Technical change and health: Evidence from the reduction of sugarcane burning in Brazil

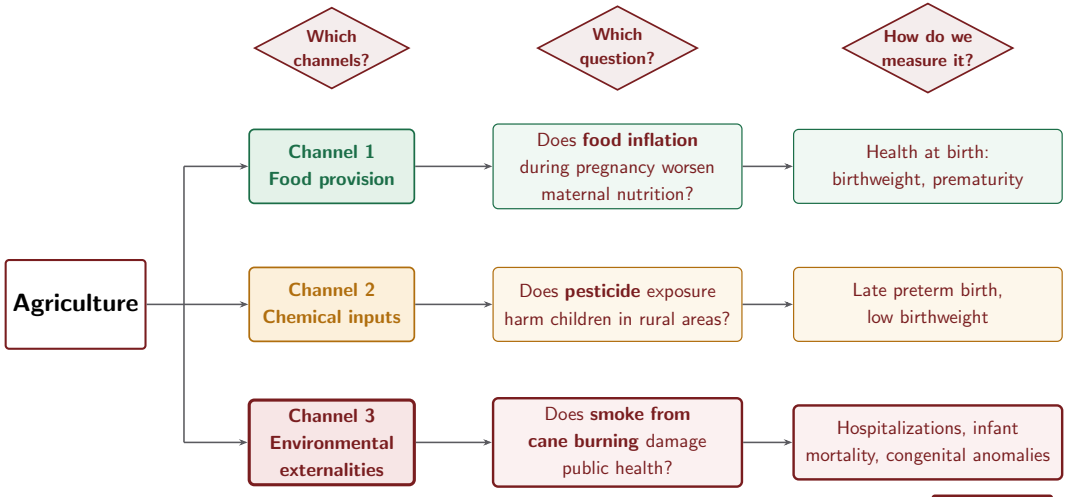
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DEPAL Seminar Series, Texas A&M University

UFV

Paper & slides

How does agriculture affect health?

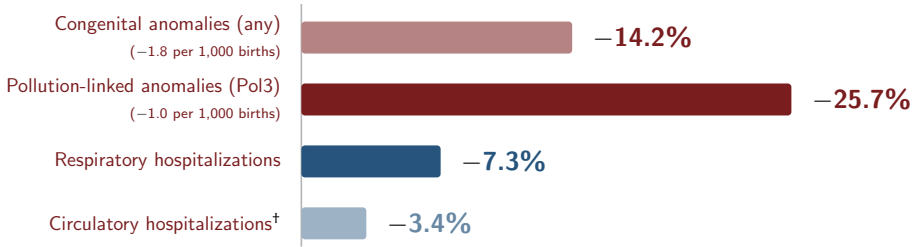


Can a technical change in agriculture improve health?

Pre-harvest burning eliminated

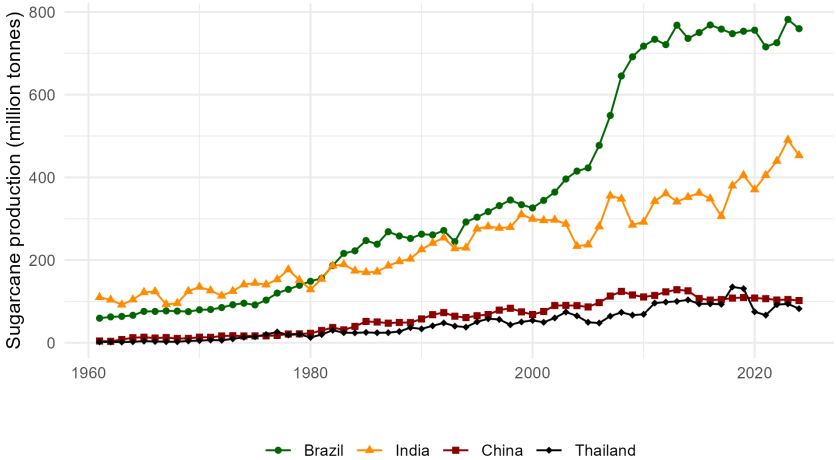
2007: 33% mechanized → **2015**: >95% mechanized

Reduction per one-standard-deviation increase in exposure



And it really is the smoke: ✓ pollution fell **only** in harvest months ✓ **upwind** areas suffered more

Brazil Leads World Sugarcane Production



Overclaiming vs. Underselling

São Paulo's shift away from cane burning is, in our view, one of the best settings in the world to study agricultural fire.

