.*, 1991; Rangel and Vogl, 2019). Usually the fires burn from a few hours to 24 hours during the peak (Lamsal, Jones, and Thomas, 2017).

We focus our attention on sugarcane since the bulk of the fires take place in areas dedicated to this crop. Nonetheless, there are others crops that also use the burning technique, such as maize, rice and wheat. Figure 2 provides sugarcane production as a share of total cultivated land in all municipalities in São Paulo while Figure 3 indicates that sugarcane plantation has increased since 2000, at the expense of the other three products. Furthermore, we can notice from Figure 4 that the areas with more fires coincide with the hot spot areas of sugarcane.

Sugarcane fires can cover large areas, emitting aerosols such as poly-cyclic aromatic hydrocarbons (PAHs), organic and black carbon, sulphur dioxide (SO_2), ozone (O_3), carbon monoxide (CO), nitrogen oxides (NOx) and particulate matters ($PM_{2.5}$ and PM_{10}) which are carried by wind often towards surrounding populations (Guoliang *et al.*, 2008; Akagi *et al.*, 2011; Wu *et al.*, 2018). According to the United States Environmental Protection Agency (EPA), $PM_{2.5}$ is the main pollutant released from agricultural burning, whereas emissions of SO_2, NOx and CO are relatively minor (Y. Zhang *et al.*, 2013). The formation of O_3 depends nonlinearly upon temperature, solar radiation and other precursors and is a by-product not instantaneously found from biomass burning (Jaffe

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[6]From Figures A1 and A2, one can also observe the time series pattern. Since 2007, several agro-environmental protocols have been enacted aiming at regulating environmental degradation from agricultural activities. The Green Ethanol Protocol (SIMA, 2017), issued in 2017, restricts sugarcane straw burning.
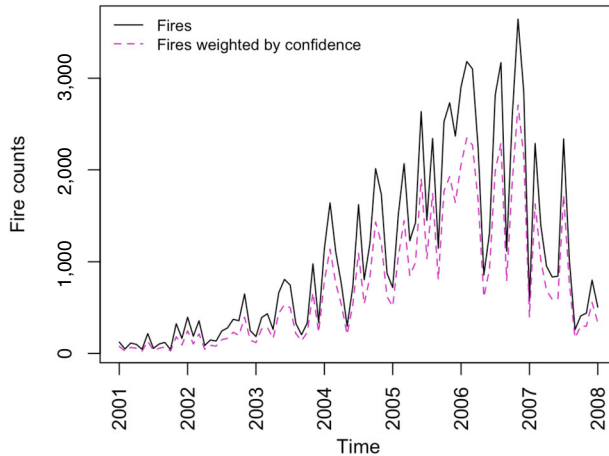
Figure 1. Monthly average of counts of fires from 2001 to 2008.
Notes: The graph shows the monthly average of counts of fires and fires confidence-weighted from 2001 to 2008 in São Paulo state. We can see a that the peak of fires occur during the winter months [Colour figure can be viewed at *wileyonlinelibrary.com*]
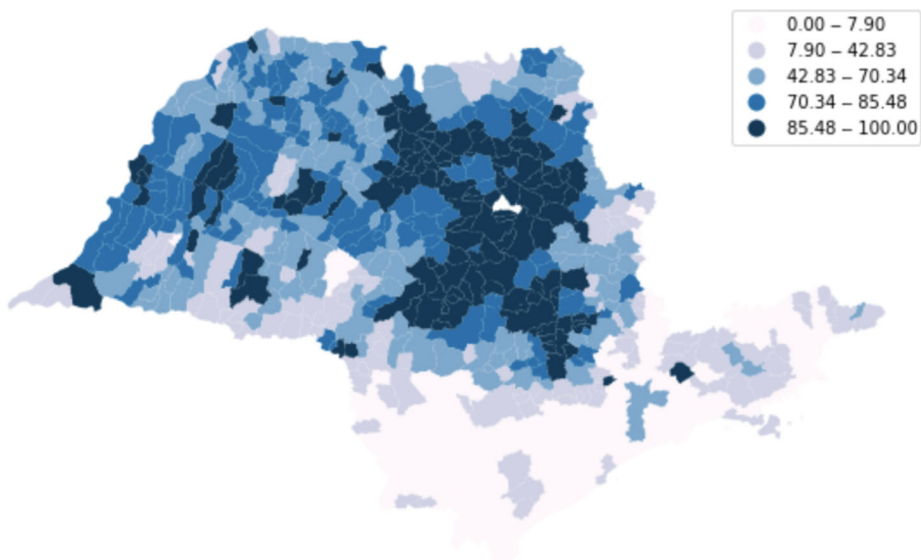
Figure 2. Share of sugarcane crop per municipality.
Notes: This figure shows the share of sugarcane crop per municipality from 2000 to 2017. One can notice that the areas with higher concentration of this crop coincide with the areas with largest number of fire counts (Figure 4) [Colour figure can be viewed at *wileyonlinelibrary.com*]

et al., 2013; Rangel and Vogl, 2019). This feature makes straw burning a rather suitable source of air pollution to analyse given that we know the exact location of the fires, but also the fact that agricultural fires are close to populated regions, raising much greater concerns about human capital impacts than is the case for wild fires which generally take place in more remote areas.
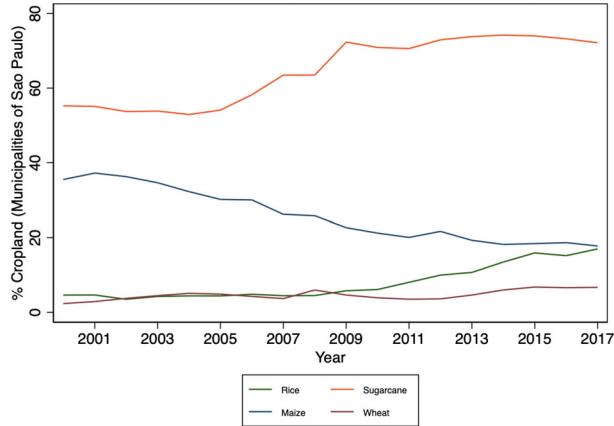
Figure 3. Share of rice, sugarcane, maize and wheat planted per municipality from 2000 to 2017.
Notes: This figure depicts the proportion of land destined to the plantation of four crops that potentially utilize agricultural burning. One can note that sugarcane is the crop that uses this technique the most in the State of São Paulo throughout the period [Colour figure can be viewed at *wileyonlinelibrary.com*]
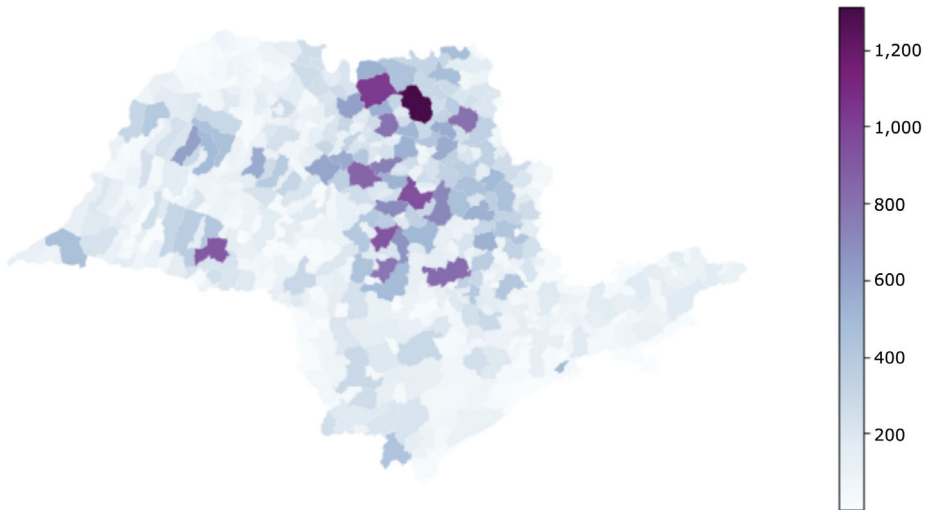
Figure 4. Total of agricultural fires per municipality from 2000 to 2008.
Notes: Total amount of fires per municipality in the state of São Paulo during the birth years of our sample cohorts [Colour figure can be viewed at *wileyonlinelibrary.com*]

