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POVERTY AND DISTRIBUTIONAL CONSEQUENCES OF AIR POLLUTION IN TBILISI

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Executive summary

Air pollution has profound impacts on welfare, causing more deaths globally than malnutrition, AIDS, tuberculosis, and malaria combined. Poorer households are often more vulnerable due to residential sorting, limited access to healthcare, and financial constraints. This report comprehensively assesses the negative effects of air pollution in Tbilisi, including from a distributional point of view.

In the Georgian capital, air pollution levels exceed international standards –the average monthly PM2.5 concentration in Tbilisi is 20 µg/m3, which is four times higher than the WHO's annual recommended limit—and surpass other cities in the region. Thus, it is critical to identify and quantify exposure to air pollution in Tbilisi and its impacts on well-being through different channels, such as health and economics outcomes. This analysis leverages multiple data sources – administrative data, surveys, satellite imagery, first-hand real-time data from outdoor, indoor, and portable monitors collected for this study, as well as government monitors – to assess how air pollution affects people in Tbilisi and suggest policy actions that can prevent and mitigate adverse effects, especially for the poor.

First, the analysis shows that air pollution adversely impacts health –especially respiratory and mental health–, labor productivity, and economic outcomes in Tbilisi. A 1 µg/m3 increase in PM2.5 concentration leads to a 2.2% increase in hospitalizations for respiratory diseases and a 4.4% increase in hospitalizations for mental health issues. Increased air pollution also affects labor productivity and work patterns, and preliminary results point to a negative impact on cognition. Air pollution also negatively affects real estate values, a 1µg/m3 increase in PM2.5 is associated with up to a 1% decrease in rent in Tbilisi. Tackling air pollution is likely to yield high benefits in terms of health and economic outcomes.

Second, the concentration of outdoor air pollution is highest in the city center, where wealthier individuals reside, and elevation is lower. Although weather patterns, including thermal inversions and wind, influence air pollution concentrations, anthropogenic emissions from traffic congestion and industrial emissions significantly drive outdoor air pollution levels, both near their source and downwind from it. Regulating these sectors further by strengthening air quality monitoring, mitigating traffic-related pollution, and enhancing control of industrial emissions is essential to reduce outdoor air pollution.

Third, at the individual level, indoor air pollution levels are higher than outdoor ones. Cooking, smoking, and building insulation are significant drivers of indoor pollution. Hence, the taxation of tobacco and polluting cooking fuels could be effective policy tools. Despite the high exposure to indoor air pollution, adaptation is low, and only 8.6% of households own an air purifier. Identifying and addressing barriers to adoption could be an effective way to reduce household's vulnerability.

Fourth, poorer and less-educated households are more exposed to air pollution and have a lower adaptive capacity. At the individual level, wealthy and educated households are exposed to lower pollution levels both inside and outside their dwellings. Within polluted areas, wealthier households live in dwellings where outdoor pollution is lower. Wealthier households also spend less time working outdoors. Moreover, more educated households have a higher adaptive capacity. They have better knowledge of air pollution's impacts and are more likely to take mitigation actions and own protective devices, such as air purifiers. Hence, policies should prioritize supporting less educated and poorer households who work outdoors in more polluted areas and have fewer adaptive solutions.

In the short term, providing information, access to monitoring devices, and protective measures could mitigate air pollution's impacts. In the medium term, decreasing emissions from transportation and regulating industrial emissions should be considered a priority. The findings emphasize the importance of considering the socioeconomic impact when designing policies and suggest that implementing the recommended policies could significantly improve air quality, public health, and sustainable development in Tbilisi. The proposed measures also align with international standards and agreements and support Georgia's engagement in green investments.

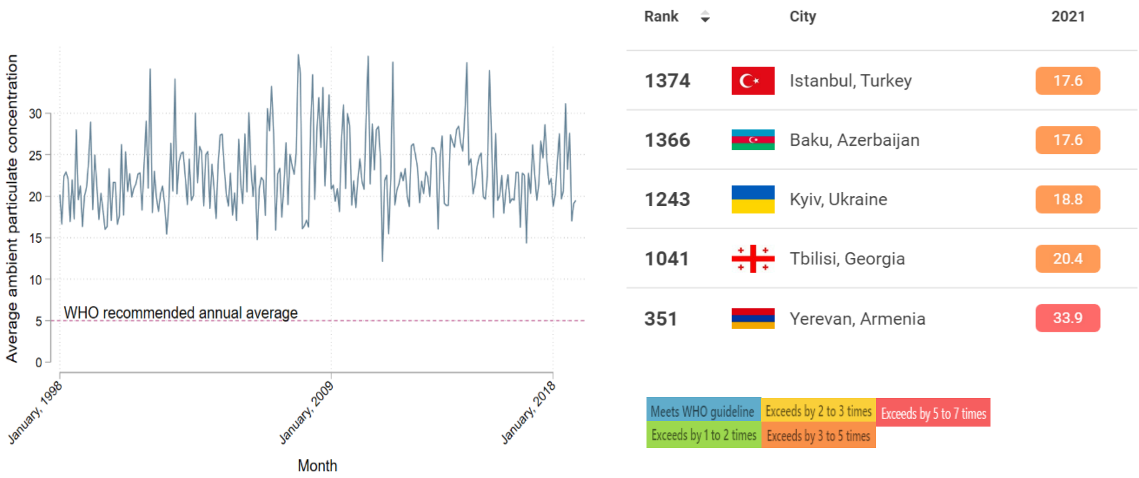
Contents

Introduction

Air pollution levels in Georgia's capital, Tbilisi, are higher than international standards and other capitals in the region. The average monthly PM2.5 concentration is higher than 20 µg/m3, four times the annual average recommended by WHO. Between 2017 and 2021, air pollution levels in Tbilisi were worse than in Istanbul (Turkey), Baku (Azerbaijan), and Kyiv (Ukraine). Tbilisi's inhabitants are aware of the issue and rank it high on the list of priorities for their cities. In a 2017 survey, 42% of Tbilisi inhabitants reported air pollution as the most important infrastructural issue (CRRC, 2018). More recently, 11% of interviewees in Tbilisi considered air pollution as one of the capital's most important issues (CRRC, 2021).

Figure 1

Monthly air pollution level in Tbilisi is above the WHO threshold and higher than in other regional capitals.