- Fast and near-complete: Mechanized harvest 33% (2007) $\rightarrow$ >95% (2015) [Conab, 2024]
- Intensive: 20% of the state's land under cane by 2010 [IBGE, 2024]
- Not a small player: São Paulo produces 21% of world sugarcane [FAO, 2025] in a area three times smaller than Texas



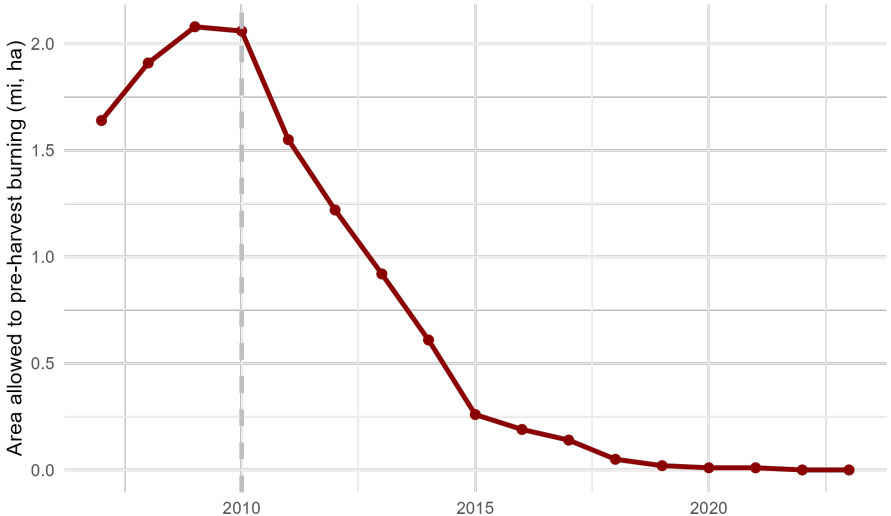
São Paulo (green) over Texas, same scale

Our Source of Identification

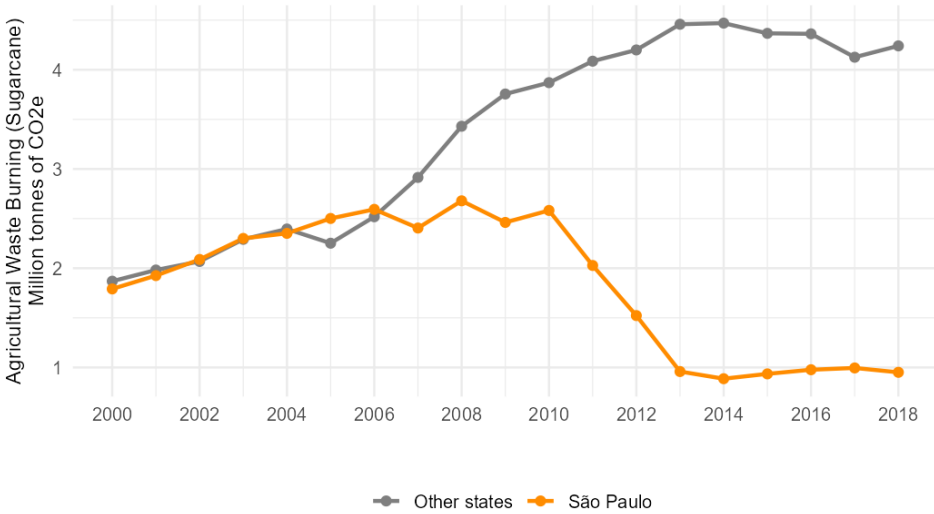
There was a reduction in burning driven by...

- Law
  - State Law 11.241/2002: gradual ban on straw burning (targets: 50% by 2011, 100% by 2021)
- Protocol
  - Green Ethanol Protocol (2007): voluntary industry agreement that accelerated deadlines to 2014–2017 in exchange for preferential financing and export market access
- Labor costs
  - Rising rural wages and export sustainability standards reinforced the shift [Davis, 2017]

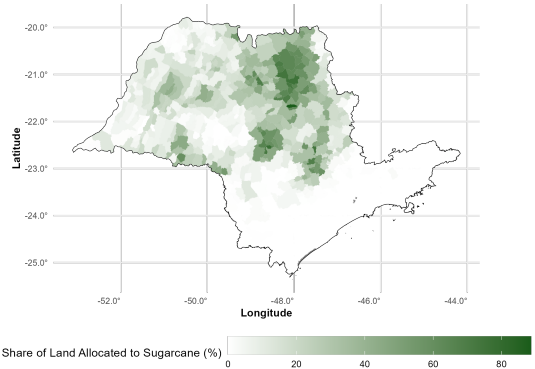
Area allowed to pre-harvest burning

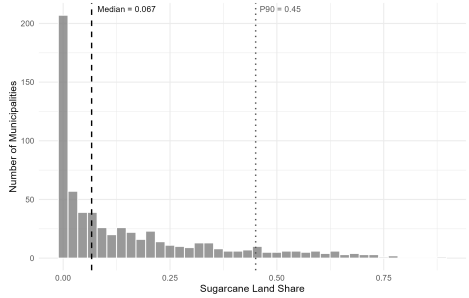


Emissions from sugarcane agricultural waste burning



With spatial heterogeneity in this reduction...





