1 Supplementary Material

Who Suffers Most? Causal Machine Learning Reveals Heterogeneous Health Effects of Air Pollution Across Brazilian State Capitals

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1.1 Table of Contents

1.2 Appendix A: Variable Definitions and Data Dictionary

1.2.1 A.1 Treatment Variable

Variable	Definition	Source
Treatment (binary)	1 if daily PM2.5 > 15 ug/m3 (WHO AQG), 0 otherwise	CAMS/Copernicus

1.2.2 A.2 Outcome Variables

Variable	Definition	Source
admissions	Total daily respiratory hospitalisations (ICD-10 J00–J99)	SIH/SUS DATASUS
admissions_age_0_14	Respiratory admissions, age 0–14 years	SIH/SUS DATASUS
admissions_age_15_59	Respiratory admissions, age 15–59 years	SIH/SUS DATASUS
admissions_age_60_plus	Respiratory admissions, age 60+ years	SIH/SUS DATASUS
admissions_female	Respiratory admissions, female	SIH/SUS DATASUS
admissions_male	Respiratory admissions, male	SIH/SUS DATASUS

1.2.3 A.3 Confounders (W)

Variable	Definition	Source
temperature_2m_mean	Daily mean temperature at 2m (C)	ERA5/Open-Meteo
dtr	Diurnal temperature range: T_max - T_min (C)	ERA5/Open-Meteo
relative_humidity_2m_mean	Daily mean relative humidity (%)	ERA5/Open-Meteo
pressure_msl_mean	Mean sea-level pressure (hPa)	ERA5/Open-Meteo
wind_speed_10m_max	Maximum 10m wind speed (m/s)	ERA5/Open-Meteo
precipitation_sum	Total daily precipitation (mm)	ERA5/Open-Meteo
day_of_week	Day of week indicators (6 dummies)	Calendar
is_holiday	Public holiday indicator	Calendar
sin_annual, cos_annual	Fourier harmonics (annual cycle)	Derived
sin_semi, cos_semi	Fourier harmonics (semi-annual cycle)	Derived
time_trend	Linear time trend (days since start)	Derived

1.2.4 A.4 Effect Modifiers (X)

Variable	Definition	Source
pop_density	Population / city area (inhabitants/km2)	IBGE Census 2022
fleet_per_capita	Registered vehicles / population x 1000	SENATRAN
pct_female	Female population / total population	IBGE Census 2022
dtr	Diurnal temperature range (C)	ERA5/Open-Meteo
region_N, region_NE, region_CO, region_SE, region_S	Macro-region indicators	IBGE

1.2.5 A.5 Model Hyperparameters

Parameter	Causal Forest	DML
n_estimators	2,000	–
min_samples_leaf	20	–
honest	True	–
discrete_treatment	True	True
cv (cross-fitting folds)	5	5
First-stage model (Y)	XGBoost (500 trees, depth 6, lr 0.05)	XGBoost (500 trees, depth 6, lr 0.05)
First-stage model (T)	XGBoost (500 trees, depth 6, lr 0.05)	XGBoost (500 trees, depth 6, lr 0.05)
Random seed	42	42

1.3 Appendix B: Average Treatment Effect Estimates

1.3.1 Table B.1: Causal Forest vs Double Machine Learning — Full Comparison

Outcome	CF ATE	CF 95% CI	CF p-value	DML ATE	DML 95% CI	DML p-value
Total Respiratory	0.599	[-3.670, 4.869]	0.783	**0.716**	**[0.083, 1.350]**	**0.027**
Children (0–14)	0.253	[-2.511, 3.017]	0.858	0.328	[-0.072, 0.728]	0.108
Adults (15–59)	0.231	[-1.301, 1.763]	0.767	**0.264**	**[0.033, 0.494]**	**0.025**
Elderly (60+)	0.207	[-1.411, 1.824]	0.802	0.210	[-0.023, 0.443]	0.077
Female	0.193	[-2.166, 2.552]	0.873	0.258	[-0.082, 0.598]	0.137
Male	0.372	[-2.220, 2.965]	0.778	**0.418**	**[0.006, 0.830]**	**0.047**

Note: Bold indicates statistical significance at alpha = 0.05. ATE = Average Treatment Effect; CI = confidence interval. Treatment: PM2.5 > 15 ug/m3. Outcome: daily respiratory hospitalisations.

1.4 Appendix C: CLAN Analysis — Full Quartile Profiles

The Classification Analysis (CLAN) sorts all city-day observations into quartiles of estimated CATE and reports the mean covariate profile of each quartile.