Air pollution and intrauterine development

Several studies have investigated the harmful impacts of prenatal exposure to air pollution on infant health and cognitive performance (Almond and Edlund, 2009; Sanders, 2012; Bharadwaj *et al.*, 2017; Almond *et al.*, 2018). As the brain requires large amounts of oxygen to function well, studies have suggested that cognitive performance is likely damaged as a result of both short- and long-term exposure to air pollutants (Calderón-Garcidueñas *et al.*, 2008). Other works associate exposure to air pollution with a decrease in total gray and white matter volumes (Erickson *et al.*, 2020). McGuinn *et al.* (2020) find links

between foetal exposure to $PM_{2.5}$ and behavioural development in children from Mexico City. Dix-Cooper *et al.* (2012) show that a decrease of children's neurodevelopmental performance in rural Guatemala is associated with prenatal and postnatal exposure to carbon monoxide from woodsmoke. As prebirth represents critical periods of vulnerability for the developing nervous system, Rice and Barone Jr. (2000) show that cognitive damage may last from utero to teens. Sunyer and Dadvand (2019) demonstrate the negative impacts of foetal exposure to pollution on brain development during the first trimester.

III. Data

We build a repeated individual-level cross-sectional data set of monthly air quality, weather conditions, agricultural fires and students' scores in the fifth grade in São Paulo state. As our data set come from the satellites Terra and Aqua, which started to operate between 1999 and 2002, we choose to examine cohorts of students born between 2001 and 2008. Furthermore, we opt for remote sensing data instead of ground-based monitoring stations since the agricultural fires are predominantly located within rural areas, in which pollution and meteorological stations were scarce during our time period of analysis.

Fires

We collect daily remote-sensing data on agricultural fires from the National Aeronautics and Space Administration (NASA)'s Fire Information for Resource Management (FIRMS). The data are captured by two satellites TERRA and AQUA which rely on Moderate Resolution Imaging Spectroradiometer (MODIS) sensors to detect ground-level fire activity. Each satellite overpasses Brazil twice per day (morning, afternoon, evening and night) (Kaufman *et al.*, 1998; Justice *et al.*, 2002). The fire detection algorithm developed by researchers at the University of Maryland is built upon thermal anomalies, surface reflectiveness, water, cloud masking and land use, and the publicly available data is provided at a resolution of 1 km × 1 km (Giglio et al., 2009; Giglio, Schroeder, and Justice, 2016). Notwithstanding, it is not possible to know the precise size of each fire from the data (Giglio *et al.*, 2009). Thus, we consider and count fires in neighbouring pixels individually (Graff-Zivin *et al.*, 2020).

The data set also provides the confidence of detection for each potential fire identified by the satellites. That is, each fire receives a probability of occurrence (from 0% to 100%) according to the meteorological conditions and vegetation at the exact time the fire was detected (Giglio *et al.*, 2016). As a result, in our specifications we use the fire weighted by its confidence to minimize classical measurement error (Rangel and Vogl, 2019; Graff-Zivin *et al.*, 2020).

A fire is attributed to a student if it occurred within a catchment area of 50km radius of her municipality's centroid.[7] Unfortunately, we do not know the municipality of birth of each individual. Hence, we use the centroid of the municipality where the pupil lives when she takes the exams as a plausible proxy for the exact location of birth as the

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[7]As in Rangel and Vogl (2019), we exclude fires within 5km from the municipality population centroid since they are unlikely to stem from agricultural sources

TABLE 1

Descriptive statistics

Variables	Mean	SD	Min	Max
Scores				
Portuguese	219	47.8	84.9	339
Maths	234	47.5	78.92	367
Pollutants (trimester average)				
$PM_{2.5}$ ($\mu g/m^3$)	14.3	4.24	4.64	59.5
CO ($\mu g/m^3$)	0.25	0.096	0.062	0.92
O_3 ($\mu g/m^3$)	57.87	9.44	38.46	95.3
Agricultural fires (trimester average)				
Upwind	4.57	8.12	0	98
Downwind	6.23	9.55	0	109
Vertical	31.40	33.97	0	279
Meteorological conditions (trimester average)				
Rain (mm)	2.73	2.66	0.00	92.4
Temperature (°C)	22.2	2.69	13.4	35.6
Wind Speed (m/s)	2.05	0.77	0.13	8.52
Cloud coverage (%)	40.4	13.1	6.24	99.9
Humidity (%)	70.3	8.54	25	97.6
Students' characteristics (%)				
Female	50.3			
Male	49.7			
White	37.7			
Mixed	30.5			
Black	17.7			
Asian	2			
Indigenous	2.2			
Non-declared	9.9			
Father's education				
Low	44.2			
High	14.1			
Non-declared	42.8			
Observations	1,190,717			
Municipalities	645			

Notes: Summary statistics of some of the key variables: scores range from 0 to 350 points for Portuguese and 0 to 400 points for Maths, counts of agricultural fires and meteorological conditions during pregnancy (from 2000 to 2008) in the municipalities in the State of São Paulo. For father's level of education, we consider low if the below UG level and high with UG or above. The fires locations are defined within 45 degrees from the daily prevalent wind direction in a municipality.

majority of students do not usually migrate.[8] Although we have secondary data on the place of birth, we cannot merge it with our main education data due to the lack of unique students' identifiers in both data sets. Alternative distances are also used and presented in the robustness checks section.

In Table 1, we report the summary statistics for agricultural fires by wind direction at the trimester level used for the whole period of the main estimation sample (2001–08).

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[8]Section IV presents more detailed explanation of this migration issue.

Also, Figures 1 and A1 present the time series behaviour of monthly average fires for that period. From these figures we can observe a strong seasonal pattern of fires with peaks in the winter months, and a not very clear time trend. The seasonality of fires coincides with the agricultural phases, corroborating the link between the sugarcane harvesting period and the peak in identified burning sites.[9]

Weather conditions

We use the Japanese 55-year Re-analysis (JRA-55) data on atmospheric conditions. The JRA-55 is the second Japanese global atmospheric re-analysis project conducted by the Japan Meteorological Agency (JMA), covering data back to 1958. Re-analysis uses past climatic observations from satellite and terrestrial monitoring stations, as well as meteorological models to systematically produce data sets for climate monitoring and research.[10]

We gather gridded daily data on temperature in Kelvins (which we transform to degrees Celsius ($^{\circ}$C)), precipitation (in millimetres, mm), relative humidity (in percentage, %), wind components and cloud coverage (in percentage, %). Apart from the latter, these weather conditions may influence the way air pollution geographically spreads. As such, we include them as control variables in our models[11]. Regarding cloud coverage, it is important since the satellite imagery for fire detection is negatively related to the amount of cloud in the sky. That is, the detection of small fires may be hindered by thicker clouds[12] (He *et al.*, 2020). The spatial resolution of each grid is $0.56^{\circ} \times 0.56^{\circ}$, and the data are 3-hourly that we average by day per grid and then aggregate to the average at the trimester level. To construct the variables for wind conditions we use the vector decomposition method and calculate the prevalent wind per trimester (Grange, 2014; Rangel and Vogl, 2019).

Air pollution

The pollutants and other chemical elements, such as $PM_{2.5}$, Carbon Monoxide (CO), Sulphate (SO_4), Ozone (O_3), Black Carbon (BC) and Organic Carbon (OC), dust (DS) and sea salt (SS), utilized in this work come from the second Modern-Era Retrospective analysis for Research and Applications (MERRA-2), provided by NASA and built upon a plethora of data sources, such as remote sensing imagery and terrestrial stations. The gridded data available has a spatial resolution of $0.5^{\circ} \times 0.625^{\circ}$ and comes in hourly intervals, which we aggregate to daily and trimester frequency. To this end we implement

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[9]In Figure A2, we present the overall time series behaviour from 2001 until 2017, that is we add the period ranging from 2009 to 2017 since the students took exams from 2011 to 2017.

[10]Auffhammer *et al.* (2013) provide a thorough discussion on the consistency of re-analysis data for economics studies.