Right-skewed exposure: median 0.067, top decile above 0.45

Combining the timing and the spatial heterogeneity

Difference-in-differences, continuous exposure [Callaway et al., forthcoming]

$$\ln\left(Y_{it}\right) = \alpha \cdot \underbrace{Land_i \times D_{t>2010}}_{\text{Tech. Change } (TC_{it})} + \theta_i + \gamma_t + \varepsilon_{it}$$

$Land_i$ = cane land share, 2000–2010 average; $D_{t>2010} = \mathbf{1}[t > 2010]$

Every municipality is treated in proportion to its cane share

- θ_i, γ_t: municipality and year FE; population weights; SEs clustered by municipality
- $SD(Land_i) = 0.19$ — the unit for all "one-SD" effects below

The Literature

- Rangel and Vogl [2019] – Review of Economics and Statistics: wind-based smoke exposure $\rightarrow$ lower birthweight, shorter gestation (São Paulo)
- Chagas et al. [2016] – Regional Science and Urban Economics: spatial DiD, sugarcane $\rightarrow$ respiratory hospitalizations, treatment is a binary median-split

Our contribution

- Broader outcomes: circulatory disease, infant mortality, a biologically-grounded congenital anomaly index
- Holding sugarcane production constant, what is the impact of reducing burning?
- Continuous rather than binary exposure, plus three sharper designs (season, wind, dose)

Data Sources

- **Hospitalizations**: SIH/SUS, 2008–2021 (ICD J00–J99, I00–I99), by patient's municipality of residence
- **Births**: SINASC, 2002–2023, $N \approx 12$M individual records
- **Mortality**: SIM, 2001–2023, by municipality of residence
- **Treatment**: PAM-IBGE sugarcane land share, 2000–2010 average
- **PM10/PM25**: CAMS global reanalysis (EAC4), 2003–2024
- **Fire**: MODIS MCD64A1 $\times$ MapBiomas LULC (cane pixels), Google Earth Engine
- **Wind**: NASA POWER/MERRA-2 reanalysis, Jul–Sep 2002–2022

All sources are administrative and cover the universe of events — no survey sampling error.

Results

Hospitalizations Fall in More Exposed Municipalities

$y = \ln(\text{hosp. per capita})$	Full (2008–2021)		Pre-Covid (2008–2019)	
	(1)	(2)	(3)	(4)
Panel A: Respiratory (J00–J99)				
Tech. Change	−0.386***	−0.384***	−0.300***	−0.302***
	(0.093)	(0.093)	(0.092)	(0.092)
Panel B: Circulatory (I00–I99)				
Tech. Change	−0.178***	−0.182***	−0.177***	−0.179***
	(0.055)	(0.054)	(0.050)	(0.050)
log(GDP/cap) control		X		X
Municipality & Year FE	X	X	X	X

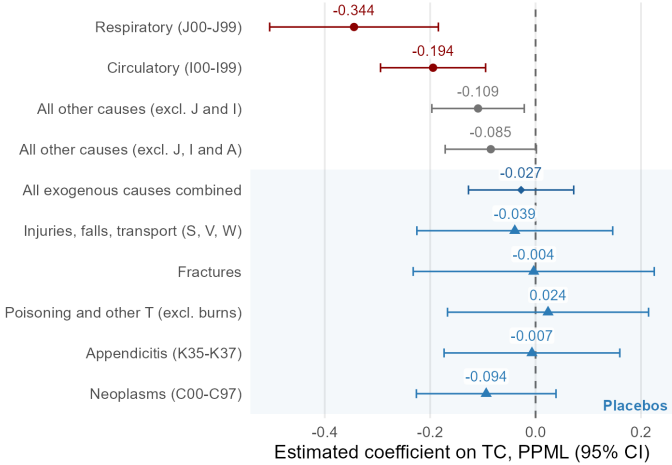
* p<0.1, ** p<0.05, *** p<0.01. Pop.-weighted; clustered SEs; by residence.

- **1 SD more exposure** ⇒ respiratory ↓**7.3%**; stable when controlling for GDP/capita
- Circulatory ↓3.4%, but circulatory outcomes were already converging before 2011 — not distinguishable from that pre-existing convergence

Leave one out

- Respiratory, leaving one municipality out: estimates range from -0.451 to -0.361 (full sample: -0.384), all significant at 1%.
- Respiratory, leaving one year out: estimates range from -0.416 to -0.329, all significant at 1%.
- Circulatory, leaving one municipality out: estimates range from -0.203 to -0.151 (full sample: -0.182), all significant at 1%.
- Circulatory, leaving one year out: estimates range from -0.224 to -0.153, all significant at 1%.