1.4.1 Table C.1: CLAN — Total Respiratory Admissions

Quartile	CATE	Pop. Density	Fleet/1000	% Female	DTR (C)	% North	% NE	% CO	% SE	% South
Q1 (lowest)	-1.558	2,564	710	52.2%	7.36	30.4%	17.7%	24.0%	16.0%	12.0%
Q2	+0.010	1,653	719	52.0%	8.10	39.2%	15.0%	28.4%	8.9%	8.5%
Q3	+0.937	2,030	710	52.0%	8.17	34.6%	14.8%	24.3%	14.7%	11.6%
Q4 (highest)	+3.009	3,779	729	52.6%	7.92	12.0%	23.5%	17.6%	31.6%	15.3%

1.4.2 Table C.2: CLAN — Children (0–14 years)

Quartile	CATE	Pop. Density	Fleet/1000	% Female	DTR (C)	% North	% NE	% CO	% SE	% South
Q1 (lowest)	-1.187	2,369	693	52.1%	7.75	33.0%	15.7%	27.6%	15.7%	8.0%
Q2	-0.086	1,863	742	52.0%	8.25	31.2%	14.7%	33.8%	10.8%	9.5%
Q3	+0.452	1,978	716	52.0%	8.21	40.1%	13.0%	20.2%	14.1%	12.6%
Q4 (highest)	+1.834	3,816	717	52.6%	7.34	11.9%	27.6%	12.8%	30.5%	17.3%

1.4.3 Table C.3: CLAN — Adults (15–59 years)

Quartile	CATE	Pop. Density	Fleet/1000	% Female	DTR (C)	% North	% NE	% CO	% SE	% South
Q1 (lowest)	-0.564	3,181	725	52.4%	6.97	22.6%	25.8%	15.2%	22.3%	14.2%
Q2	+0.017	1,778	716	51.9%	8.17	39.1%	13.9%	26.0%	10.5%	10.5%
Q3	+0.365	1,812	703	52.0%	8.19	36.0%	12.2%	29.1%	11.7%	10.8%
Q4 (highest)	+1.109	3,257	724	52.5%	8.22	18.5%	19.1%	24.1%	26.6%	11.7%

1.4.4 Table C.4: CLAN — Elderly (60+ years)

Quartile	CATE	Pop. Density	Fleet/1000	% Female	DTR (C)	% North	% NE	% CO	% SE	% South
Q1 (lowest)	-0.822	2,969	702	52.4%	6.85	26.9%	23.3%	13.5%	17.9%	18.4%
Q2	-0.012	1,418	708	51.8%	8.44	42.9%	10.9%	27.2%	7.9%	11.1%
Q3	+0.396	1,875	727	51.9%	8.29	32.0%	12.7%	31.7%	12.7%	10.9%

Quartile	CATE	Pop. Density	Fleet/1000	% Female	DTR (C)	% North	% NE	% CO	% SE	% South
Q4 (highest)	+1.266	3,767	732	52.7%	7.97	14.3%	24.2%	21.9%	32.7%	6.9%

1.4.5 Table C.5: CLAN — Female

Quartile	CATE	Pop. Density	Fleet/1000	% Female	DTR (C)	% North	% NE	% CO	% SE	% South
Q1 (lowest)	-0.976	3,220	750	52.4%	7.38	15.7%	23.4%	21.0%	23.4%	16.4%
Q2	-0.074	1,712	720	51.9%	8.61	41.0%	8.7%	29.0%	13.2%	8.1%
Q3	+0.388	1,710	718	51.9%	8.39	38.3%	12.0%	28.4%	8.6%	12.6%
Q4 (highest)	+1.434	3,385	681	52.5%	7.17	21.1%	26.9%	16.0%	25.9%	10.1%

1.4.6 Table C.6: CLAN — Male

Quartile	CATE	Pop. Density	Fleet/1000	% Female	DTR (C)	% North	% NE	% CO	% SE	% South
Q1 (lowest)	-1.130	2,316	651	52.2%	6.82	37.9%	21.8%	20.0%	10.4%	10.0%
Q2	-0.039	1,691	743	51.8%	8.57	36.5%	14.0%	32.2%	9.0%	8.3%
Q3	+0.586	2,000	728	52.0%	8.10	35.1%	11.1%	22.4%	16.7%	14.7%
Q4 (highest)	+2.075	4,018	745	52.7%	8.06	6.8%	24.2%	19.8%	34.9%	14.3%