[11]Our intention is not to allow pollution to have differential impacts based on weather conditions, but to control for the independent effects of weather and ensure that our estimates of pollution effects are robust and not influenced by weather-related variability (Dell, Jones, and Olken, 2014; Graff Zivin, Hsiang, and Neidell, 2018; Deryugina *et al.*, 2019; Cook and Heyes, 2020; Garg, Jagnani, and Taraz, 2020)

[12]We include cloud coverage in our estimations and, as robustness checks, we show that the results remains similar when not accounting for cloud coverage.

the same procedure as for the weather variables; that is we first average per day, then we calculate the quarterly average.

$PM_{2.5}$ is not directly available from the Merra-2's data set and so is calculated using the formula below (Buchard *et al.*, 2016; Provençal *et al.*, 2017).

$$PM_{2.5} = 1.375 * SO_4 + 1.8 * OC + BC + DS + SS, \tag{1}$$

where SO_4, OC, BC, DS and SS are measured in kilogram per cubic metre (kg/m^3), which we finally transform to micro-gram per cubic metre (μ/m^3). Our calculated $PM_{2.5}$ concentrations are consistent with those observed by terrestrial monitoring stations.

Table 1 presents the descriptive statistics for our main estimation sample with 1,190,717 students. The average quarterly concentration of $PM_{2.5}$ in our sample is 14.3 $\mu g/m^3$, with a maximum concentration of 59.5 $\mu g/m^3$ and a SD of 4.24.[13] Table 1 also shows the number of fires similarly distributed per wind direction, indicating the randomness of the latte during the burning periods.

Education

Our data on students' exam scores come from the National Institute for Educational Research *Instituto Nacional de Estudos e Pesquisas Educacionais Anísio Teixeira* (INEP), an agency from the Brazilian Ministry of Education. Every 2 years the students in the 5th grade pass a nationwide examination to assess the quality of education in Brazil (*Prova Brasil)* via tests and socio-economic questionnaires (INEP, 2017). This forms a rich administrative data set with detailed information on the students' scores in Portuguese and Mathematics, demographic information, such as their age, race and gender, as well as parental level of education. From this data we build a repeated pooled cross-section at the student level with cohorts taking examinations from 2011 to 2017 (in the 5th grade) (Table 1 summarizes this information). The Portuguese scores range from 0 to 350 points, and Maths from 0 to 400 points, and, in our regressions, we follow the literature and use these scores in SD form as dependent variables (Garg *et al.*, 2020). As for the year of birth, the children in our data set were born from 2001 to 2008.[14]

IV.   Empirical strategy

First, we examine the long-term impacts of foetal exposure to agricultural fires on students' scores in the 5th grade (reduced form). Second, to show that air pollution is the channel through which fires affect cognitive performance we estimate the partial correlation between agricultural fires and air pollution (first stage) and, finally, the impacts

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[13]To put these figures in context, the World Health Organisation guidelines state that annual mean exposure to $PM_{2.5}$ should not exceed $5\mu g/m^3$ (reduced from 10 $\mu g/m^3$ in 2021) and 24-hour mean exposure should not exceed $15\mu g/m^3$.

[14]Although the students also take tests in the ninth grade, we do not include these cohorts in our analysis. Firstly because the data for the ninth graders are less complete. Secondly, the dropout and repetition rates for older students are far higher than for younger ones, hence, there would be pupils born well before 2001, that is, the first year of our satellite data.

of being exposed *in utero* to air pollution from these fires on students' outcomes later in life (second stage).

Prenatal exposure to fires and students' scores

To estimate the effects of prenatal exposure to agricultural fires on students' scores we start by using the following basic equation:

$$\text{Scores}_{jmi} = \beta \text{fires}_{mi} + \psi W_{mi} + \alpha X_j + \mu_m + \iota_i + \theta_t + \epsilon_{jmi}, \tag{2}$$

where Scores$_{jmi}$ is the standardized 5th grade test score in either Portuguese or Maths of child j born in municipality m, at time i. The term fires$_{mi}$ denotes the number of fires in a municipality at the trimester level in SD for ease of interpretation. We include W_{mi}, a vector of weather condition controls during pregnancy, such as temperature, relative humidity, wind speed, cloud coverage and rainfall per trimester. To allow for nonlinearity in the effect of temperature on scores we create five temperature bins between less than 15 and more than 35 degrees (5 degree bins) in our main specification but also, for completeness, experiment with using temperature in the linear form, squared, and interacted with other weather variables (Deschênes, Greenstone, and Guryan, 2009). The term X_j is a vector of controls for observable individual characteristics that can be related to their exam scores, such as the father's highest level of education[15], students' race and gender. The term μ_m accounts for municipality fixed effects, while ι_i is a vector controlling for month and year of birth fixed effects. The latter accounts for unobserved time-invariant municipality and cohort characteristics, and θ_t controls for the year of the exam.

SEs in equation (2) are clustered by municipality to control for spatial and serial correlation within each locality. Although we do not have the exact place of birth, we believe that using the municipality where the student attended school as a proxy for municipality of birth is reasonable enough since the *Educational Census* assesses that 92% of children did not move location between birth and the exam year.

A concern that arises with the above approach is that agricultural burning could be related to positive temporary income shocks for local families who have an increase in income during the harvesting season, which would also affect foetal health and students' scores as a result via the income channel. More precisely, as seasonal agricultural fires increase both farmers' productivity and revenues, it may affect students' academic performance since the overall household income increases, allowing parents to invest more in their children.[16] Furthermore, sugarcane is harvested in São Paulo in the winter, hence seasonality in weather conditions and winter-related diseases could cause a spurious correlation between fires and foetal health.[17]

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[15]We do not have the years of education of the student's parents. Rather, the original micro-data provides the highest level of education achieved by them. As such, we build dummies indicating each of these levels.

[16]One of the referees suggested using thermal inversion as instrument for air pollution (Jans, Johansson, and Nilsson, 2018). We have tried to use it, and the results are counter-intuitive, with positive signs for PM2.5 coefficients. Moreover, the F-test of the instrument is low (1.3). We thus have opted not to use thermal inversion as an instrument.

[17]Regarding the potential predictability of these fires and following one of the referees' suggestion, we estimate a trend and then use the residual as a surprise (or shock) at the municipality level, and the results using the predicted residuals of the trend equation are exact the same as the results using the actual instruments.

Another challenge to the identification strategy above relates to the fact that students' exam scores may be correlated with air pollution from agricultural fires since wealthier parents could choose to live in less polluted areas (Banzhaf and Walsh, 2008; Currie *et al.*, 2014). This location choice is a form of avoidance behaviour which may bias our estimations (Neidell, 2004, 2009; Bharadwaj *et al.*, 2017; Carneiro, Cole, and Strobl, 2021). In addition, our meteorological data set, which is produced by re-analysis modelling, may bias our estimates if children's actual exposure to outdoor air pollution differs from the forecast readings in our data. Hence, our IV approach detailed below is also intended to address this classical measurement error problem (Moretti and Neidell, 2011; Schlenker and Walker, 2015; Chen *et al.*, 2018).[18]

To address the aforementioned potential biases we follow Rangel and Vogl (2019) and adopt the following model as our main specification:

$$\text{Scores}_{jmi} = \beta_0 \text{upwindfires}_{mi} + \beta_1 \text{downwindfires}_{mi} + \psi W_{mi} + \alpha X_j$$
$$+ \mu_m + \iota_i + \theta_t + \epsilon_{jmi}. \tag{3}$$

In this reduced form, $\beta_0 \text{upwindfires}_{mi}$ is the count of agricultural fires in the upwind direction of a municipality centroid, and $\beta_1 \text{downwindfires}_{mi}$, fires located in the opposite direction. Our parameter of interest is the difference between β_0 and β_1, which we expect to be negative, and unveils the causal relation between fires and cognitive performance. That is, we take advantage of the fact that upwind fires have a stronger negative impact on air pollution than downwind fires, while wind direction is plausibly exogenous not affecting income and students' scores. Therefore, we expect β_0 minus β_1 to be negative, that is students' born upwind from the fires are more negatively affected than their counterparts born downwind.