Placebo: Outcomes Smoke Cannot Affect



Backup: Dose-Response by Exposure Quartile

Post-2010 × quartile of cane share	Q1	Q2	Q3	Q4
Mean cane share in quartile	0.005	0.055	0.175	0.465
Respiratory hosp.	0.002	−0.034	−0.138***	−0.171***
	(0.054)	(0.057)	(0.049)	(0.045)
Circulatory hosp.	0.025	−0.019	−0.080***	−0.063*
	(0.031)	(0.036)	(0.022)	(0.034)

Terciles and quintiles show the same pattern.

Birth Outcomes: Fewer Congenital Anomalies

	Any Anomaly (SINASC flag)	Pol3 Index (NTD+Orofac.+Card.)	LBW (<2,500g)	VLBW (<1,500g)
Tech. Change	−0.009 22*	−0.005 45**	0.003 33**	−0.000 33
	(0.004 86)	(0.002 29)	(0.001 68)	(0.000 73)
Baseline mean (post-2010)	12.31/1000	4.02/1000	9.21%	1.44%

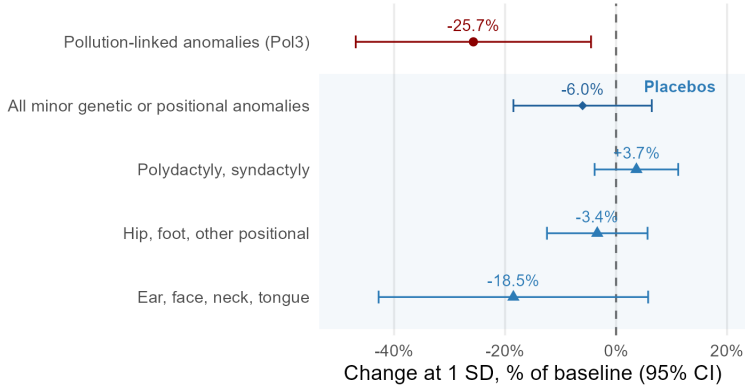
Individual (Sinasc) 2002–2023, $N \approx 12$M. FE: Mun., year, educ., sex, marital status.

- **Congenital anomalies fall 14.2%**; the **Pol3 pollution-linked index falls 25.7%** at 1 SD of exposure
- **Very low birthweight: null.** Low birthweight carries a small positive coefficient ($p = 0.048$), not corroborated by mean birthweight or VLBW — we do not read it as an effect

Which Anomalies?

$y = \Pr(\text{anomaly type})$	Neural Tube (Q00–Q07)	Orofacial (Q35–Q37)	Cardiac (Q20–Q26)	Pol3 Index
Tech. Change	$-0.000\,743^{***}$	$-0.000\,122$	$-0.004\,724^{**}$	$-0.005\,445^{**}$
	$(0.000\,254)$	$(0.000\,128)$	$(0.002\,038)$	$(0.002\,291)$
Baseline, post-2010 (per 1,000)	1.15	0.76	2.27	4.02
Relative effect (1 SD)	-12.3%	ns ($p = 0.34$)	$\mathbf{-39.5}\%$	-25.7%
Per 1,000 births (1 SD)	-0.14	ns	-0.90	-1.03

Placebo: Anomalies Smoke Cannot Cause



Minor genetic or positional anomalies (extra or fused fingers, clubfoot, hip, ear, tongue) are as common as Pol3 but do not move.

Mortality: No Detectable Effect, Respiratory or Circulatory

PPML, 2001–2023	Respiratory		Circulatory	
All ages	0.021	(0.101)	−0.134	(0.081)
Children (<5)	−0.061	(0.138)	−0.126	(0.239)
Elderly (60+)	−0.014	(0.119)	−0.162	(0.089)

Deaths by municipality of residence (SIM), with population (births for children) as exposure. Circulatory coefficients are at most marginal ($p < 0.1$) and circulatory mortality was already converging before 2011 (pre-trend $p < 0.01$).

Mortality is the least sensitive margin: the gains appear in morbidity — hospitalizations and congenital anomalies — not in deaths.

Is It Really the Smoke?

Less Particulate Matter, Only During Harvest

$$\ln\left(Y_{it}\right) = \alpha \cdot Land_i \times D_{t>2010} + \theta_i + \gamma_t + \varepsilon_{it}$$ (same treatment as before)

$Y_{it} \in \{$ PM10, PM25 $\}$

	Harvest (Jul–Sep)	Off-season (Jan–Mar)
Particulate matter (CAMS reanalysis)		
ln(PM10)	−0.096***	−0.005
	(0.010)	(0.007)
ln(PM25)	−0.094***	−0.001
	(0.010)	(0.007)