A. Timeseries over 1998 – 2018

B. Ranking of cities based on their air pollution

Rank	City	2021
1374	Istanbul, Turkey	17.6
1366	Baku, Azerbaijan	17.6
1243	Kyiv, Ukraine	18.8
1041	Tbilisi, Georgia	20.4
351	Yerevan, Armenia	33.9

Sources: Panel A: Authors' calculation. PM2.5 concentration is expressed in µg/m3. It presents the average of re-analysis data from Van Donkelaar et al. (2019) across the urban area of Tbilisi. The line in orange represented the WHO recommended threshold. Panel B: IQ Air's ranking of most polluted cities in the world based on the comparison of annual average PM2.5 concentration 2017-2021.

Air pollution significantly impacts various dimensions of welfare, from mortality to morbidity to productivity and real estate values. Globally, air pollution causes 6.7 million deaths per year, a higher death toll than malnutrition AIDS, tuberculosis, and malaria (Fuller *et al.*, 2022). Significant adverse impacts on mortality have been documented in India (Greenstone and Hanna, 2014) , China (Ebenstein *et al.*, 2017), Indonesia (Jayachandran, 2008), and in the US (Deryugina *et al.*, 2016). Welfare is further impacted by air pollution due factors including decreased productivity (Chang *et al.*, 2016), reduced cognitive ability (Lavy, Ebenstein and Roth, 2014), worsened mental health (Chen *et al.*, 2018), and lower housing values (Davis, 2011; Currie *et al.*, 2015). Although air pollution impacts have been studied in other countries, to our knowledge, the estimates presented in this report are the first to evaluate the adverse effects on health, real estate values, cognitive performance, and productivity in Tbilisi.

The burden from air pollution is unequally distributed. Inequalities are present at all spatial scales. Across countries, low- and middle-income countries suffer more from air pollution issues than high-income countries (Zhang and Day, 2015). Within countries, the correlation between the spatial distribution of pollution and poverty is more complex. Analyzing the correlation between exposure to ambient NO2 concentration and income in the US, (Hsiang, Oliva and Walker, 2017) show that at the metropolitan area level, the richest areas (cities) are more polluted. However, they find that, within metropolitan areas, the poor are more exposed. They may live in more polluted neighborhoods or spend more time outdoors or in less-insulated buildings. Even if they are exposed similarly to air pollution, poor households are likely to suffer more than wealthier households. This higher vulnerability stems from several factors, including lower access to healthcare, credit constraints preventing defense investments such as air purifiers, and limited access to information.

This report assesses the distributional impact of air pollution in terms of exposure and vulnerability to inform whether policies tackling air pollution in Tbilisi, the capital of Georgia, can benefit the poorest households, be progressive, and under which conditions. The resulting evidence could support the engagement of Georgia's Government in committing to green investments in line with the EU's Green Deal. Internally, this project also contributes to Objective 3.3 of the current World Bank Georgia CPF: "Enhance management of natural resources and climate risk."

The remainder of this report is organized as follows. The first section presents and compares the various sources of air pollution data in Tbilisi. They include official monitoring stations, satellite imagery, and the data collected by 50 outdoor air pollution monitors for this project. The second section assesses whether poor people are more exposed to air-borne pollutants by overlaying poverty maps with spatially disaggregated air pollution measures. Section 3 investigates potential sources of variation in air pollution in Tbilisi, including wind patterns, traffic, and industrial emissions. The fourth section leverages natural experiments to provide the first causal estimates of air pollution impacts on health and economic outcomes for Tbilisi. Sections 5 to 7 leverage the project's surveys and air pollution data collected from indoor, outdoor, and portable monitors to inform air pollution factors and consequences at the individual level. The fifth section investigates household-level drivers of indoor and outdoor air pollution level and their difference across income and education levels. Section 6 uses household-level survey and air pollution data collected during the project to deepen the analysis of the distributional consequences of air pollution exposure on health, economic outcomes, and cognitive performance. The last section explores adaptation capacity by evaluating the differences in behaviors and information regarding air pollution across income and education levels. The report concludes with a summary of policy recommendations and a description of future work.

1 Measuring air pollution in Tbilisi

Throughout this report, we measure air pollution by the concentration of ground-level fine particulate matter (PM2.5) and leverage three different data sources:

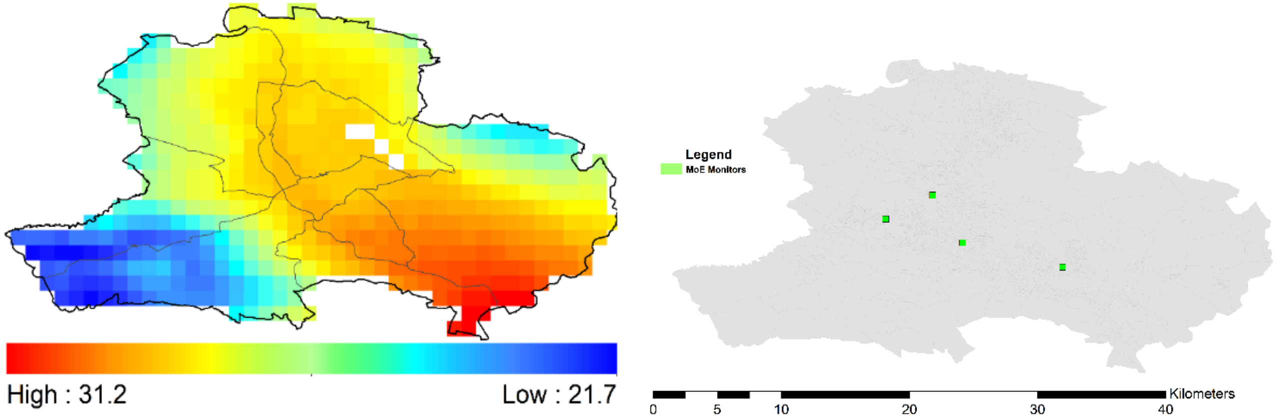
1. Tbilisi's official air pollution monitors (Ministry of Environment Protection and Agriculture of Georgia, 2018). Four high-quality monitors have reported daily concentrations of PM2.5 from August 2016. Their location is presented in Figure 2B.
2. Reanalysis data combining station data, satellite measurements, and a chemical transport model (van Donkelaar *et al.*, 2021).

   This dataset provides modeled estimates of monthly PM2.5 pollution from 1998 to 2020 on a 0.01x0.01 decimal degree grid. It has been used widely in the literature due to its global spatial coverage and long time series. We favor it in the section leveraging natural experiments to maximize the temporal and geographic range of the panel data we construct.
3. Data collected by outdoor, indoor, and individual monitors for this project.