1.5 Appendix D: City-Level CATE Estimates

1.5.1 Table D.1: Mean CATE by Capital (Total Respiratory Admissions)

City	UF	Region	Mean CATE	Median CATE	SD	N obs	Mean daily admissions
Sao Paulo	SP	SE	**+2.577**	+3.291	3.582	1,247	150.5
Brasilia	DF	CO	+1.381	+1.115	2.033	1,247	54.6
Salvador	BA	NE	+1.127	+0.566	2.498	1,246	29.9
Rio de Janeiro	RJ	SE	+0.909	+0.957	1.135	1,247	43.4
Campo Grande	MS	CO	+0.820	+0.747	1.015	1,237	14.6
Florianopolis	SC	S	+0.693	+0.739	1.253	1,241	14.5
Aracaju	SE	NE	+0.692	+0.767	1.845	1,245	13.3
Natal	RN	NE	+0.656	+0.696	1.727	1,244	13.3
Belo Horizonte	MG	SE	+0.568	+0.797	2.183	1,246	47.2
Porto Velho	RO	N	+0.443	+0.425	0.622	1,215	6.4
Curitiba	PR	S	+0.334	+0.599	2.427	1,245	44.4
Belem	PA	N	+0.320	+0.216	1.515	1,231	24.4
Rio Branco	AC	N	+0.300	+0.280	0.500	1,199	5.0
Goiania	GO	CO	+0.146	+0.082	0.875	1,247	21.2
Macapa	AP	N	+0.002	+0.216	1.192	1,232	7.0
Manaus	AM	N	**-0.395**	-0.548	1.907	1,234	31.1
Cuiaba	MT	CO	**-0.428**	-0.307	0.976	1,232	8.9

Note: Sorted by mean CATE (descending). Bold indicates highest and lowest values.

1.6 Appendix E: SHAP Feature Importance

1.6.1 Table E.1: Mean Absolute SHAP Values for CATE Heterogeneity (Total Respiratory Admissions)

Rank	Feature	Mean SHAP	
1	dtr	0.594	Diurnal temperature range (C)
2	pop_density	0.457	Population density (inhabitants/km2)
3	fleet_per_capita	0.292	Vehicles per 1,000 inhabitants
4	pct_female	0.265	Proportion female in population
5	region_CO	0.045	Central-West region indicator
6	region_NE	0.025	Northeast region indicator
7	region_N	0.024	North region indicator
8	region_S	0.023	South region indicator
9	region_SE	0.021	Southeast region indicator

Note: SHAP values decompose heterogeneity in Conditional Average Treatment Effects, not outcome prediction. Higher values indicate greater contribution to CATE variation across observations.

1.7 Appendix F: Policy Counterfactuals

1.7.1 Table F.1: Prevented Admissions by City Under WHO Compliance (PM2.5 <= 15 ug/m3)

City	Total admissions	Treated days	Prevented admissions	Mean CATE	Prevented (%)
Sao Paulo	187,646	864	2,268.5	+2.577	1.21%
Rio de Janeiro	54,132	862	840.1	+0.909	1.55%
Belo Horizonte	58,791	177	286.4	+0.568	0.49%
Curitiba	55,219	147	249.6	+0.334	0.45%
Rio Branco	5,975	286	170.1	+0.300	2.85%
Porto Velho	7,818	365	63.9	+0.443	0.82%
Brasilia	68,030	40	54.0	+1.381	0.08%
Florianopolis	18,049	61	48.1	+0.693	0.27%
Campo Grande	18,030	87	42.6	+0.820	0.24%
Salvador	37,235	13	27.7	+1.127	0.07%
Natal	16,487	20	14.4	+0.656	0.09%
Macapa	8,568	18	10.0	+0.002	0.12%
Goiania	26,479	86	9.9	+0.146	0.04%
Aracaju	16,572	1	-0.6	+0.692	-0.00%
Belem	29,976	42	-15.5	+0.320	-0.05%
Cuiaba	10,923	161	-27.6	-0.428	-0.25%
Manaus	38,391	355	-208.1	-0.395	-0.54%
Total	**658,321**	**3,585**	**3,833.7**	–	**0.58%**

Note: Negative prevented admissions indicate cities where the CATE is negative, suggesting possible harvesting effects or unmeasured protective factors. Treated days = days PM2.5 exceeded 15 ug/m3.