*** p<0.01.

- PM10 and PM25 ↓**1.8%** at 1 SD — **only during harvest**

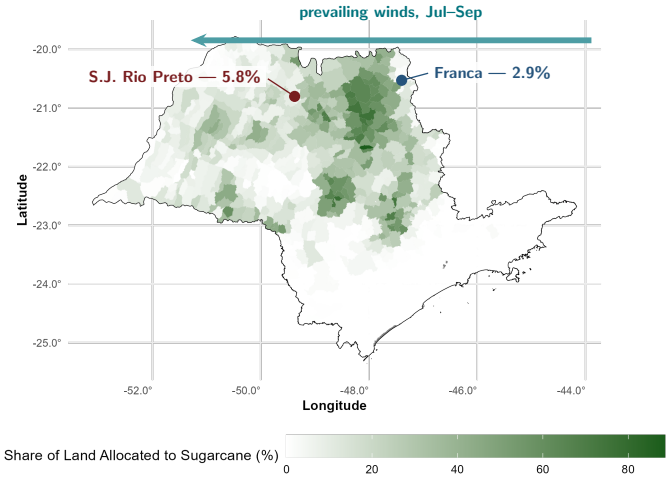
Health Gains Concentrate in Harvest Months

$$\ln Y_{itm} = \alpha \cdot TC_{it} + \beta \cdot (TC_{it} \times Harvest_m) + \theta_{i \times m} + \gamma_t + \varepsilon_{itm}$$

$y = \ln(\text{hosp./pop})$	Respiratory	Circulatory
Tech. Change (off-season)	-0.122^{***}	-0.071^{***}
	(0.030)	(0.019)
Tech. Change $\times$ Harvest	$\mathbf{-0.064}^{***}$	-0.016
	(0.009)	(0.010)

Respiratory hospitalizations fall more when burning would have occurred. Circulatory hospitalizations show no such difference. An income or employment channel from mechanization would not concentrate in harvest months.

Why the wind matters



$$Up_{id} = \sum_{f \in F^{night}_{d-3..d}} \mathbb{1}\left[dist_{if} \leq 50\,\text{km}\right] \times \mathbb{1}\left[\left|\theta^{wind}_{id} - \theta_{i \to f}\right| \leq 45^\circ\right]$$

$Down_{id}$: angle $\geq 135^\circ$; $Side_{id}$: the rest.

Night fires (FIRMS/MODIS); wind = that day's direction at i; $Down$ and $Side$ held fixed, so total fire is constant.

Night Fires Fell Where the Technical Change Happened

$$NightFires_{it} = \alpha \cdot TC_{it} + \theta_i + \gamma_t + \varepsilon_{it}$$

	Night fires (cane burning)	Day fires (placebo)	Difference (stacked)
α (TC)	$\mathbf{-0.575}^{***}$	$+0.210$	$\mathbf{-0.785}^{***}$
	(0.140)	(0.125)	(0.173)
% at mean cane municipality	-14%	$+6\%$	-19%

- Decline concentrated after 2014–2017, matching the Protocol's deadlines

FIRMS/MODIS fire detections in municipality i, harvest months (Jul–Sep), 2008–2021. Estimated by Poisson (PPML)

Smoke Travels with the Wind: Daily Evidence

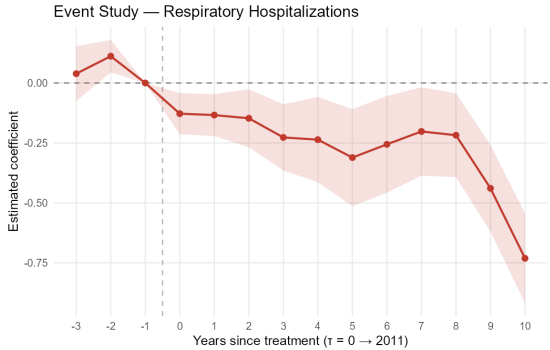
$$\ln[Y_{i,d}] = \beta_{up}\, UP_{i,d-3} + \beta_{down}\, DOWN_{i,d-3} + \beta_{side}\, SIDE_{i,d-3} + W'_{i,d}\gamma + \theta_{i\times y\times m} + \delta_d$$

W: temperature bins, rain, humidity, wind speed. PPML, SEs clustered by municipality.

- $H_1:\ \beta_{up} > \beta_{down}$
- **Cane is burned at night**: night fire detections fall 60–85% after 2011; daytime detections do not
- **$PM_{2.5}$** (2003–2010): an upwind fire raises $PM_{2.5}$ **twice** as much as a downwind fire ($+1.6\%$ vs $+0.8\%$); the gap disappears after 2011
- **Respiratory admissions, ages 0–4**: **+0.3% per upwind fire** in the following days ($p = 0.07$); downwind fires: ≤ 0
- Ages 60+, circulatory, and placebos (injuries, neoplasms): **null**
- Mechanization of neighbours removed precisely the fires that sat **upwind** of each city

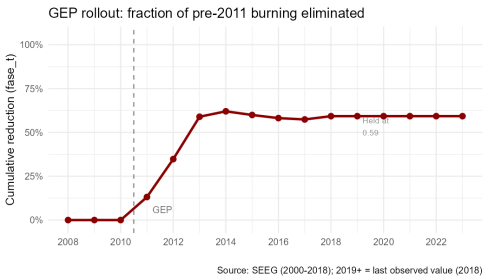
More Robustness

Did Exposed Municipalities Already Trend Differently?