   This project has dramatically increased the number of air pollution monitors in Tbilisi by installing 40 outdoor monitors throughout the city. They are represented by the circles without borders in Figure 2C. Monitors were installed in public schools or households in randomized districts selected with stratified randomization on income and elevation. Each monitor collects data on air pollution every minute, giving a real-time measure of air pollution in Tbilisi. To complement these outdoor measures, the project also distributed indoor air monitors to 145 randomly selected households for the Randomized Control Trial described in Annex A.2. Forty-three enumerators further measured air pollution throughout the city with individual monitors while conducting the surveys.

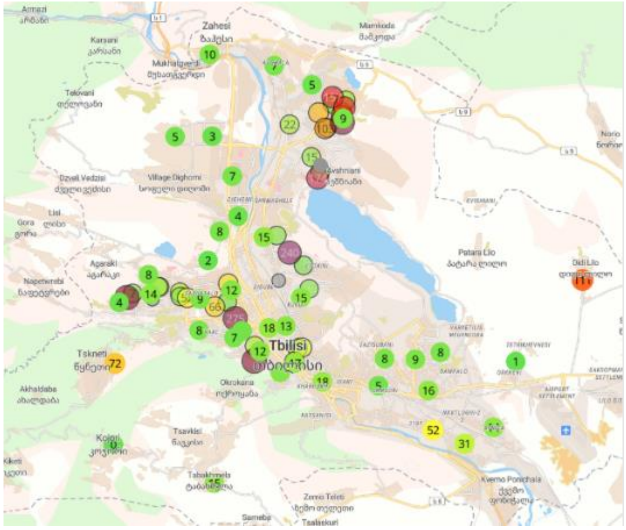
Figure 2

Data sources provide a fine measure of PM2.5 concentration in the capital.



A. Satellite imagery reanalysis (monthly, 1998-2020)

B. The Ministry of Environmental Protection and Agriculture of Georgia's monitors (daily, 2016-2022)



C. Project’s outdoor and indoor monitors
(Every minute, March-May 2023)

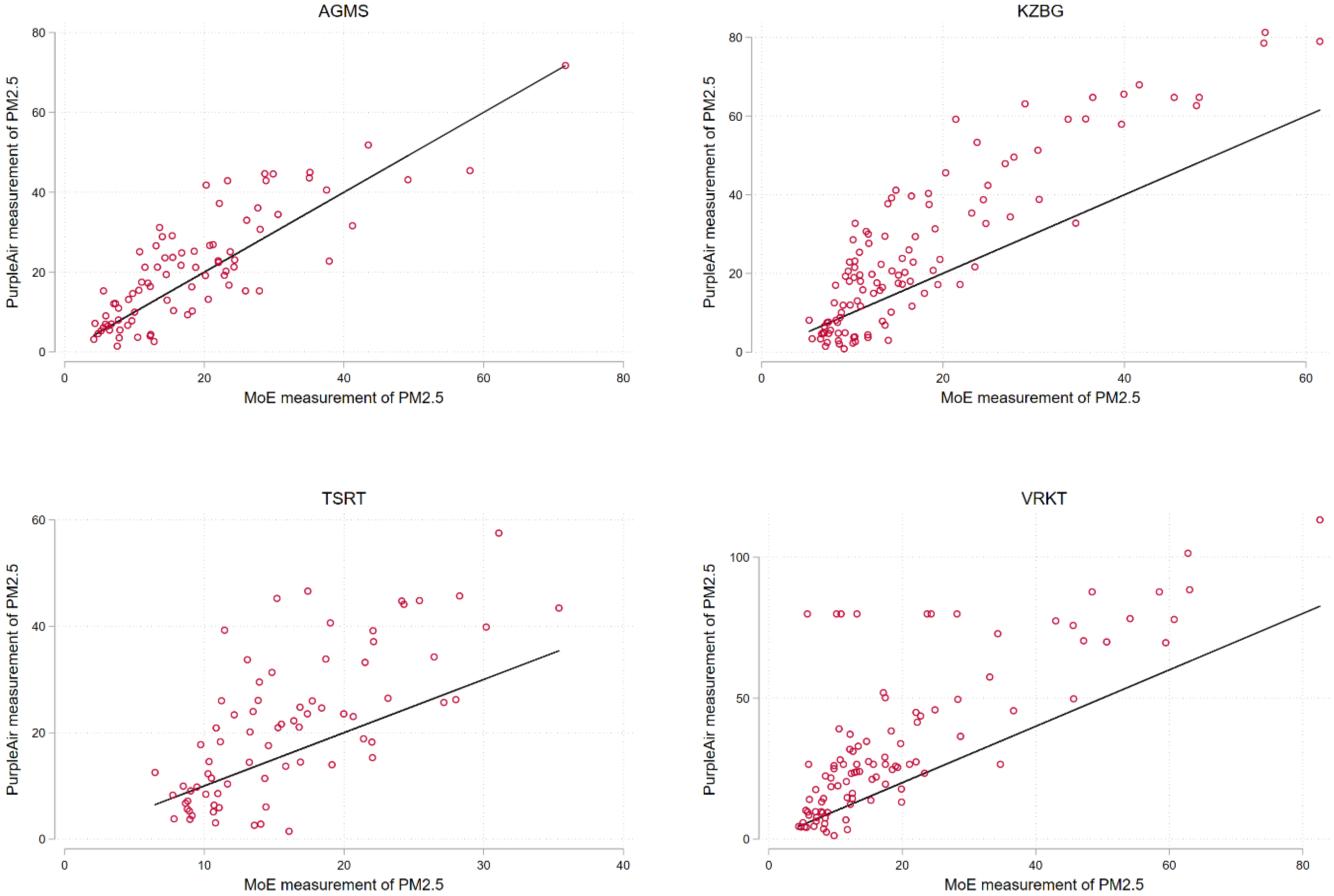
Notes and sources: Panel A: (van Donkelaar *et al.*, 2021). Global estimate for November 2013. Panel B: Location provided on the official government website air.gov.ge monitors (Ministry of Environment Protection and Agriculture of Georgia, 2018). Panel C: Snapshot of real time PurpleAir measures taken on March 27, 2023. Circles with a black border are indoor air pollution monitors and circles without border are outdoor monitors.