To build our fire variables, we follow Rangel and Vogl (2019); He *et al.* (2020); Graff-Zivin *et al.* (2020) and count the daily number of fires within 50 km of a municipality's centroid. Alternatively we also consider fires detected within the same wind octant in a day to be upwind, fires located in the opposite octant to be downwind, and all the remainder fires are defined as vertical, setting a 45° angle. As such, we define upwind fires as those located within a 45 central angle from the average daily wind direction within each municipality. In other words, upwind fires have the smoke blowing towards the municipality's centroid. Downwind fires are located in the opposite direction, while we call the ones situated in the other directions vertical fires. The rationale of this classification is that upwind fires leads to more exposure air pollution than downwind, whereas the air pollution in the municipalities located in the vertical direction is less influenced by smoke than the upwind villages, but more affected by fires than their downwind counterparts.[19]

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[18]Pollution levels and weather conditions on exam days are unlikely to influence the scores via examiners' productivity since all the tests are mechanically marked.

[19]In our sensitivity analysis section we aggregate vertical and downwind directions to form an alternative set of analysis since these directions present similar behaviour; and use other angles to define upwind fires. All results remain very close to the main specification.

Mechanisms: agricultural burning, air pollution and students' scores

We now turn our attention to the air pollution channel through which agricultural fires may impact cognitive performance. To do so we start by estimating the effect of sugarcane burning on air pollution (first stage) and then the impact of the foetal exposure to it on students' scores (second stage).

The instrumental variable approach

We utilize our fire variables constructed via the analysis above as instruments for air pollution and estimate the effects of prenatal exposure to air pollution on students' scores by pooling our individual-level cross-sectional data for the exams occurring $2011-17$. The structural equation is as follows:

$$\text{Scores}_{jmi} = \phi \text{pollutant}_{mi} + \psi W_{mi} + \alpha X_j + \mu_m + \iota_i + \theta_t + \epsilon_{jmi}, \tag{4}$$

where the terms in equation (4) are defined as in equation (2), except for pollutant, which is the average level of pollution at the trimester and municipality levels. Our study focuses on the effect of the pollutant $PM_{2.5}$ on cognitive performance, although in robustness exercises we include O_3 and CO as co-pollutants.

Our main assumption relies upon the exogeneity of the upwind/downwind fires since they do not directly affect the children's cognitive performance, except from their effect on air pollution. As such, our approach can be considered as a natural experiment that utilises exogenous shocks to local air pollution in a specific area (Anderson, 2015; Schlenker and Walker, 2015; Deryugina *et al.*, 2019; Graff-Zivin *et al.*, 2020; He *et al.*, 2020; Carneiro *et al.*, 2021). Our model can be formally described as:

$$\text{Pollutant}_{mi} = \gamma_0 \text{upwindfires}_{mi} + \gamma_1 \text{downwindfires}_{mi} + \psi W_{mi}$$
$$+ \alpha X_j + \mu_m + \iota_i + \theta_t + \epsilon_{mi}$$

$$\text{Scores}_{jmi} = \beta \widehat{\text{Pollutant}}_{mi} + \omega W_{mi} + \rho X_j + \nu_m + \lambda_i + \delta_t + \eta_{jmi}, \tag{5}$$

where equation (5) is identical to equation (3), except for the outcome variable, which here is the pollutant measure (in $\mu g/m^3$) linked to students j, in municipality m and time of birth i. The main explanatory variable in equation (5) is $\beta \widehat{\text{Pollutant}}_{mi}$, which is the predicted value from equation (5). The coefficient of interest in equation (5) is γ, which provides the estimated effect of upwind fires on $PM_{2.5}$. The pollution level and weather controls correspond to the average during each of the three trimesters of pregnancy while the fire count is the amount of fires in each trimester. In equation (5), we are interested in β as it reports the estimated causal effects of pollution on pupils' scores.

Identification concerns

A limitation of our analysis relates to the lack of information on the conception date, therefore, we cannot precisely establish the trimesters of pregnancy. For instance, if there are more preterm births in the second instead of the third trimester (Heft-Neal *et al.*, 2022), then this would mean that we are classifying some students incorrectly, that is we are

assuming that their first trimester is earlier than it really is. If so, this would then lead to some measurement error in all three trimesters. Nonetheless, our results can be interpreted in light of the overall harmful effects of foetal exposure to burning pollution.[20]

Another concern is that people may migrate to avoid air pollution, which could also bias our estimates. To demonstrate that our estimates are unlikely to be affected by migration, we used secondary data from the Education Census of the Ministry of Education in Brazil and from the Education Assessment on the Quality of Education in the State of São Paulo (SARESP). According to these secondary data sets, 92% of students who responded to the Census questionnaire were still living in the same municipality of birth. The remaining 8% lived around 8 km from the school and were born in locations at maximum 44 km away from the municipality where they attend school, with 90% living less than 23 km away. Furthermore, from the SARESP data set, we calculate that roughly 82% of respondents who knew where the mother lived for the last 10 years were born in the same location where they attended school. That is, their mothers did not migrate during pregnancy[21].

Lastly, a limitation for studies on foetal shocks effects later in life is how to address the influence of time-varying investments in human capital parents may make to overcome prenatal exposure to pollution, which is not possible to control for in our sample (Bharadwaj *et al.*, 2017; Almond *et al.*, 2018). Nonetheless, other works have shown that the compensating parental responses present very small effects (Bharadwaj, Eberhard, and Neilson, 2013; Halla and Zweimüller, 2014; Bharadwaj, Eberhard, and Neilson, 2018). Any unobservable investments that parents make to compensate cognitive impairments stemming from *in utero* pollution exposure will be contained in our error term and represent another negative externality from air pollution.[22]

V. Results

The effects of agricultural fires on academic performance

Table 2 reports the results for our main model (equation 3) which estimates the impacts of foetal exposure to agricultural fires on students' performance. All models include flexible weather controls, and the equations include the number of fires (weighted by their probability of occurrence) by wind direction (in SD). We start by presenting our estimates for equation (2) in Columns 1 and 2, where we count the fires together irrespective of wind direction. We find the effect of fires on both Portuguese and Maths to be negative and statistically significant in the first and third trimesters. Columns 3 and 4 report the results from our main specification, in which we categorize fires according to wind direction, per trimester of pregnancy. We show that an increase of one SD in the difference between the number of upwind and downwind fires in the first trimester leads to a decrease of

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[20]Rangel and Vogl (2019) also face this caveat when estimating the impact of fires on birth outcomes in São Paulo and focus their attention on the third trimester of pregnancy.

[21]Regarding the coverage of School Census data in Brazil for the state of São Paulo, the Ministry of Education aims to include all educational institutions and students within the state. Regarding the respondents who 'knew where the mother lived', these account for around 87% of the total sample size analysed. Please, note that to draw this comparison, we used the secondary data for 2011 and 2013 only because there is no such questions in further years' questionnaires.

[22]Almond *et al.* (2018) reports a thorough review of the literature on foetal shocks.

TABLE 2
Effects of agricultural fires on students' scores (SD)

Variables (SD)	(1) Portuguese	(2) Maths	(3) Portuguese	(4) Maths
All fires(1tr)	−0.029*** (0.0063)	−0.0235*** (0.0062)		
All fires(2tr)	0.0131 (0.008)	0.0176* (0.0078)		
All fires(3tr)	−0.0147*** (0.0045)	−0.0092* (0.0048)		
Upwind (1tr)			−0.0146*** (0.0028)	−0.0149*** (0.0039)
Downwind (1tr)			0.0013 (0.0052)	0.0047 (0.006)
Upwind (2tr)			0.0011 (0.0033)	0.006 (0.0032)
Downwind (2tr)			0.0092 (0.0073)	0.0082 (0.0073)
Upwind (3tr)			−0.0076*** (0.0029)	−0.0068* (0.0032)
Downwind (3tr)			0.0023 (0.0047)	0.0031 (0.0048)
Upwind-downwind (1tr)			−0.0159* (0.0067)	−0.0196* (0.009)
Upwind-downwind (2tr)			−0.0081 (0.0077)	−0.0022 (0.0081)
Upwind-downwind (3tr)			−0.0098 (0.0061)	−0.0099 (0.0065)
Upwind-downwind (Whole pregnancy)			−0.0339*** (0.0119)	−0.0317* (0.0137)
Observations	1,187,660	1,187,660	1,187,660	1,187,660
R^2	0.143	0.122	0.143	0.122
Municipality FE	Y	Y	Y	Y
Month and year birth FE	Y	Y	Y	Y
Year exam FE	Y	Y	Y	Y
Weather	Y	Y	Y	Y

Notes: Robust SEs in parentheses clustered by municipality centroid. All models control for municipality FE, year of exam, month and year of birth, and students' controls. Estimates for controls not shown: temperature bins, rainfall and its square, relative humidity and its square, wind speed and cloud coverage. Upwind and downwind direction account for the sum of fires (weighted by confidence) upwind and downwind from the municipality centroid (in SD). Upwind-Downwind stands for the difference between the coefficients of the respective directions. *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$.

