Supplementary Material

Evaluating the Effectiveness of COVID-19 Lockdown Measures through Air Pollution Trends in the Republic of Georgia (March-June 2019-2022): An Interrupted Time-Series Analysis

Supplementary Figure S1

Figure S1. Daily concentrations of NO_2, SO_2, $PM_{2.5}$, PM_{10}, and O_3 (μg/m³) at three monitoring stations in Georgia (Tbilisi, Batumi, Rustavi) during March-June 2019-2022, with 2020 COVID-19 intervention phases overlaid.



Description of Figure S1

Figure S1 presents smoothed daily concentration time-series (3-day moving average) for five air pollutants across all three monitoring cities over the study period. Each row corresponds to one pollutant; each column to one city. The four panels within each row share the same x-axis (day of season, 1 March to 30 June) but independent y-axes to accommodate the different concentration scales across cities. The 2019 pre-pandemic year (solid blue line) serves as the reference baseline against which subsequent years are compared. The 2020 lockdown year (solid red line, heavier weight) is the primary year of interest; the 2021 (dashed green) and 2022 (dotted purple) lines represent the post-lockdown recovery period. Shaded background regions denote the four successive COVID-19 intervention phases in Georgia: state of emergency (16-20 March), quarantine measures (21 March-5 April), nationwide curfew (6 April-10 May), and progressive easing of restrictions (11 May-15 June). The dashed red horizontal line indicates the applicable WHO Air Quality Guideline for each pollutant.

The figure serves a complementary role to Figures 3-7 (main text boxplots) and Supplementary Table S1: while the boxplots and table summarise the year-to-year distributional shifts with formal statistical measures, Figure S1 provides the temporal context within the March-June season, showing how concentrations evolved day-by-day and how changes aligned with specific policy events rather than the season as a whole. This context is particularly informative for NO_2 in Tbilisi, where the sharpest concentration decline corresponds to the onset of the nationwide curfew phase (6 April), and for O_3 in Rustavi, where the anomalously high 2019 values are visible throughout the entire season.

Panel-by-panel notes

Row 1 - NO_2. The Tbilisi panel shows the clearest lockdown signal in the dataset: concentrations tracked closely with the 2019 baseline until mid-March 2020, then fell steeply during the quarantine and curfew phases, reaching their lowest seasonal values in April–May 2020 and remaining low throughout. By contrast, the 2021 curve is flat and narrow throughout the season, confirming near-total suppression of traffic peaks. The 2022 curve overlies and in places exceeds the 2019 curve, confirming full rebound. Batumi shows a similar directional pattern but with shallower declines and greater within-season variability. Rustavi shows four near-identical overlapping curves across all years, confirming the absence of any traffic-related response.

Row 2 - SO_2. All three cities show the 2020 line tracking close to or below the 2019 line throughout the season, but with substantial day-to-day variability. The most notable feature is the Rustavi 2022 curve (dotted purple), which is elevated far above all other years from the beginning of March, consistent with the anomalous mean value reported in Table S1 above (38.1 ± 14.7 μg/m³). The Tbilisi 2022 curve also shows isolated high-concentration spikes not present in other years, visible as sharp upward excursions in the time-series.

Row 3 – $PM_{2.5}$. The Tbilisi panel illustrates why the mean reduction in 2020 was modest despite lockdown: while the baseline level is lower, several sharp upward spikes are visible in March-2020 (early lockdown period), likely corresponding to domestic heating events. The Batumi 2020 curve sits above the 2019 and 2021-2022 curves for much of April and May, consistent with the elevated 2020 mean (+19.7% vs. 2019) discussed in the main text. Rustavi shows high and variable concentrations in all four years with no year clearly lower than the others.