This report leverages each data source and weighs its advantages and disadvantages. Although government data relies on a few monitoring stations, they are very sophisticated and precise. We use them to calibrate and validate the project’s collected data. These monitors can also distinguish pollutants, which is necessary to deepen the understanding of mechanisms from source to effect. In what follows, we have explored the impact of specific pollutant concentrations whenever outcome data was collected near these monitors. The reanalysis from satellite imagery provides global monthly estimates of PM2.5 concentration. The main advantage of this dataset is its long timespan and expansive geographic cover, allowing us to build balanced panel data to leverage natural experiments. However, the reanalysis is not calibrated to Tbilisi and is often less accurate than ground-based monitors. Finally, the data collected during this project relies on PurpleAir monitors. Although they do not distinguish specific pollutants, these monitors have a good value for money and a very high time frequency as data is collected every minute. Their accuracy is sufficient for research studies (Krebs *et al.*, 2021; Liang *et al.*, 2021; Burke *et al.*, 2022), and their relatively accessible price allowed the project to significantly increase the spatial coverage of air pollution monitoring in Tbilisi. We use this data to complement the other two sources and infer individual daily and weekly exposure of the surveyed households.

The measures of PM2.5 concentration from the PurpleAir monitors are highly correlated with those provided by the monitors of the Ministry of Environmental Protection and Agriculture of Georgia (MEPA). Figure 3 presents the correlation of the readings of a monitor station operated by MEPA with the daily readings of its nearest PurpleAir monitor. Each graph corresponds to a different MEPA’s monitor, named AGMS, KZBG, TSRT, and VRKT. The correlation between MEPA’s data and the PurpleAir one is between 0.71 and 0.9. As shown in Figure 3, the PurpleAir monitors slightly overestimate pollution levels relative to MEPA’s monitors, particularly at high levels of pollution. The discrepancy is relatively small and may be due to the spatial mismatch between the exact location of the monitors. Indeed, the Ministry’s monitor with the closest corresponding PurpleAir monitor (AGMS) has the smallest amount of bias. This alignment between the measures of the high-quality Ministry’s monitors and the PurpleAir ones confirms that they are a reliable data source.

Figure 3

The measures from the Ministry of Environmental Protection and Agriculture of Georgia's monitors and the PurpleAir ones are highly correlated.

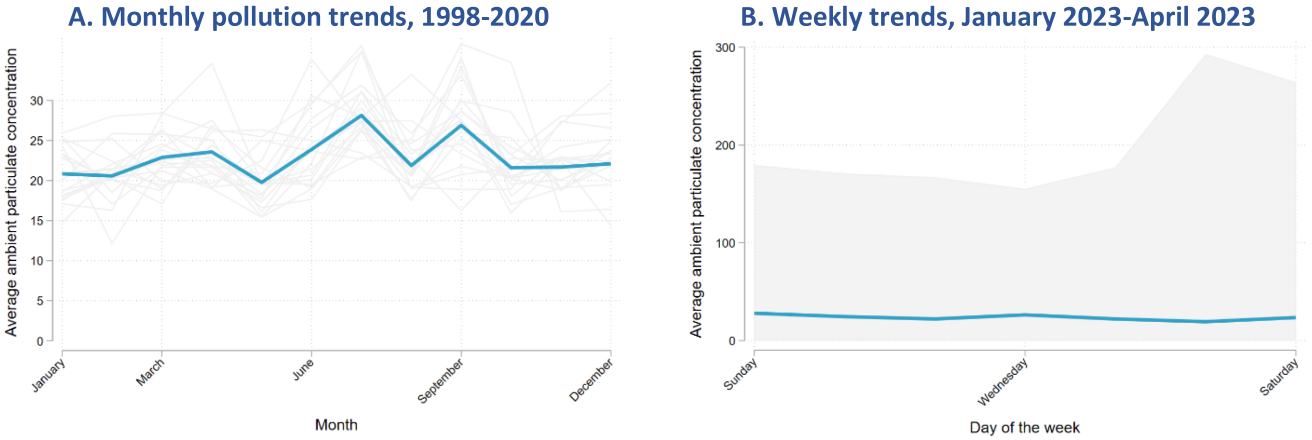


Notes and sources: Each panel represents the data from one of the four monitors operated by the Ministry of the Environment in Tbilisi with the name of the monitor at the top of each panel. The data is measured PM2.5 on a daily basis from January 1, 2023 to April 30, 2023. For each monitor operated by the Ministry of the Environment, we average of the nearest PurpleAir monitor's readings to the daily level over the same time period.

Pollution levels are relatively stable throughout the year and within a week. Using satellite data, we can examine the trends by month over the period 1998-2020. Pollution is slightly elevated in the late summer and early fall relative to the rest of the year (Figure 4A). However, seasonal variation is limited, and the full range of seasonal variation only amounts to approximately 40% of the mean. Weather patterns could explain part of the slight summer increase. Wind speed, which disperses pollutants, is lower between July and November than the rest of the year, and precipitation, which reduces pollution by diluting or settling pollutants to the ground, decreases in June-July. This pattern also suggests a limited role for residential heating in the winter compared to other emission sources. Using data from the installed PurpleAir monitors, we can examine how pollution levels vary over the days of the week from January 2023 to April 2023 (Figure 4B). Average daily pollution is relatively stable, around 25 µg/m3, with no notable spikes on the weekends. However, the maximum and minimum daily values, represented in grey in Figure 4B, show that the variance of air pollution is higher on weekends, with air pollution levels reaching nearly 300 µg/m3 on Fridays and Saturdays in some locations.