0.0159SD in Portuguese and 0.0196 in Maths scores; 0.0098SD decrease in Portuguese due to exposure during the third trimester and no significant effect found for Maths during the third trimester. The bottom part of the table presents the sum of coefficients for the three gestational periods, from which we can see that an increase in 1SD in the fires occurred during the prenatal phase decreases students' scores by 0.0339SD in Portuguese and 0.0317SD in Maths. Thus, despite some measurement error from potential trimester

misclassification (due to lack of data on prebirths and/or conception date), altogether, the whole pregnancy period effects (the sum of the three trimesters) are substantial and significant, revealing the negative impacts of foetal exposure to students' outcomes later in life.

Our findings are in line with the literature on the impacts of prenatal exposure to air pollution on cognitive impairment. Several studies have shown a negative association between poor air quality during pregnancy and brain cell formation mainly during the first and third trimesters of pregnancy (Woody and Brewster, 1990; Ikonomidou *et al.*, 1999; Sunyer and Dadvand, 2019), effects that may last from utero to childhood and teens (Rice and Barone Jr., 2000; Dix-Cooper *et al.*, 2012). The economics research also sheds light on the negative impacts of foetal exposure to pollution and later life academic performance (Currie *et al.*, 2009b; Bharadwaj *et al.*, 2017).

Mechanisms

Relevance of upwind and downwind fires as instruments
Since we have three endogenous variables – the average $PM_{2.5}$ by trimester – we need three first-stage equations. But, since we interact each wind direction with fires also per trimester there are enough instruments to identify the causal effect of the three endogenous variables. In Table 3 we show results for separate equations per trimester of pregnancy (Columns 1–3), and for equations with the three trimesters together (Columns 4–6). We are interested in the difference between upwind and downwind fires, which is shown to be positive and significant for all trimesters. Hence, as expected, fires located upwind increase air pollution more than downwind fires. Column 1 shows that a 1SD increase in upwind fires increases $PM_{2.5}$ by 0.439 $\mu g/m^3$ or 10% SD, 0.4775 $\mu g/m^3$ or 11% SD, and 0.2824 $\mu g/m^3$ or 7% SD during the first, second and third trimesters, respectively. The last three columns account for the three trimesters together and show similar conclusions, that is upwind fires are strongly causally related to the level of air pollution per trimester of pregnancy.

These first-stage results confirm that upwind fires persistently affect pollution more than the other directions across the different forms for which we build the instrument set. This reinforces the main assumption that we rely on that local air quality is more affected by fires located upwind from the municipality's population centroid. In addition, and in line with previous research, these findings suggest that poor air quality is the channel through which agricultural fires affect humans' cognitive health (Lai *et al.*, 2018; Graff-Zivin *et al.*, 2020; He *et al.*, 2020).

Impact of air pollution on students' scores (Second stage)
Table 4 reports the results regarding the effects of $PM_{2.5}$ on students' scores for each trimester of pregnancy. We start by presenting our OLS estimates of Portuguese and Maths scores (Columns 1 and 2). These results show that $PM_{2.5}$ in the first and second trimesters seem to have a positive impact on Portuguese and on Maths, and no effects on the third gestational period. However, for the reasons explained above, OLS estimates are likely biased.

TABLE 3
Impact of fires on particulate matter (First Stage)

Dep. Var. ($\mu g/m^3$)	(1) $PM_{2.5}\_1tr$	(2) $PM_{2.5}\_2tr$	(3) $PM_{2.5}\_3tr$	(4) $PM_{2.5}\_1tr$	(5) $PM_{2.5}\_2tr$	(6) $PM_{2.5}\_3tr$
Upwind_1tr	0.563***			0.527***	-0.220***	-0.000534
	(0.0487)			(0.0599)	(0.0432)	(0.0439)
Downwind_1tr	0.124			0.167***	-0.176***	-0.0907*
	(0.0664)			(0.0439)	(0.0430)	(0.0398)
Upwind_2tr		0.500***		0.117***	0.479***	-0.112***
		(0.0773)		(0.0297)	(0.0696)	(0.0415)
Downwind_2tr		0.0225		0.138***	0.0977**	-0.0959***
		(0.0537)		(0.0296)	(0.0420)	(0.0340)
Upwind_3tr			0.404***	-0.0451	0.0879***	0.382***
			(0.0331)	(0.0441)	(0.0255)	(0.0295)
Downwind_3tr			0.121**	-0.166***	0.249***	0.137***
			(0.0573)	(0.0506)	(0.0506)	(0.0496)
Upwind-downwind (1tr)	0.439***			0.36***	-0.044	0.091
	(0.1017)			(0.08)	(0.064)	(0.0738)
Upwind-downwind (2tr)		0.4775***		-0.0205	0.3818***	-0.0166
		(0.1199)		(0.0466)	(0.0931)	(0.0565)
Upwind-downwind (3tr)			0.2824***	0.1208	-0.1607*	0.2457***
			(0.0746)	(0.0816)	(0.0703)	(0.0627)
Observations	1,187,660	1,187,660	1,187,660	1,187,660	1,187,660	1,187,660
R-squared	0.793	0.797	0.810	0.814	0.814	0.818

Notes: Robust standard errors in parentheses clustered by municipality centroid. All models control for municipality FE, year of exam, month and year of birth, and students' controls. Estimates for controls not shown: temperature bins, rainfall and its square, relative humidity and its square, wind speed and cloud coverage. Upwind and downwind direction account for the sum of fires (weighted by confidence) upwind and downwind from the municipality centroid (in SD). Upwind-Downwind stands for the difference between the coefficients of the respective directions. *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$.

We therefore turn to our specifications using the counts of upwind and downwind fires as instrumental variables (Columns 3 and 4). One can observe that an increase of 1 $\mu g/m^3$ of $PM_{2.5}$ during the first trimester of pregnancy causes a reduction in Portuguese and Maths scores by 0.0205SD and 0.0167SD; the rise in the exposure to particulate matter during the third gestational period appears to decrease scores in Portuguese by 0.0266 and Maths by 0.0274SD. The increase in the exposure to poor air quality during the second trimester, although positive, does not seem to significantly affect students' performance. These results relating to earlier gestational periods are not as surprising as one might think since the literature points to the existence of selection bias when it comes to backwards dating of exposure to air pollution and the exact date of birth. Thus, this is a recurrent issue in several works on *in utero* shocks. For example, Rangel and Vogl (2019)'s findings also suffer from the same limitation. These results are in line with the medical and economics literature on foetal exposure to air pollution and cognitive performance (Rice and Barone Jr., 2000; Dix-Cooper *et al.*, 2012; Currie *et al.*, 2014; Almond *et al.*, 2018; Sunyer and Dadvand, 2019; McGuinn *et al.*, 2020).