- 2008: near zero.
- 2009: a positive spike that coincides with the **H1N1 influenza pandemic** — it disappears when 2009 is dropped, and post-treatment estimates do not change

Continuous Treatment Intensity



	Respiratory	Circulatory
Binary (0/1)	-0.330***	-0.159***
Continuous ($\times fase_t$)	-0.576***	-0.218**

Replacing the post-2010 dummy with $fase_t$ — the fraction of burning emissions already eliminated — gives an implied respiratory effect at the mean of -0.323, essentially the binary estimate (-0.330).

Robustness: Excluding São Paulo City

	Respiratory		Circulatory	
	Full	Pre-Covid	Full	Pre-Covid
Baseline	-0.386^{***}	-0.300^{***}	-0.178^{***}	-0.177^{***}
Excl. SP city	-0.416^{***}	-0.335^{***}	-0.179^{***}	-0.159^{***}

São Paulo city has 12M inhabitants and zero cane share — a heavily weighted, mechanically untreated observation. Dropping it leaves the estimates essentially unchanged.

What Are the Stakes?

- Aggregating the hospitalization reduction over 2011–2021 across exposed municipalities: $\approx$**74,000** fewer respiratory hospital admissions
- At 2019 SUS reimbursement rates: **R$ 84 million** (USD 21M) in avoided hospitalization costs
- $\approx$**2,504** fewer births with cardiac malformations (2011–2023) $\Rightarrow$ **R$ 34 million** (USD 9M) in avoided surgical costs

R$ 118 million (USD 30 million) over a decade — a conservative *lower bound* (it excludes outpatient care, productivity losses, and BPC/LOAS transfers; circulatory hospitalizations, up to R$ 100 million, are left out). These are health-system savings only: they do not net out the costs of mechanization to growers or to displaced cane cutters.

Takeaway

- A gradual, phased ban on pre-harvest sugarcane burning delivered measurable respiratory and perinatal health gains
- The pattern across outcomes traces a **dose-response gradient**: null mortality at all ages $\rightarrow$ significant respiratory hospitalizations $\rightarrow$ significant congenital anomalies — morbidity and fetal development respond before mortality does
- Mechanization also displaced manual cane cutters — a cost we do not measure
- Relevant beyond São Paulo: Northeast Brazil (Pernambuco: $>$90% manual), India, Thailand, Florida still rely on pre-harvest burning

Thank you! Questions?

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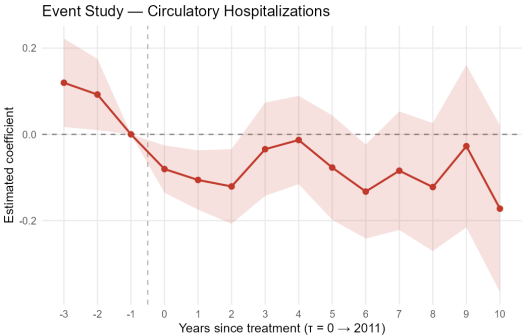
Backup Slides

Summary Statistics

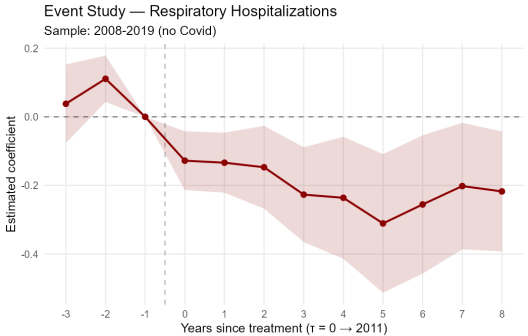
Variable	N	Mean	Median	SD	Max
Sugarcane land share (2000–2010)	642	0.150	0.067	0.190	0.886
Respiratory hosp. per 1,000 pop.	8,988	7.784	—	5.198	46.398
Circulatory hosp. per 1,000 pop.	8,988	8.107	—	3.980	38.560
Any anomaly (per 1,000 births)	11,882	18.662	—	91.807	1,000
Infant resp. mortality (per 1,000 births)	14,765	0.832	—	3.343	111.111

Event Study — Circulatory and Pre-Covid Samples

Circulatory (full sample)