Figure 4

Monthly and weekly trends of outdoor air pollution in Tbilisi


A. Monthly pollution trends, 1998-2020

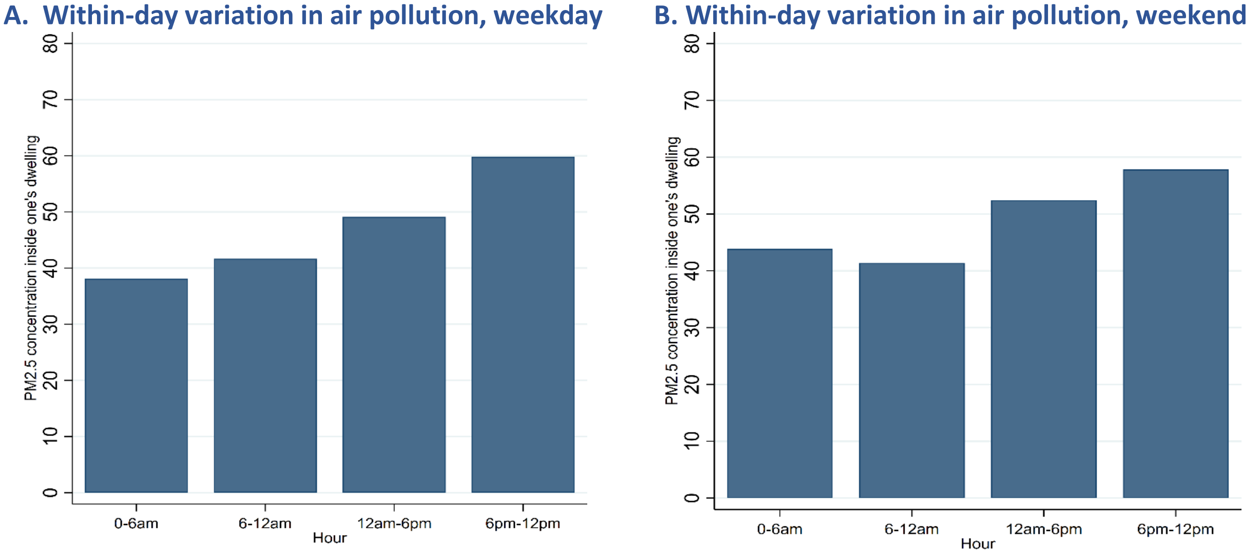
B. Weekly trends, January 2023-April 2023

Notes and sources: Panel A: (van Donkelaar *et al.*, 2021). Monthly average pollution over the full sample in blue. Grey lines indicate pollution in the months of each year from 2000-2020. Panel B: Shows the daily average from January 2023-April 2023 from the PurpleAir monitors. The grey area indicates the maximum and minimum of the daily average across all monitors in the city over that time period.

On average, indoor air pollution levels are higher than outdoor pollution levels and only 8.6% of households own an air purifier. The average indoor PM2.5 concentration measured during the survey is 33 μg/m3 higher than the average measured outdoor PM2.5 concentration. In addition to data collected by enumerators during the survey, this project installed 145 indoor air monitors in randomly selected households. This data shows indoor air pollution is higher on weekends than on weekdays, 53.7 vs. 50.6 μg/m3 (Figure 5). Although pollution levels are relatively similar in the morning (6-12am), weekend pollution is higher in the afternoon (12-6pm) and at night. This result suggests that some household activities performed in the evening and on weekends could cause an increase in indoor air pollution levels. Survey results also show that adaptive capacity is low in Tbilisi, where only 8.6% of households owning an air purifier compared to 25% in the US (*The Washington Post*, 2020). We explore further potential sources of indoor air pollution and barriers to adaptation in Section 5.

Figure 5

Within-day trend of indoor air pollution for weekdays and weekends in Tbilisi


A. Within-day variation in air pollution, weekday

B. Within-day variation in air pollution, weekend

Notes and sources: PurpleAir indoor monitors installed in randomly selected households during the first survey.

2 Spatial distribution of air pollution and wealth in Tbilisi

Pollution is concentrated in the city's center, which is also the lowest elevation part, and where the wealthiest individuals live. Figure 6A shows that pollution is higher in the center, likely due to elevation, weather patterns, and the geography of urban development. Indeed, the center has a lower altitude than the suburb, trapping air pollution between the surrounding high hills (Figure 6B). Coincidentally, wealthier households also disproportionately live in the center due to residential sorting (Figure 6C). As a result, pollution is strongly correlated with wealth, negatively correlated with elevation, and negatively correlated with distance from the city's center. The correlation with wealth disappears once elevation and distance from the center are included as control variables (Figure 6D). This suggests that these two factors may drive the relationship between wealth and pollution at the district level.

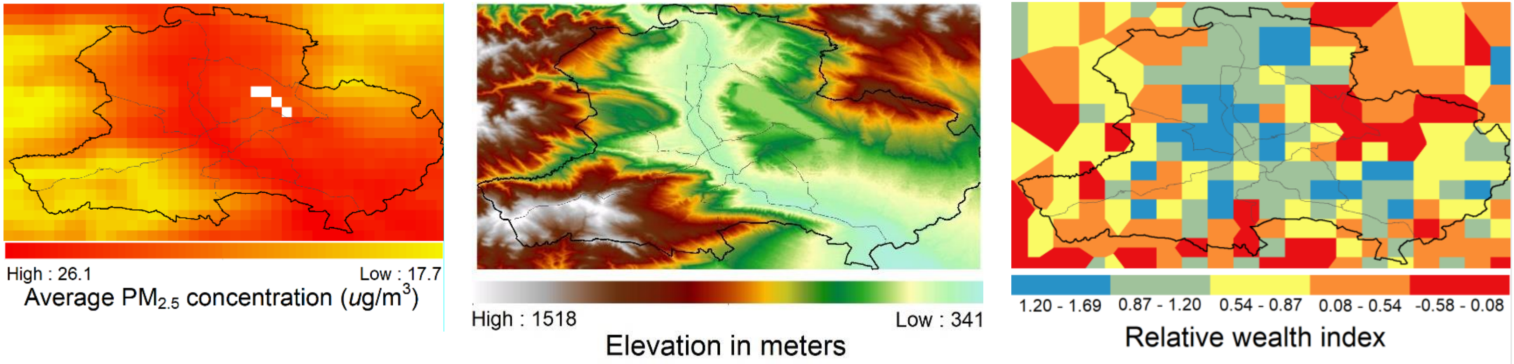
Figure 6

In Tbilisi, PM2.5 concentration is negatively correlated with elevation and positively correlated with wealth.

A. Pollution is concentrated in the city center
(Red=more polluted)

B. Elevation is higher in the suburb
(Brown=Higher)

C. Wealthier people tend to live in the center
(Blue=wealthier)



D. Positive correlation between PM2.5 concentration and relative wealth index

	(1)	(2)	(3)	(4)
Relative wealth	1.334***			0.033
	(0.039)			(0.039)
Elevation		-0.008***		-0.008***
		(0.000)		(0.000)
Distance from CBD			-7.160***	-1.568***
			(0.288)	(0.281)
N	57,204	57,204	57,204	57,204

Notes and sources: Panel A: Authors' calculation. Panel A plots the elevation of the city. Data comes from NASA's ASTER platform and elevation is measured in meters. Panel B shows the average level of pollution across Tbilisi averaged over the full sample period from 1998 to 2018. White indicates cells for which there is no estimate and pollution is measured in µg/m^3. Panel C plots the grid-cell level estimates of wealth called relative wealth index (Chi et al., 2022). Bluer shades indicate larger positive index values. Larger positive index values indicate relatively wealthier areas. The index is unit-less. Panel D shows results from regressions in which the Dependent variable is the average monthly PM$_{2.5}$ concentration in the grid-cell for which the relative wealth index is observed. All regressions include month and year FE. (* p<.10 ** p<.05 *** p.01). CBD stands for Central Business District and N is the number of observations.