TABLE 4

Effects of particulate matter on students' scores (SD) – OLS and IV

Variables	(1) Portuguese	(2) Maths	(3) Portuguese	(4) Maths
	OLS		IV	
$PM_{2.5}(1tr)$	0.0022*	0.0014	−0.0205*	−0.0167*
$(\mu g/m^3)$	(0.0011)	(0.0013)	(0.0093)	(0.0074)
$PM_{2.5}(2tr)$	0.0123***	0.0123***	0.00690	0.013
$(\mu g/m^3)$	(0.0022)	(0.002)	(0.0079)	(0.0067)
$PM_{2.5}(3tr)$	−0.0019	−0.0021	−0.0266***	−0.0274***
$(\mu g/m^3)$	(0.0038)	(0.0034)	(0.0068)	(0.0076)
$PM_{2.5}$ $(\mu g/m^3)$			−0.04***	−0.031**
(Whole pregnancy)			(0.014)	(0.0126)
First-stage F-test			10	10
Observations	1,187,660	1,187,660	1,187,660	1,187,660
R^2	0.143	0.122	0.052	0.038
Municipality FE	Y	Y	Y	Y
Month and year birth FE	Y	Y	Y	Y
Year exam FE	Y	Y	Y	Y
Weather	Y	Y	Y	Y

Notes: Robust SEs in parentheses clustered by municipality centroid. All models control for municipality FE, year of exam, month and year of birth, and students' controls. Estimates for controls not shown: temperature bins, rainfall and its square, relative humidity and its square, wind speed and cloud coverage. Instruments are the sum of fires (weighted by confidence) upwind and downwind from the municipality centroid (in SD). First stage Kleibergen–Paap rk Wald F statistic. PM_{25}_1tr, PM_{25}_2tr and PM_{25}_3tr account for their linear form for trimester 1, 2, and 3 of pregnancy measured in $\mu g/m^3$. *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$.

When we look at the bottom part of the table, altogether, an increase of 1 $\mu g/m^3$ of $PM_{2.5}$ during the whole gestational period, leads to a significant and sizeable drop in students' scores by 0.04SD in Language and by 0.031SD in Maths. With regard to this, the literature shows evidence that different parts of the brain perform different functions with white matter being linked to language and verbal reasoning skills and gray matter associated with mathematical skills (Houston *et al.*, 2019; Popescu *et al.*, 2019). In addition, pollution affects the white and gray matter differently, corroborating our findings suggesting that air pollution generates slightly different effects on exam performance by subject (Clougherty, 2010; Calderón-Garcidueñas *et al.*, 2011; Erickson *et al.*, 2020; Graff-Zivin *et al.*, 2020; Carneiro *et al.*, 2021).

On one hand, one would expect some degree of correlation between contemporaneous and prenatal pollution since areas with worse prenatal air quality might also register higher pollution levels due to environmental and behavioural factors, for example, pregnant women avoiding highly polluted areas or being more likely to reside in areas with better air quality. Thus, to address omitted variable bias concerns, we experimented with including the means of pollution, weather and fires variables for the month of November as additional controls. In contrast to other examinations in Brazil, unfortunately we do not have the precise date when each school sat these tests, only information of the month it took place in (November). It is perhaps not surprising that these controls are not statistically significant. Particularly, their inclusion causes the instrumental variable

to lose its precision and renders it weak (with a First-stage Kleibergen–Paap rk Wald F statistic equals to 0.7).

In our preferred models (using IV), the estimated impacts of pollution in the first and third trimesters become smaller and lose statistical significance when we include contemporaneous pollution, where the latter acts as a weak instrument in the IV models, leading to possibly imprecise estimates. In addition, high correlation between prenatal and contemporaneous pollution can generate multicollinearity issues, making it difficult to distinguish their individual effects. Furthermore, the causal link between contemporaneous pollution and test results may be more difficult to establish compared to the direct prenatal pollution. Nonetheless, the first and third trimesters' coefficients retain their negative direction presence of contemporaneous pollution, suggesting that the core findings are still consistent albeit potentially attenuated. On the other hand, pollution measures can vary within cities. Thus, some pregnant individuals may experience relatively low prenatal pollution while being exposed to high contemporaneous pollution, and vice versa. Also, pollution levels can vary daily, with certain days experiencing spikes in pollution due to weather patterns and industrial activities, for instance, resulting in days of elevated contemporaneous pollution that do not necessarily coincide with higher prenatal exposure. Another factor to be considered is environmental regulations, which may induce occasional improvements in air quality, which may not necessarily be correlated with long-term trends in prenatal pollution. Therefore, we prefer not to include the mean values as additional controls. Nevertheless, we acknowledge that our results may be overestimating the total effects of air pollution during pregnancy on students' scores (Table A1).

VI. Sensitivity analysis

To assess the internal validity of our research design and results we carry out a set of robustness tests. In the first exercise, we vary the distance between the location of fires and the population centroid of each municipality, using 20–100 km (50 km was used in the main equations)[23]. The results remain overall similar as can be seen in Tables A2 and A3.[24]

We also vary the angles used to classify students living upwind or downwind of the fires (originally, 45°). Since wider angles capture more observations from vertical directions that are not exactly upwind, and hence more students with lower levels of exposure, our results in Table A4 show that larger angles yield coefficients with smaller magnitude than the baseline (Column 2).[25]

In Table 5, we use placebo trimesters to show that the exposure to agricultural fires in trimesters before conception and after birth do not compete with the actual gestational

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[23]Underlying our main specification is the assumption of counting fires within 50 km of the municipality centroid. To address concern related to the possibility of micro-climates lead to different exposures within municipalities, we weighted the pollution's and fires' measures by the size of the municipalities in km^2. As shown on Table A6, the results remain qualitatively the same.

[24]There may indeed be more measurement error (hence attenuation bias) in only considering small distances, as this may not capture the spatial effect of the pollution due to the fires. Similarly in Rangel and Vogl (2019) and He *et al.* (2020).

[25]Graff-Zivin *et al.* (2020) find similar exercise and results.

Bulletin

TABLE 5
Agricultural fires and students' scores – pre- and postbirth

Variables	(1) Portuguese	(2) Maths
Panel A: Trimesters prior to conception		
Upwind-downwind (-3)	-0.0028	0.0003
	(0.0077)	(0.0092)
Upwind-downwind (-2)	0.017^{***}	0.018^{***}
	(0.0048)	(0.0051)
Upwind-downwind (-1)	-0.0028	0.0012
	(0.0082)	(0.0087)
Observations	$1,187,622$	$1,187,622$
Upwind-downwind (Three trimesters)	0.0114 (0.0122)	0.0206 (0.0137)
Panel B: Trimesters after birth		
Upwind-downwind ($+1$)	0.007	0.0002
	(0.0077)	(0.0078)
Upwind-downwind ($+2$)	0.0053	0.0085
	(0.0085)	(0.0085)
Upwind-downwind ($+3$)	0.008	0.0069
	(0.011)	(0.0098)
Observations	$1,187,660$	$1,187,660$
Upwind-downwind (Three trimesters)	0.0203 (0.014)	0.0156 (0.0151)
Panel C: Year after birth		
Upwind-downwind ($+1$ year)	0.0142^{***}	0.0183^{***}
	(0.046)	(0.0052)
Upwind-downwind ($+2$ years)	-0.008	-0.0063
	(0.0044)	(0.0044)
Upwind-downwind ($+3$ years)	0.0105	0.01
	(0.064)	(0.007)
Upwind-downwind ($+4$ years)	-0.0117	-0.0138
	(0.076)	(0.0071)
Observations	$1,187,467$	$1,187,467$
Upwind-downwind (4 years ahead)	0.005 (0.0118)	0.0082 (0.0121)

Notes: All equations follow specification from Table 2. Panel A displays coefficients for trimesters prior to conception (Column 1 refers to Portuguese, and Column 2 to Maths as outcome variables. Panels B and C show two equations each using trimesters and 4 years after birth.

periods in determining test scores, confirming that our controls for time of birth and year of exam are capturing serial correlation in smoke exposure. Panels A and B present results from placebo tests for periods prior to conception and postbirth, revealing generally non-significant impacts of fires on student scores across both subjects, although we note that a significant coefficient emerges for the second trimester preconception, a finding

we're unable to fully explain. Panel C, covering 4 years postbirth, indicates that the effects of poor air quality on scores are largely non-significant.

As biomass burning contains not only $PM_{2.5}$ but also CO and O_3 in smaller proportions[26], Table 6 presents results of our estimations with the three in separate equations and as co-pollutants. One can notice that the First stage Kleibergen–Paap rk Wald F statistics for both pollutants drops below the threshold of 10. Hence, first, we use the LIML estimator for those equations. When we compare the results with co-pollutants, we notice that the main results with $PM_{2.5}$ remain stable as when estimated separately (Columns 1 and 6). Besides this, in Table 7, we report the relation between fires and the three pollutants at the municipality level, suggesting that all of them are affected by fires and wind[27].