1.7.2 Table F.2: Prevented Admissions by CATE Vulnerability Quartile

Quartile	N obs	Total admissions	Treated days	Prevented admissions	Mean CATE	Prevented (%)
Q1 (least vulnerable)	5,260	172,613	786	-1,339.5	-1.558	-0.78%
Q2	5,260	105,846	733	+13.9	+0.010	+0.01%
Q3	5,257	128,783	861	+809.6	+0.937	+0.63%
Q4 (most vulnerable)	5,258	251,079	1,205	+4,349.7	+3.009	+1.73%

Note: The Q4 quartile alone accounts for 4,350 of the 3,834 net prevented admissions. The net total is lower because Q1 shows negative prevented admissions.

1.7.3 Table F.3: Dose-Response Policy Curve — Alternative Thresholds

Threshold (ug/m3)	Exceedance days	Exceedance (%)	Prevented admissions	Prevented (%)
15 (WHO AQG)	3,585	17.04%	3,833.7	0.58%
25 (CONAMA intermediate)	1,371	6.52%	1,564.8	0.24%
35 (CONAMA final)	633	3.01%	553.3	0.08%
50 (pre-2024 standard)	253	1.20%	144.4	0.02%

1.7.4 Table F.4: Bootstrap Confidence Interval for Prevented Fraction

Metric	Value
Mean prevented (%)	0.58%
95% CI lower	0.54%
95% CI upper	0.62%
Bootstrap resamples	1,000

1.8 Appendix G: Cost Estimation

1.8.1 Table G.1: Economic Impact of WHO Compliance

Metric	Value
Total SUS respiratory costs (study period)	R$ 1,282,441,262
Total admissions	658,321
Mean cost per admission	R$ 1,948.05
Prevented admissions (WHO scenario)	3,833.7
Saved costs	R$ 7,468,189
Saved costs (% of total)	0.58%
Saved costs (USD, approx.)	USD 1,494,000

Note: Costs based on SIH/SUS reimbursement data. USD conversion at approximate 2024 exchange rate of R$5.00/USD.

1.9 Appendix H: Sensitivity and Robustness Analyses

1.9.1 Table H.1: Placebo Test (PM2.5 at t+7)

Metric	Value
Test	Future PM2.5 (7-day lead) as placebo treatment
ATE	-0.540
95% CI	[-5.280, 4.200]
p-value	0.823
Result	**Passed** (null effect of future pollution on current admissions)

1.9.2 Table H.2: Leave-One-City-Out Jackknife

Excluded city	ATE	95% CI	p-value	N rows
Aracaju	0.716	[-4.241, 5.673]	0.777	19,790
Belo Horizonte	0.654	[-4.609, 5.918]	0.808	19,789
Belem	0.687	[-4.550, 5.923]	0.797	19,804
Brasilia	0.623	[-4.391, 5.636]	0.808	19,788
Campo Grande	0.747	[-4.672, 6.165]	0.787	19,798
Cuiaba	0.859	[-4.884, 6.602]	0.769	19,803
Curitiba	**0.970**	[-4.232, 6.172]	0.715	19,790
Florianopolis	0.636	[-4.770, 6.043]	0.818	19,794
Goiania	0.672	[-4.782, 6.126]	0.809	19,788
Macapa	0.802	[-4.583, 6.187]	0.770	19,803
Manaus	0.803	[-5.321, 6.927]	0.797	19,801
Natal	0.450	[-4.547, 5.448]	0.860	19,791
Porto Velho	0.795	[-4.528, 6.119]	0.770	19,820
Rio Branco	0.710	[-4.490, 5.910]	0.789	19,836
Rio de Janeiro	0.822	[-6.334, 7.979]	0.822	19,788
Salvador	0.542	[-4.561, 5.644]	0.835	19,789
Sao Paulo	**0.339**	[-3.598, 4.275]	0.866	19,788

Summary statistic	Value
Minimum ATE	0.339 (excl. Sao Paulo)
Maximum ATE	0.970 (excl. Curitiba)
Mean ATE	0.696
Coefficient of variation	0.22

Note: Bold indicates minimum and maximum ATE values. No single city exclusion changes the direction of the main finding.

1.9.3 Table H.3: Threshold Sensitivity (Causal Forest ATE)

Threshold (ug/m3)	ATE	95% CI	p-value	Treatment prevalence
15 (primary)	0.625	[-4.336, 5.587]	0.805	17.04%
25	0.375	[-12.130, 12.880]	0.953	6.52%

Threshold (ug/m3)	ATE	95% CI	p-value	Treatment prevalence
35	0.423	[-15.205, 16.050]	0.958	3.01%
50	1.717	[-72.189, 75.623]	0.964	1.20%

Note: As the threshold increases, treatment prevalence decreases and confidence intervals widen substantially, reflecting reduced statistical power.