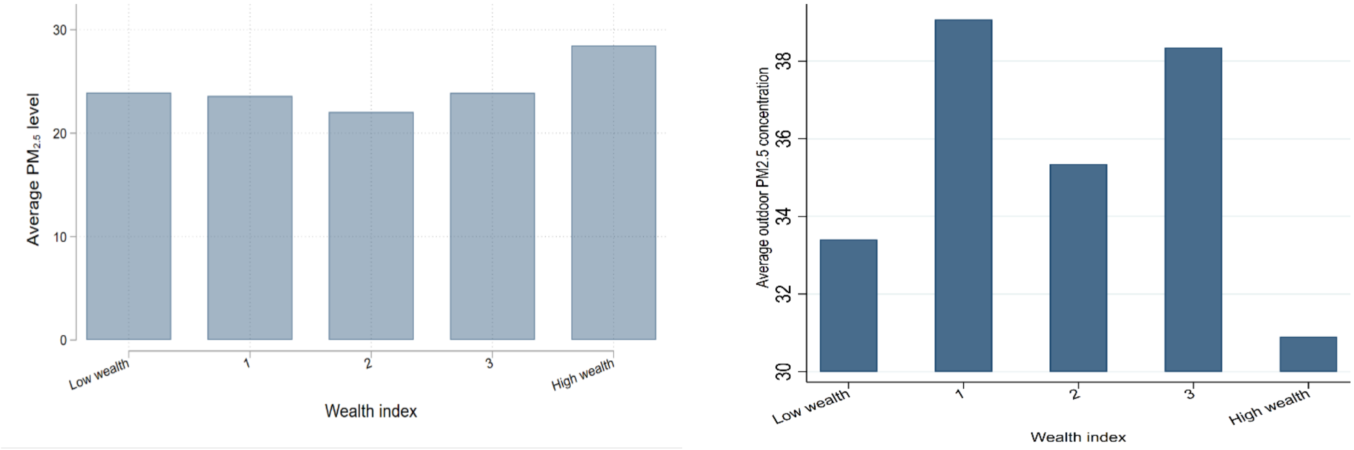
The positive correlation between outdoor air pollution and wealth holds at the neighborhood level, but at the individual level, the wealthiest households live in buildings less exposed to outdoor air pollution. This project involves the survey of 880 households and the measurement of outdoor air pollution levels with 40 outdoor air pollution monitors throughout the city. Combining the survey results with the average outdoor air pollution level measured by the project's nearest PurpleAir monitor shows that the above results hold at the neighborhood level. Outdoor air pollution levels are highest in neighborhoods where the wealthiest households live (Figure 7A), likely in the center of the city. However, this relationship changes when considering measures of outdoor air pollution by enumerators using a portable monitor outside of the dwelling after the survey. Despite living in the most polluted neighborhoods, outdoor pollution outside the dwelling of the wealthiest 8% is lower than for other income groups (Figure 7B). This result suggests that two competing drivers of urban sorting are at play. Wealthier households live in more central and polluted neighborhoods. However, within polluted neighborhoods, wealthy households likely select dwellings with lower outdoor air pollution. This selection may be based on proxies of air pollution, such as living close to parks or avoiding dwellings on high traffic roads. This sorting mechanism is consistent with our result on real estate values dropping with air pollution, showing that clean air is a valued amenity. This result is consistent with (Hsiang, Oliva and Walker, 2017) findings showing that wealthy urban areas are more exposed to air pollution, but that within them, poorer people are more exposed.

Figure 7

At the neighborhood level, higher levels of wealth are associated with higher outdoor pollution, but the relationship changes at the individual level.

A. Households with the highest wealth live in neighborhoods with highest outdoor air pollution

B. At the individual level, outdoor air pollution is lower outside the housing of the wealthiest households.



Notes and sources: Authors calculation based on collected survey data. Outdoor air pollution levels are the average measured by the PurpleAir monitors from January 2023 to April 2023 in Panel A. In Panel B, outdoor air pollution was measured by enumerators outside the interviewee's dwelling at the time of surveying.

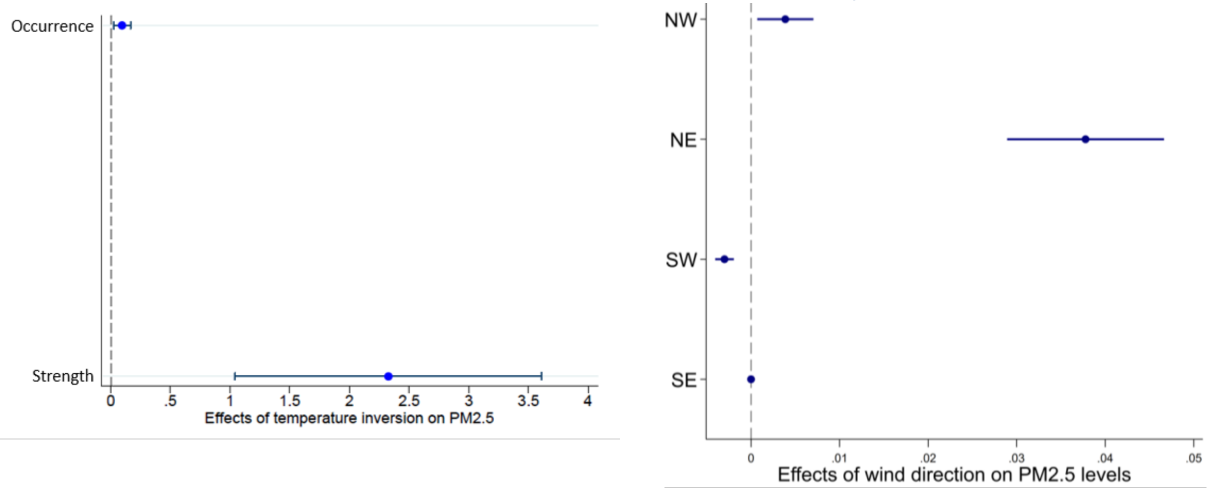
Poorer households are more exposed to indoor air pollution and more vulnerable to air pollution because they are less likely to own protection devices. Results exploring differences across wealth levels suggest that poor households are disproportionately exposed to indoor air pollution. The average indoor air pollution concentration in their dwelling at the time of the survey was 68µg/m3 compared to 60µg/m3 for high-wealth households. Poor households are also less likely to own devices to mitigate air pollution. Only 4% of low-wealth households own an air purifier compared to 16% of high-wealth households.