In our fifth set of robustness checks (Table A5), we present results for specifications with linear weather variables (Columns 1 and 2) to demonstrate that our baseline estimates with binned weather controls are not sensitive to different forms of meteorological controls. The results remain generally the same, indicating that our main estimates are not driven by unobserved weather conditions correlated with wind and students' performance. In addition, we show specifications using fire counts non-weighted by probability of occurrence (Columns 3 and 4) and without controlling for cloud coverage (Columns 5 and 6). From Table A5 Panels A and B, one can observe that the results remain broadly similar.

VII. Heterogeneity

In this section we explore the heterogeneity of the treatment effects (air pollution) for our preferred specifications (Table 4): (i) by gender (Table 8); (ii) across the distribution of scores (Table 9); and (iii) income per municipality (Table 9).

With regards to gender differentials, overall our findings reported in Table 8 suggest that boys are more negatively affected by pollution from agricultural burning than girls. Columns 1 and 4 repeat the results of our baseline models for ease of comparison with girls' and boys' performances in Portuguese (Columns 2 and 3) and Maths (Columns 5 and 6) exams. Firstly, one can note that the pattern of signs and significance concerning the gestational periods remains the same, with exposure to fires during the first and third trimesters showing significant effects on cognitive performance at school. From Column 3, we notice that boys are more affected in the third trimesters, though the effects are not statistically significant.

Epidemiology studies are still coming to terms on the part played by gender when it comes to the impacts of bad air quality on health. However, there are a few works suggesting that boys are more affected than girls. Abbey *et al.* (1998) find association between being exposed to PM_{10} and impaired lung function for males but not for females, and Galizia and Kinney (1999) show the equivalent aftermath regarding O_3. In a similar vein, Ebenstein *et al.* (2016) suggest that boys present lower academic performance than

[26]$PM_{2.5}$, CO and O_3 present a pairwise correlation of 51% and 54% significant at the 5% level.
[27]The literature finds it challenging to model O_3, with the direction of coefficients usually counter-intuitive (Gardner and Dorling, 2000; Dominici *et al.*, 2003; Chen, Zhao, and Weschler, 2012).

TABLE 6

Impacts of carbon monoxide and ozone on students' scores

Variables	(1) Portuguese	(2) Portuguese	(3) Portuguese	(4) Portuguese	(5) Portuguese	(6) Maths	(7) Maths	(8) Maths	(9) Maths	(10) Maths
PM25_1tr	−0.0205*			0.00515	−0.00390	−0.0167*			0.0172	−0.00947
	(0.0093)			(0.0332)	(0.0428)	(0.0074)			(0.0341)	(0.0410)
PM25_2tr	0.0069			0.0226	−0.00	0.013*			0.0323	−0.00
	(0.0079)			(0.0226)	(0.0253)	(0.0067)			(0.0241)	(0.0225)
PM25_3tr	−0.0266***			−0.0314***	−0.0379***	−0.0274***			−0.0273***	−0.0393***
	(0.0068)			(0.0081)	(0.00979)	(0.0076)			(0.00857)	(0.0120)
CO_1tr		−0.673		−0.619			−0.968*		−1.220	
		(0.450)		(0.810)			(0.443)		(0.880)	
CO_2tr		−0.993***		−2.091			−0.748		−2.311	
		(0.378)		(1.507)			(0.432)		(1.694)	
CO_3tr		−0.493		−1.817			−0.203		−2.231	
		(0.473)		(1.846)			(0.389)		(2.010)	
O3_1tr			−0.0186		−0.0454			−0.0258*		−0.0461
			(0.0102)		(0.0384)			(0.0119)		(0.0441)
O3_2tr			−0.0172**		−0.0311			−0.0107		−0.0197
			(0.00620)		(0.0359)			(0.00734)		(0.0396)
O3_3tr			−0.000945		−0.0144			0.000648		−0.00878
			(0.00681)		(0.0334)			(0.00615)		(0.0345)
F	10	6	11	0.6	1.3	10	6	11	0.6	1.3
Observations	1,187,660	1,187,660	1,187,660	1,187,660	1,187,660	1,187,660	1,187,660	1,187,660	1,187,660	1,187,660

Notes: All equations follow specification from Table 4. First-stage Kleibergen–Paap rk Wald F statistic. We estimate the equations using LIML due to the F statistics below 10. *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$.

TABLE 7

Effects of fires on co-pollutants

Variables	(1) PM$_{2.5}$ (1tr)	(2) PM$_{2.5}$ (2tr)	(3) PM$_{2.5}$ (3tr)	(4) CO (1tr)	(5) CO (2tr)	(6) CO (3tr)	(7) O$_3$ (1tr)	(8) O$_3$ (2tr)	(9) O$_3$ (3tr)
Upwind-downwind (1tr)	0.252***			0.003***			0.039		
	(0.038)			(0.0004)			(0.036)		
Upwind-downwind (2tr)		0.245***			0.003***			0.106***	
		(0.040)			(0.0004)			(0.034)	
Upwind-downwind (3tr)			0.259***			0.003***			0.087***
			(0.038)			(0.0004)			(0.03)
Observations	58,050	58,050	58,050	58,050	58,050	58,050	58,050	58,050	58,050
Municipalities	645	645	645	645	645	645	645	645	645
R^2	0.191	0.159	0.150	0.072	0.077	0.082	0.184	0.167	0.217

Notes: Robust SEs in parentheses clustered by municipality centroid. All models control for municipality FE, month and year. Estimates for controls not shown: temperature bins, rainfall, relative humidity, wind speed and cloud coverage. *** $P < 0.01$, ** $P < 0.05$, *** $P < 0.1$.

TABLE 8

Heterogeneity per gender – second stage

Pollution and scores (Second stage)	(1) Portuguese (SD) All	(2) Girls	(3) Boys	(4) Maths (SD) All	(5) Girls	(6) Boys
PM$_{2.5}$ (1tr) (μg/m^3)	−0.0205* (0.00931)	−0.0278*** (0.0103)	−0.0157 (0.00978)	−0.0167* (0.00744)	−0.0200** (0.00830)	−0.0144 (0.00822)
PM$_{2.5}$ (2tr) (μg/m^3)	0.00690 (0.00787)	−0.000648 (0.00925)	0.0127 (0.00749)	0.0130 (0.00674)	0.00452 (0.00722)	0.0198*** (0.00703)
PM$_{2.5}$ (3tr) (μg/m^3)	−0.0266*** (0.00683)	−0.0202*** (0.00694)	−0.0292*** (0.00899)	−0.0274*** (0.00755)	−0.0171** (0.00778)	−0.0310*** (0.00935)
First-stage F-test	10	11	10	10	11	10
Observations	1,187,660	543,030	644,630	1,187,660	543,030	644,630
PM$_{2.5}$ (μg/m^3) (Whole pregnancy)	−0.04*** (0.014)	−.0486*** (0.0155)	−0.0322** (0.0153)	−0.031** (0.0126)	−0.0326*** (0.0135)	−0.0256* (0.0143)
Low-high (*P*-value)	> 0.1			> 0.1		

Notes: Equations follow specification from Table 4. First-stage Kleibergen–Paap rk Wald F statistic. We estimate the equations using LIML due to the F statistics below 10. Girls-Boys show the *P*-value from the difference between the respective coefficients for the whole pregnancy period. *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$.

girls once exposed to contemporaneous air pollution, and Kim (2019) find that males are more sensitive to both contemporaneous and cumulative exposure to bad air quality than females. However, when we consider the whole pregnancy period, it seems girls are more negatively affected than boys, although the difference between genders is not statistically significant.