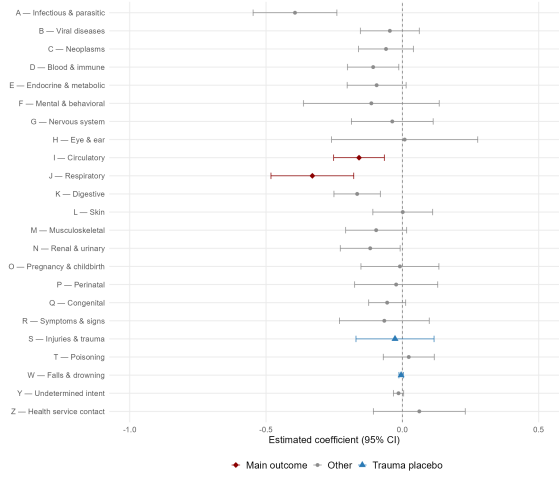


Respiratory (pre-Covid)



Respiratory: the pattern survives dropping the Covid years. Circulatory: pre-treatment coefficients are positive and decline toward 2010 ($p = 0.04$) — the circulatory estimates cannot be distinguished from a pre-existing convergence.

Backup: All ICD-10 Chapters



Placebo chapters — injuries (S) and falls (W) — do not move, and most other chapters are null. Infectious diseases (A) also fall, mostly intestinal infections.

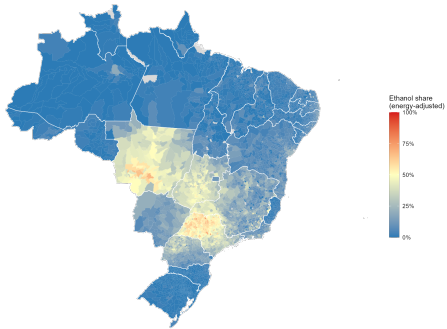
Backup: What About the Labor Channel?

Mechanization displaced manual cane cutters; changes in income or migration could affect health on their own. Four pieces of evidence point to smoke instead:

- **Seasonality**: respiratory effects concentrate in harvest months (Tech. Change $\times$ Harvest $= -0.064^{***}$) — an income or employment channel would not be seasonal
- **Wind**: downwind municipalities gain more, holding own exposure fixed (suggestive)
- **Income**: controlling for municipal GDP per capita leaves the estimate unchanged (-0.384 vs. -0.386)
- **Placebos**: hospitalizations for injuries and falls do not move

Composition does shift: births to mothers with 12+ years of schooling fall (-0.034, $p = 0.03$); the individual birth models control for maternal education.

Backup: Ethanol Market Context



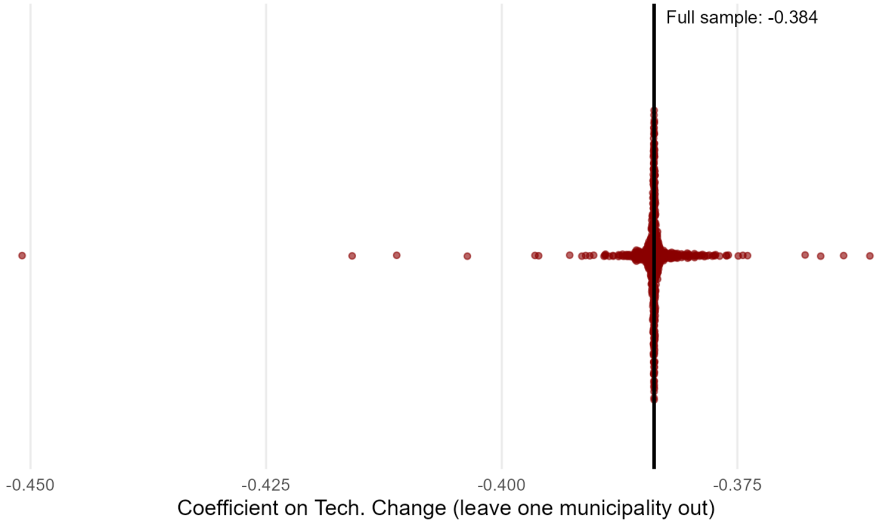
Energy-adjusted hydrated ethanol share in the fuel mix, 2020–2024. Hydrated ethanol competes directly with gasoline where transport costs from the cane belt are low.