3 Sources of air pollution variations in Tbilisi: weather patterns, traffic, and industrial emissions.

Thermal inversions and wind blowing from the South increase PM2.5 concentration in Tbilisi. On a typical day, the air at the surface is hotter than the upper layers of the atmosphere. As a result, polluted surface-level air moves up before cooling down and coming down again, forming a continuous movement of air that dilutes pollution in the atmosphere. Thermal inversions occur when the air near the surface is colder than the air at higher altitudes due to meteorological conditions. In this situation, the cold, polluted air at the surface is trapped, resulting in higher air pollution levels. On average, thermal inversions occur three times a month per district and significantly increase monthly PM2.5 concentrations where they occur (Figure 8A). The higher the temperature gradient, i.e., the stronger the inversion, the higher the increase in PM2.5 level. Air pollution also increases when the wind blows from the South (Figure 8B). As we will explain below, this is likely due to emitting industries in the Southeast and the fact that many districts are located to the northeast of high-traffic areas. The results highlight the need for adaptation solutions to mitigate impacts on days when atmospheric conditions are expected to increase air pollution. In addition, wind patterns and thermal inversions are exogenous sources of variations in air pollution (Deryugina *et al.*, 2016; Chen *et al.*, 2018) that we use as instruments for air pollution in the study of its impact on health and economic outcomes (Section 4).

Figure 8

Thermal inversions and wind from the South increase PM2.5 concentration in Tbilisi.



A. Thermal inversions increase PM2.5 levels

B. On average, wind from the South (NW, NE directions) increases PM2.5 levels

Notes and sources: Authors calculation using (van Donkelaar *et al.*, 2021) and ERA5 for weather variables: temperature, wind, and precipitation (Hersbach *et al.*, 2023). Thermal inversion occurs when air temperature increases with height in layers of the atmosphere. Since warm air is higher, the air under the inversion cannot escape because it is cooler than the air farther aloft. As a result, pollutants get trapped in the surface area, making air pollution more severe. The strength of the inversion is represented by the temperature difference between the levels at which the inversions occur. Wind direction dummy variables are equal to 1 when the wind vector is directed in this direction. For instance, NE corresponds to a wind vector with positive projections on the u and v axes. The regressions include year-month and district fixed effects as well as weather controls (temperature bins, precipitation bins and wind speed). Robust standards errors are clustered at the district level.

Traffic is a major issue in the city center, where recurrent traffic jams strongly affect air quality. Transportation is the primary source of air pollution in Tbilisi, according to IQAir, but quantitative estimates of the relationship are scarce. In this project, we use daily traffic data on Tbilisi's roads from Mapbox to quantify its impact on air pollution in Tbilisi (Mapbox, 2023). Mapbox provides daily speed and delay time for all Tbilisi roads. We match each road segment to its district and quantify traffic intensity by the number of days with traffic jams within a month in each district. A traffic jam in a district is defined as an observed traffic speed lower than 5km/h on one of the district's roads at any point during the day. Figure 9A shows that congestion is an important issue in the city center. In this area, most districts experience traffic-jam days more than half of the year, and some experience traffic jams 90% of the days.

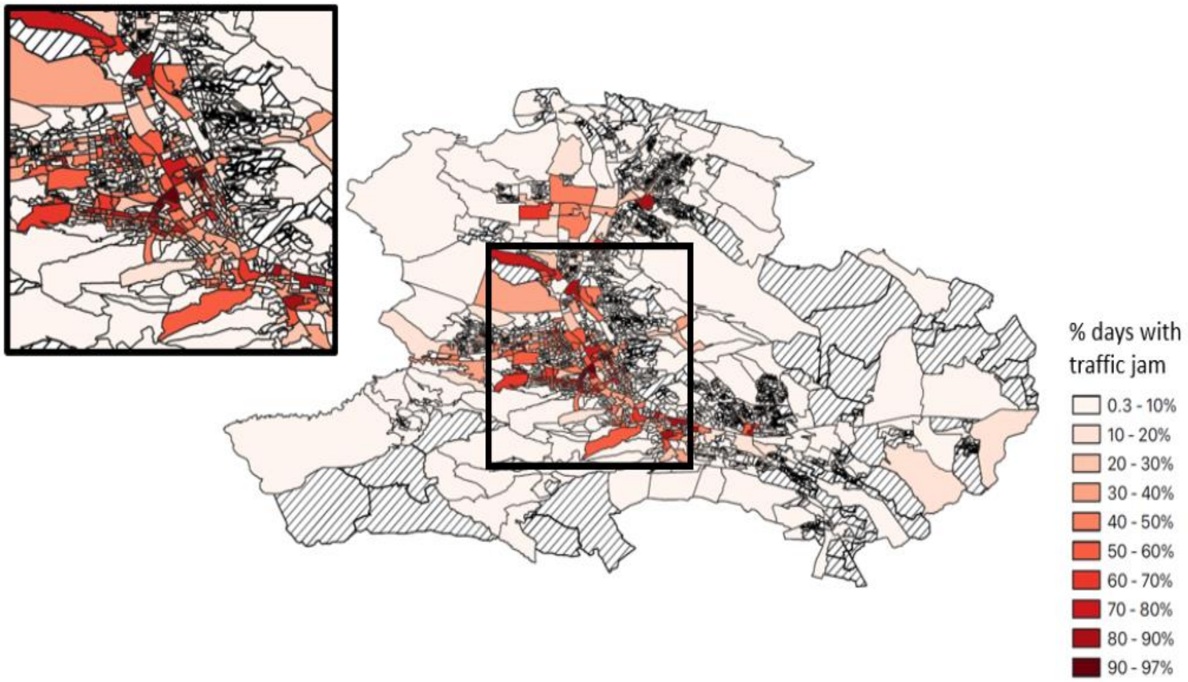
Traffic congestion significantly increases air pollution levels where they occur. Our analysis shows that each additional day with traffic jam increases monthly air pollution by 0.006 µg/m3 in the district (Figure 9B). Like most districts in the city center, having ten traffic jam days per month increases PM2.5 concentration by 0.06µg/m3, representing one-tenth of the WHO recommended threshold for air pollution exposure. This relationship is linear; the marginal effect of a traffic jam day on air pollution is constant and does not depend on the cumulative number of traffic jam days in a month. Therefore, a reduction in the number of traffic jam days would yield the same decrease in PM2.5 concentration no matter the location. However, since impacts on health worsen with high PM2.5 concentration, a policy tackling traffic in highly congested areas is likely to yield more health benefits. Traffic management would also benefit areas downwind of traffic hotspots. Indeed, although wind decreases the concentration of pollutants in heavy-traffic areas, it displaces them to downwind districts.