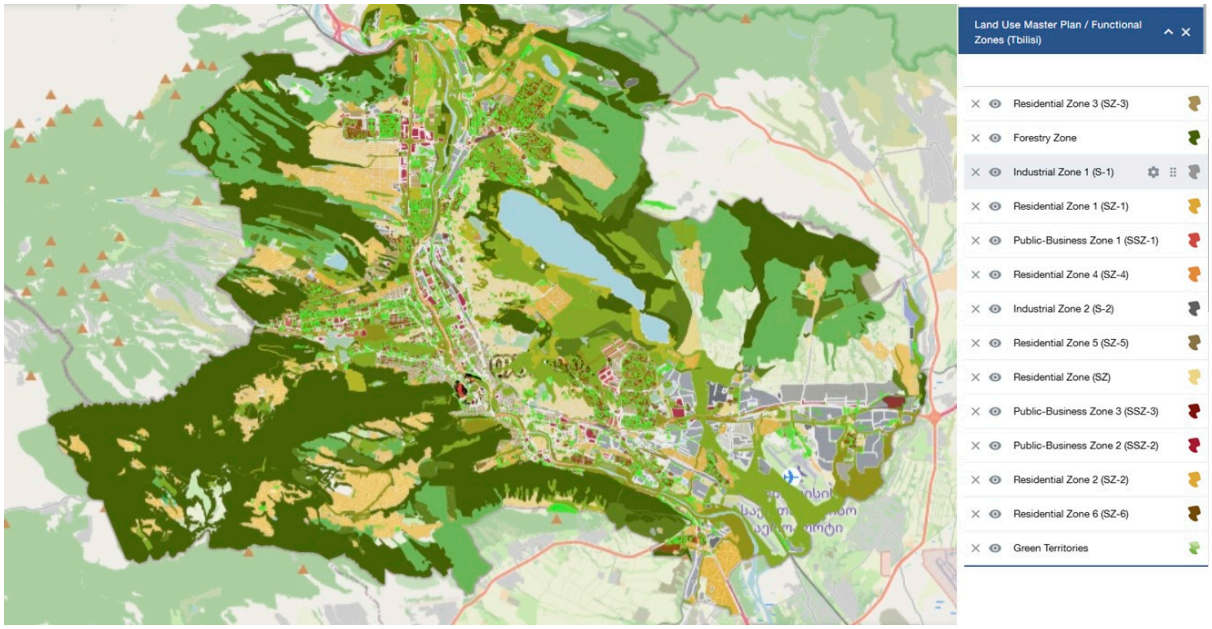
Row 4 - PM_{10}. The Rustavi panel is the most visually striking in this row: the 2020 and 2021 curves show multiple extreme spike events (single-day values exceeding 150 µg/m³ visible as sharp peaks) that do not appear in 2019 or 2022, suggesting episodic industrial dust events of unusual intensity during those years. The Tbilisi 2020 curve sits below the 2019 curve for most of April and May, consistent with reduced road dust resuspension during the curfew phase, before converging with 2019 levels in June as restrictions eased.

Row 5 - O_3. The Tbilisi panel clearly shows the 2020, 2021, and 2022 curves all running above the 2019 baseline for most of the season, consistent with the photochemical consequence of reduced NO_2 titration. The elevation is most pronounced in April–May, coinciding with the peak curfew period and maximum reduction in traffic. The Rustavi panel shows the opposite: the 2019 curve (solid blue) is distinctly higher than all subsequent years throughout the season, with the 2020 line (red) running approximately 30-40 µg/m³ below it from late March onwards. The Batumi 2019 curve is anomalously low relative to all other years, as discussed in the main text.

Methods note. All series displayed use post-imputation data. A 3-day centred moving average was applied to the daily values prior to plotting to reduce day-to-day noise while preserving weekly and monthly patterns. Batumi NO_2 2021 is displayed at n = 67 observed days without imputation; gaps in that series appear as discontinuities in the 2021 curve in the Batumi NO_2 panel.

Supplementary Figure S2

Figure S2. Map of Tbilisi with industrial, residential and recreational zones highlighted. Source - Municipal Services Development Agency of Georgia (https://ms.gov.ge/)



Supplementary Table S1

Table S1. Descriptive statistics (mean ± SD, median [IQR]) and Mann-Kendall (MK) trend test results (Kendall's τ, two-tailed p-value) for daily air pollutant concentrations at three monitoring stations in Georgia, March-June 2019-2022 (post-imputation). This table was relocated here from the main manuscript: the MK test, used in earlier drafts as the primary trend analysis, is now a secondary, descriptive measure only. The main text's primary inferential results are the meteorologically-adjusted interrupted time-series and across-year models reported in Table 1 of the main manuscript.