We also split our final sample into subsets according to low and high scores within each municipality. From Panel A of Table 9, one can note that weaker students (below median) are more sensitive to exposure during the third trimester of pregnancy than the others (above median) in the scores distributions for both subjects, though not significant. These findings are in accordance with Ebenstein *et al.* (2016) who also show

TABLE 9

Heterogeneity per scores and income distributions – second stage

	(1) Baseline	(2) Low	(3) High	(4) Baseline	(5) Low	(6) High
	Portuguese			Maths		
Panel A: Scores Dep. Var. (SD)						
$PM_{2.5}$ (1tr)	−0.0205*	−0.0112	−0.0089	−0.0167*	−0.0096	−0.0074
	(0.0093)	(0.0078)	(0.0063)	(0.0074)	(0.0066)	(0.0062)
$PM_{2.5}$ (2tr)	0.0069	0.00103	0.00235	0.013*	0.0078	0.0056
	(0.0079)	(0.0067)	(0.0046)	(0.0067)	(0.0053)	(0.0043)
$PM_{2.5}$ (3tr)	−0.0266***	−0.0176**	−0.001	−0.0274***	−0.0146**	−0.0118*
	(0.0068)	(0.0072)	(0.0061)	(0.0076)	(0.0067)	(0.0071)
F	10	10	10	10	10	10
Observations	1,187,660	593,099	594,560	1,187,660	593,214	594,446
$PM_{2.5}$	−0.04***	−.0278**	−0.0076	−0.031*	−0.0164	−0.0136
(Whole pregnancy)	(0.014)	(0.0126)	(0.0099)	(0.0126)	(0.0108)	(0.0104)
Low-High (*P*-value)	> 0.1			> 0.1		
Panel B: Income Dep. Var. (SD)						
$PM_{2.5}$ (1tr)	−0.0205*	−0.0234**	−0.0236*	−0.0167*	−0.0242***	−0.0134
	(0.0093)	(0.0095)	(0.0135)	(0.0074)	(0.0082)	(0.0104)
$PM_{2.5}$ (2tr)	0.0069	0.0053	0.0095	0.013*	0.0105	0.0255***
	(0.0079)	(0.0078)	(0.0099)	(0.0067)	(0.007)	(0.0083)
$PM_{2.5}$ (3tr)	−0.0266***	−0.0277***	−0.032**	−0.0274***	−0.0276***	−0.0288**
	(0.0068)	(0.0089)	(0.014)	(0.0076)	(0.0093)	(0.0131)
F	10	9	9	10	9	9
Observations	1,187,660	275,712	148,899	1,187,660	275,712	148,899
$PM_{2.5}$	−0.04***	−0.0458***	−0.0461**	−0.031***	−0.0413***	−0.0167
(Whole pregnancy)	(0.014)	(0.0152)	(0.0218)	(0.0126)	(0.0142)	(0.0187)
Low-High (*P*-value)	> 0.1			> 0.1		

Notes: Panels A and B follow specification from Table 4. First-stage Kleibergen–Paap rk Wald F statistic. We estimate the equations using LIML due to the F statistics below 10. Low-High shows the *P*-value from the difference between the respective coefficients for the whole pregnancy period. *** $P < 0.001$, ** $P < 0.01$, * $P < 0.05$.

evidence of weaker students' poorer performance as a result of poor air quality during examinations.

Finally, we use parents' level of education as a proxy for socio-economic status and display the results by low or high level of income. The bottom part of Panel B in Table 9 suggests there is no significant overall difference between students below and above the median. However, these results have to be interpreted with caution as this particular question contains a lot of missing values from students who did not know their parents' education level.[28]

VIII. Economic significance

The literature on the returns of education has shown that better cognitive test scores at school are positively related to individual higher earnings in the future (Murnane, Willett,

[28]In the Appendix S1, we include Tables A7 and A8 with the heterogeneity analysis for the reduced form equations, with overall qualitatively similar results to those of the second stage regressions in this section.

and Levy, 1995; Murphy and Peltzman, 2004; Blau and Kahn, 2005; Chetty *et al.*, 2011; Currie, Thomas, *et al.*, 2012; Curi and Menezes-Filho, 2015; Bharadwaj *et al.*, 2017), to lower probability of drop-outs (Rivkin, 1995; Hanushek, 1996); and to higher economic growth (Hanushek and Kimko, 2000). Curi and Menezes-Filho (2015) shows evidence of a 5% reduction of salary per 10% reduction of scores. Therefore, using our estimated cognitive performance effects for the whole pregnancy period (Table 4) and estimates of the returns to exams scores from Brazil (Curi and Menezes-Filho, 2015), we present a back-of-the-envelope calculation suggesting that, *ceteris paribus*, a drop of $PM_{2.5}$ by 10% ($0.1*14.3 = 1.43\mu g/m^3$ [Table 1]) during the gestational period would raise students' scores in languages by 1.3% ($1.43*0.04*47.8/219$ [Table 4]) and in Maths by 0.9% ($1.43*0.031*47.5/234$); and consequently elevate future individuals' earnings by 2.6% and 1.8%, respectively.

IX. Conclusion

In this paper we examined the relationship between foetal exposure to air pollution from agricultural fires and cognitive performance in 5th grade exams in Brazil. To this end we merge data from the Brazilian Ministry of Education, NASA's satellite remote sensing data with active fire detection, and air pollution data and atmospheric conditions data from the Japanese Reanalysis archive, JRA-55.

Our empirical strategy, which relies upon wind direction and fires' location as predictors of air pollution, provides evidence that exposure to agricultural burning, and as a result poor air quality, during the gestational period causes a reduction in the cognitive ability of students. More precisely, we show that students living in municipalities affected by upwind fires present lower academic performance than their downwind counterparts. To put our findings into perspective, we demonstrate that students exposed to an additional 1SD of fires during their gestational period suffer a reduction of 0.0339SD in Portuguese and 0.0317SD in Maths scores in the 5th grade. We also find evidence that weaker pupils are significantly more sensitive to prenatal burning exposure in terms of both subjects' scores. In addition, we demonstrate the impact of agricultural burning on higher levels of $PM_{2.5}$ and of this on reduced scores later in life. More specifically, we find that a 1 $\mu g/m^3$ of $PM_{2.5}$ during the first trimester of pregnancy causes a reduction in Portuguese and Maths scores by 0.021SD and 0.0167SD. In contrast, an increase in exposure to particulate matter during the third gestational period appears to decrease scores in Portuguese by 0.0266 and Maths by 0.0274SD.[29]

Back-of-the-envelope calculations indicate that a reduction of 10% of $PM_{2.5}$ during the whole gestational period, that is, $1.43\mu/m^3$, would increase scores by 1.3% in Portuguese and by 0.9% in Maths and ultimately increase wages by 2.6%. These findings are in line with the economics and medical literature on the harmful effects of foetal exposure to air pollution to the foetus' brain development, particularly during the first and third trimester (Rice and Barone Jr., 2000; Sunyer and Dadvand, 2019; McGuinn *et al.*, 2020).

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[29]The main assumption is that the effect of fires (air pollution) on scores is via cognitive skill formation. However, it might be the case that the health effects of pollution exposure affect school outcomes (e.g. physical health, missing school days). That is, the effect may go through the indirect physical channel. However, we do not have data on missing days or physical health to test for this.

One limitation of our study is the lack of data to control for contemporaneous air pollution (at the time of the exams), potentially resulting in a source of omitted variable bias. To what extent such omitted variable bias might be driving our results should be subject of future research when better data becomes available. Another potential weakness of our analysis is that we are unable to identify preterm births, the occurrence of which may be partially associated with air pollution. Again better data could allow one to investigate what role this might be playing in introducing attenuation bias. Nonetheless, unless these aspects are the main drivers of our benchmark estimates, which seems unlikely, our results can overall be taken as evidence that cognitive performance may be hindered by *in utero* exposure to agricultural fires. This finding is relevant for the many parts of the world where agricultural fires are commonplace, and could have important implications for policy. For example, the signing of the Green Ethanol Protocol in 2017, which aims to boost the mechanisation of harvesting, should reduce the extent of the burning in São Paulo state to the benefit of air quality and human capital accumulation. If successful, this policy perhaps provides a model for other countries to follow.

Final Manuscript Received: April 2022

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Supporting Information

Additional Supporting Information may be found in the online Appendix:

Appendix S1. Supporting information

Data replication package: the data replication package is available at
https://doi.org/10.3886/E188961