1.9.4 Table H.4: Omitted Variable Bias Analysis

Metric	Value
R2 of Y given W (observed confounders)	0.2386
Pseudo-R2 of T given W	0.1037
Residual variance of Y	0.7614
Residual variance of T	0.8963
Robustness value	**0.8261**
Interpretation	An unobserved confounder would need partial R2 of at least 0.826 with both Y and T (after controlling for observed confounders) to reduce the ATE to zero.

Note: The robustness value of 0.826 indicates that any unobserved confounder would need to explain more variance than the entire set of observed confounders combined — an implausibly strong requirement.

1.10 Appendix I: Figures

1.10.1 Figure S1: CATE Map of Brazil

Geospatial map of estimated Conditional Average Treatment Effects (CATEs) across 17 Brazilian state capitals. Dot colour represents CATE magnitude (blue = negative/low, red = high); dot size represents confidence interval width.

(See: outputs/figures/cate_map_brazil.pdf)

1.10.2 Figure S2: CATE Scatter by Capital

Scatter plot of mean CATE vs mean daily admissions for each capital, coloured by macro-region.

(See: outputs/figures/cate_scatter_capitals.pdf)

1.10.3 Figure S3: Forest Plot — ATE by Subgroup

Forest plot of Average Treatment Effects (CF and DML) for total, age-stratified, and sex-stratified outcomes. Diamond = point estimate; horizontal line = 95% confidence interval; vertical dashed line = null effect.

(See: outputs/figures/forest_ate_subgroups.pdf)

1.10.4 Figure S4: Forest Plot — CLAN Quartiles

Forest plot of Group Average Treatment Effects by CLAN quartile, showing the monotonic gradient from Q1 (lowest vulnerability) to Q4 (highest vulnerability).

(See: outputs/figures/forest_clan_quartiles.pdf)

1.10.5 Figure S5: SHAP Beeswarm Plot

Beeswarm plot of SHAP values for all effect modifiers. Each point represents one city-day observation; horizontal position indicates the SHAP value (positive = higher CATE); colour indicates the feature value (blue = low, red = high).

(See: outputs/figures/shap_beeswarm_admissions.pdf)

1.10.6 Figure S6: SHAP Dependence — DTR

SHAP dependence plot for diurnal temperature range (DTR), showing the non-linear relationship between DTR and its contribution to CATE heterogeneity.

(See: outputs/figures/shap_dependence_dtr_admissions.pdf)

1.10.7 Figure S7: SHAP Dependence — Population Density

SHAP dependence plot for population density, illustrating how densely populated cities show higher CATE contributions.

(See: outputs/figures/shap_dependence_pop_density_admissions.pdf)

1.10.8 Figure S8: SHAP Dependence — Fleet per Capita

SHAP dependence plot for fleet per capita (vehicles per 1,000 inhabitants).

(See: outputs/figures/shap_dependence_fleet_per_capita_admissions.pdf)

1.10.9 Figure S9: Policy — Prevented Admissions by City

Bar chart showing prevented respiratory hospitalisations under WHO compliance for each of the 17 capitals, sorted by magnitude.

(See: outputs/figures/policy_city_prevented.pdf)

1.10.10 Figure S10: Policy — Stratified by Vulnerability Quartile

Stacked bar chart showing the distribution of prevented admissions across CATE vulnerability quartiles under the WHO scenario.

(See: outputs/figures/policy_stratified_quartiles.pdf)

1.10.11 Figure S11: Policy — Threshold Response Curve

Dose-response curve showing prevented admissions as a function of the PM2.5 threshold (15, 25, 35, 50 ug/m3), demonstrating diminishing returns at higher thresholds.

(See: outputs/figures/policy_threshold_response.pdf)

1.10.12 Figure S12: Policy — Cost Summary

Bar chart of estimated cost savings (R$ millions) under WHO compliance, stratified by vulnerability group.

(See: outputs/figures/policy_cost_summary.pdf)

1.11 Code Availability

The complete analytical pipeline, including data extraction, processing, causal estimation, SHAP analysis, policy counterfactuals, sensitivity analyses, and visualization code, is available at:

https://github.com/Roverlucas/causal-pollution-health-brazil

The pipeline can be reproduced with a single command: `make all`

End of Supplementary Material