Backup: Aggregate Birth Outcomes (Municipality-Year)

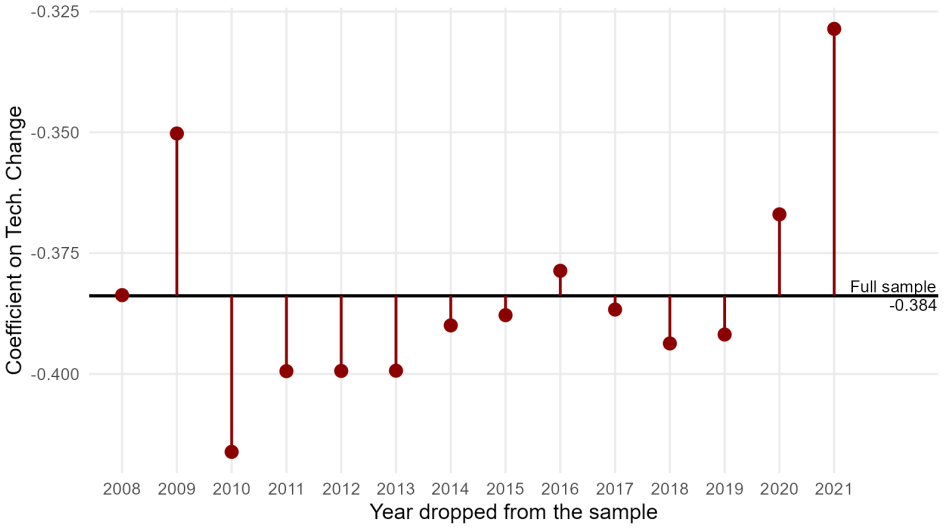
	ln(birthweight)	ln(LBW)	ln(VLBW)	ln(anomalies)
Tech. Change	−0.003	0.029	−0.064	−0.844***
	(0.004)	(0.023)	(0.058)	(0.319)

The aggregate specification confirms the anomaly result; the individual-level LPM shown earlier additionally decomposes it by diagnostic group.

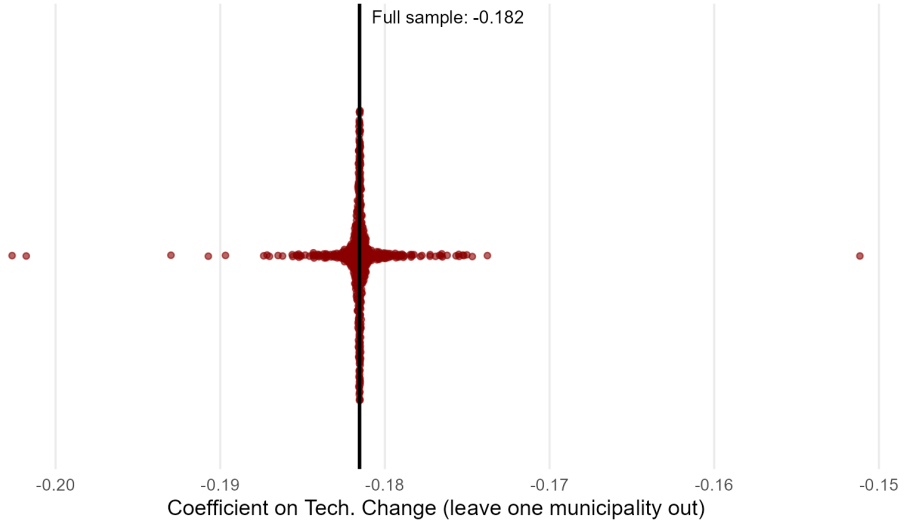
Leave-One-Out: Municipalities — Respiratory



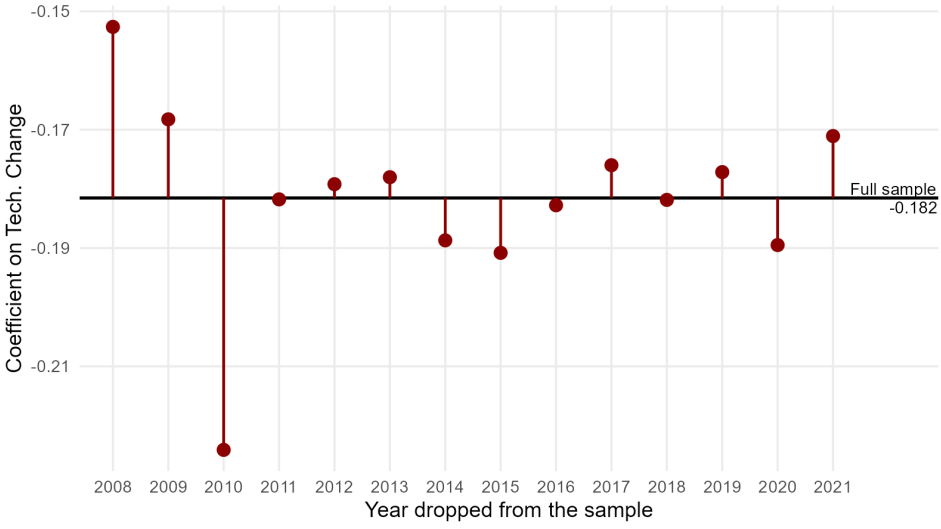
Leave-One-Out: Years — Respiratory



Leave-One-Out: Municipalities — Circulatory



Leave-One-Out: Years — Circulatory



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