City	Pollutant	Year	Mean ± *SD* (μg/m³)	Median [IQR] (μg/m³)	*τ*	*p*
Tbilisi	NO_2	2019	51.52 ± 18.41	54.59 [39.03-62.16]	*−0.200*	0.300
		2020	26.84 ± 5.53	25.97 [23.07-30.14]		
		2021	20.01 ± 1.74	19.84 [18.77-21.19]		
		2022	56.66 ± 14.01	55.67 [46.90-64.86]		
	SO_2	2019	22.70 ± 8.68	21.62 [15.62-25.53]	*+0.150*	0.444
		2020	23.24 ± 6.40	21.34 [18.46-26.02]		
		2021	28.91 ± 11.10	24.55 [22.80-33.36]		
		2022	24.18 ± 28.20	20.62 [7.06-23.20]		
	$PM_{2.5}$	2019	17.18 ± 5.65	18.11 [12.90-20.14]	*−0.250*	0.192
		2020	15.67 ± 8.31	14.78 [11.56-17.31]		
		2021	15.45 ± 5.40	14.14 [11.84-18.64]		
		2022	14.59 ± 6.32	12.95 [10.29-17.15]		
	PM_{10}	2019	40.72 ± 15.87	39.14 [27.33-52.73]	*−0.083*	0.685
		2020	35.51 ± 17.40	33.63 [23.45-42.06]		
		2021	40.01 ± 12.83	37.42 [31.27-47.52]		
		2022	35.00 ± 11.58	34.50 [26.59-40.95]		
	O_3	2019	50.71 ± 15.52	52.67 [40.43-62.83]	*+0.300*	0.115
		2020	63.40 ± 14.99	63.75 [53.91-72.53]		
		2021	62.17 ± 13.11	62.25 [53.60-69.53]		
		2022	59.12 ± 17.59	57.63 [47.05-70.81]		
Batumi	NO_2	2019	45.89 ± 17.86	44.25 [28.04-59.84]	N/A[1]	N/A[1]
		2020	38.19 ± 15.11	36.53 [26.95-47.20]		
		2021	22.90[2] ± 8.03	21.64 [18.77-28.45]		
		2022	38.75 ± 8.24	39.59 [33.49-44.91]		
	SO_2	2019	1.65 ± 1.64	1.25 [0.00-3.44]	*−0.133*	0.499
		2020	0.92 ± 1.03	0.61 [0.46-0.91]		
		2021	0.78 ± 0.96	0.52 [0.27-0.84]		
		2022	0.91 ± 0.56	0.78 [0.57-1.07]		
	$PM_{2.5}$	2019	14.43 ± 9.16	11.15 [8.49-17.74]	*−0.300*	0.115
		2020	17.27 ± 9.55	15.40 [11.50-20.06]		
		2021	13.97 ± 6.85	12.41 [9.32-16.16]		
		2022	12.81 ± 5.90	11.16 [8.34-16.29]		

City	Pollutant	Year	Mean ± *SD* (μg/m³)	Median [IQR] (μg/m³)	*τ*	*p*
	PM_{10}	2019	28.13 ± 17.58	23.19 [16.92-32.21]	*−0.333*	0.079
		2020	34.73 ± 21.79	28.43 [22.75-39.83]		
		2021	27.70 ± 13.75	24.48 [19.31-30.42]		
		2022	23.55 ± 13.40	19.66 [13.91-29.95]		
	O_3	2019	14.46 ± 14.17	7.21 [4.47-28.88]	*−0.050*	0.822
		2020	37.89 ± 16.47	36.06 [24.20-50.84]		
		2021	27.87 ± 8.07	26.73 [22.11-31.84]		
		2022	23.73 ± 6.24	23.16 [18.77-27.75]		
Rustavi	NO_2	2019	18.78 ± 6.23	18.43 [13.50-22.57]	*−0.050*	0.822
		2020	18.89 ± 9.08	16.90 [12.35-22.41]		
		2021	17.23 ± 5.30	17.23 [13.19-20.71]		
		2022	19.55 ± 7.82	18.55 [13.47-23.70]		
	SO_2	2019	3.25 ± 4.68	2.12 [1.31-4.20]	*+0.167*	0.392
		2020	2.18 ± 5.85	0.97 [0.49-1.54]		
		2021	1.68 ± 0.97	1.48 [1.02-2.08]		
		2022	38.07[3] ± 14.72	38.04 [28.68-52.21]		
	$PM_{2.5}$	2019	19.63 ± 12.18	17.50 [9.61-26.31]	*+0.050*	0.822
		2020	21.22 ± 15.50	19.11 [14.40-24.02]		
		2021	22.93 ± 14.47	19.55 [11.28-30.32]		
		2022	22.60 ± 14.62	18.70 [11.87-31.33]		
	PM_{10}	2019	38.92 ± 23.31	34.06 [19.56-57.55]	*+0.117*	0.558
		2020	42.91 ± 35.10	39.92 [21.76-48.74]		
		2021	51.60 ± 31.01	42.67 [30.00-65.52]		
		2022	47.89 ± 30.72	40.69 [23.76-67.83]		
	O_3	2019	83.30 ± 18.71	83.50 [71.41-96.25]	*+0.167*	0.392
		2020	47.32 ± 10.10	46.86 [41.17-53.22]		
		2021	67.65 ± 13.14	68.34 [60.41-77.00]		
		2022	71.33 ± 22.83	81.06 [61.09-87.13]		

[1] Batumi NO_2 2021: 45.1% of daily values missing; excluded from Mann-Kendall analysis (n = 67 observed days retained for descriptive statistics only).

[2] Batumi NO_2 2021 mean based on n = 67 observed days; remaining 55 days not imputed.

[3] Rustavi SO_2 2022 anomalously elevated (38.07 ± 14.72 μg/m³ vs. 1.68-3.25 in 2019-2021); data quality verification recommended.

IQR, interquartile range (Q1-Q3); τ, Kendall's rank correlation coefficient; MK, Mann-Kendall test applied to 16 monthly means (March-June × 4 years); all p-values two-tailed; $\alpha = 0.05$. No MK trend reached statistical significance. Values in μg/m³ for all pollutants

Mann-Kendall Trend Test: Methodology and Discussion

Methodology. The non-parametric Mann-Kendall (MK) test was applied to assess the statistical significance of monotonic concentration trends across the four-year study period. The MK test is distribution-free, robust to non-normally distributed environmental data, and is the recommended method for trend detection in air quality and hydrometeorological time series. The test statistic S is computed as the algebraic sum of the signs of all pairwise

differences between ordered observations; the variance-corrected standardised statistic Z is used to obtain a two-tailed p-value. Kendall's rank correlation coefficient τ is reported as an effect-size index, where $\tau > 0$ indicates an increasing trend and $\tau < 0$ a decreasing trend over the study period. Trends were considered statistically significant at $\alpha = 0.05$. The MK test was applied to the series of 16 monthly mean concentrations per station-pollutant pair (four months × four years, ordered chronologically: March 2019 through June 2022), giving $n = 16$ per test. Monthly means were used as the unit of analysis rather than daily values to reduce within-season autocorrelation, which inflates the effective sample size and yields spuriously low p-values when raw daily observations are tested directly. Kendall's τ and the two-tailed p-value are reported for each station-pollutant pair in Table S1 above. Batumi NO_2 2021 was excluded from the MK test due to 45.1% missingness. All statistical analyses were implemented in Python using scipy.stats.

Relationship to the main manuscript's primary analysis. The Mann-Kendall results reported here are unadjusted for meteorology and are retained only as a descriptive summary. The meteorologically-adjusted interrupted time-series and across-year models are the basis for the inferential claims made in the paper. Even with meteorological adjustment, observed changes should be interpreted as associations rather than definitive causal attributions, since residual confounding (e.g., unmeasured boundary-layer dynamics, regional transport, or other concurrent economic changes) cannot be fully excluded in this observational design; precipitation and boundary-layer height in particular could not be incorporated due to data availability constraints, a limitation discussed further in Section 4 of the main manuscript.

Discussion. The absence of statistically significant monotonic trends (all $p > 0.05$; Table S1) is the expected outcome given the V-shaped inter-annual trajectories induced by the lockdown-rebound pattern: a test designed to detect unidirectional change cannot capture a temporary dip followed by recovery. The τ values closest to significance – Batumi PM_{10} ($\tau = -0.333$, $p = 0.079$) and Tbilisi O_3 ($\tau = +0.300$, $p = 0.115$) – reflect sustained directional shifts that extend beyond the lockdown year itself, suggesting incipient long-term trends that a longer data series would be needed to confirm.

Supplementary Table S2

Table S2. Sensitivity comparison of meteorologically-adjusted interrupted time-series (Model A) and across-year (Model B) estimates using imputed versus raw (complete-case) data, for all 15 city-pollutant pairs. Estimates are identical between raw and imputed data for every pair.

Note on relationship to Table 1 of the main manuscript: the "Estimate (imputed)" and "p (imputed)" columns below reproduce the same values reported in Table 1 of the main text; they are repeated here only so they can be compared directly against the "Estimate (raw)" and "p (raw)" columns. This table does not report a new finding; it is a robustness check confirming that the imputation procedure does not materially alter the results presented in Table 1.

City	Pollutant	Model	n (imputed)	n (raw)	Estimate (imputed)	p (imputed)	Estimate (raw)	p (raw)
Batumi	NO2	A (within-2020 step-change)	122	122	-20.117	0.004	-20.117	0.004
Batumi	NO2	B (across-year effect)	366	366	-4.175	0.214	-4.175	0.214

Rustavi	NO2	A (within-2020 step-change)	122	122	-14.569	0.000	-14.569	0.000
Rustavi	NO2	B (across-year effect)	488	488	0.617	0.578	0.617	0.578
Tbilisi	NO2	A (within-2020 step-change)	122	122	-8.784	0.001	-8.784	0.001
Tbilisi	NO2	B (across-year effect)	488	488	-14.444	0.000	-14.444	0.000
Batumi	O3	A (within-2020 step-change)	122	122	18.063	0.004	18.063	0.004
Batumi	O3	B (across-year effect)	488	488	16.093	0.000	16.093	0.000
Rustavi	O3	A (within-2020 step-change)	122	122	6.197	0.046	6.197	0.046
Rustavi	O3	B (across-year effect)	488	488	-27.845	0.000	-27.845	0.000
Tbilisi	O3	A (within-2020 step-change)	122	122	13.831	0.049	13.831	0.049
Tbilisi	O3	B (across-year effect)	488	488	4.881	0.056	4.881	0.056
Batumi	PM10	A (within-2020 step-change)	122	122	-9.918	0.290	-9.918	0.290
Batumi	PM10	B (across-year effect)	488	488	7.606	0.001	7.606	0.001
Rustavi	PM10	A (within-2020 step-change)	122	122	-40.329	0.089	-40.329	0.089
Rustavi	PM10	B (across-year effect)	488	488	-6.543	0.148	-6.543	0.148
Tbilisi	PM10	A (within-2020 step-change)	122	122	-19.009	0.103	-19.009	0.103
Tbilisi	PM10	B (across-year effect)	488	488	-5.250	0.042	-5.250	0.042
Batumi	PM2.5	A (within-2020 step-change)	122	122	-1.385	0.716	-1.385	0.716
Batumi	PM2.5	B (across-year effect)	488	488	3.278	0.001	3.278	0.001
Rustavi	PM2.5	A (within-2020 step-change)	122	122	-16.229	0.068	-16.229	0.068
Rustavi	PM2.5	B (across-year effect)	488	488	-1.131	0.536	-1.131	0.536
Tbilisi	PM2.5	A (within-2020 step-change)	122	122	-9.758	0.050	-9.758	0.050
Tbilisi	PM2.5	B (across-year effect)	488	488	-0.743	0.499	-0.743	0.499
Batumi	SO2	A (within-2020 step-change)	122	122	-0.862	0.041	-0.862	0.041
Batumi	SO2	B (across-year effect)	488	488	-0.231	0.127	-0.231	0.127
Rustavi	SO2	A (within-2020 step-change)	122	122	-4.567	0.027	-4.567	0.027
Rustavi	SO2	B (across-year effect)	488	488	-12.778	0.000	-12.778	0.000
Tbilisi	SO2	A (within-2020 step-change)	122	122	-5.270	0.001	-5.270	0.001
Tbilisi	SO2	B (across-year effect)	488	488	-2.001	0.243	-2.001	0.243