Figure 9

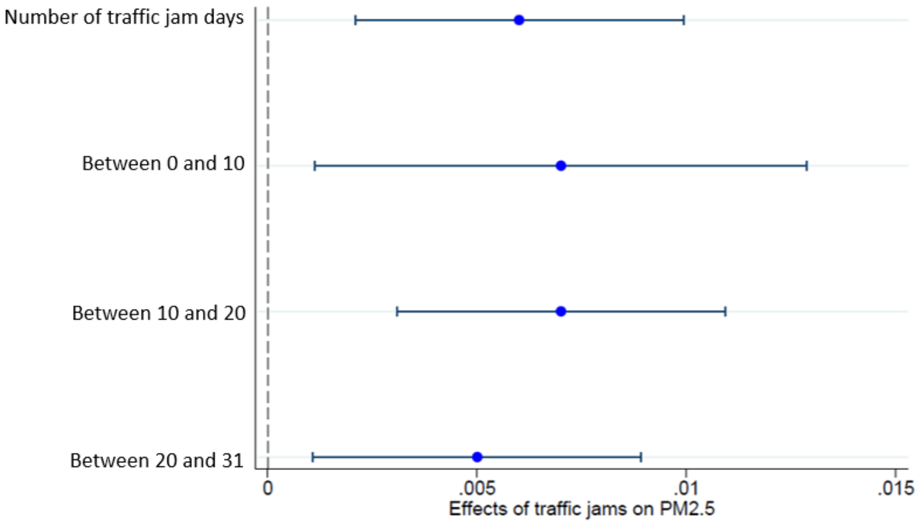
Traffic congestion is extremely high in the center of the city and hot spots suffer from higher air pollution.

A. Traffic is concentrated in the city center

(Red=more traffic)



B. An additional traffic jam day increases district's monthly PM2.5 concentration by 0.006 µg/m3



Notes and sources: Authors calculation using van Donkelaar *et al.*, (2021) for pollution, Mapbox for traffic (Mapbox, 2023), ERA5 for wind direction, wind speed, temperature and precipitation (Hersbach *et al.*, 2023). A traffic jam in a district is defined as an observed traffic speed lower than 5km/h on one of the district's roads at any point during the day. Robust standards errors are clustered at the district level.

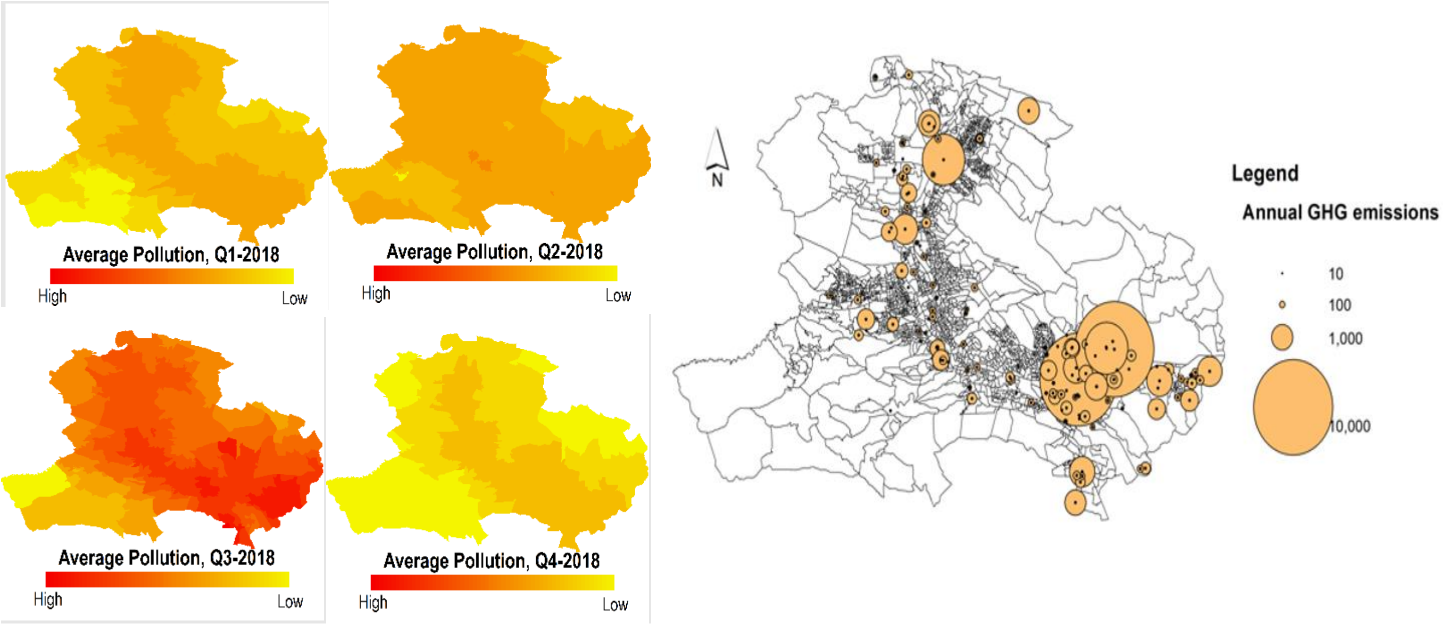
Policies reducing traffic, such as regulating car imports and accelerating the implementation of technical inspection reform, could decrease outdoor air pollution in Tbilisi. Some countries have significantly improved health outcomes by reducing traffic-related air pollution. In India, the regulation on mandated catalytic converters significantly decreased PM2.5 and NO2 concentrations and infant mortality rates (Greenstone and Hanna, 2014). Recent work also suggests that exposure to road traffic pollution is highly localized and damaging to health (Bassi *et al.*, 2022). To reduce traffic emissions in Georgia, the government is considering introducing a mandatory Euro-5 emission standard, limiting the import of old cars that would not meet the standard (Government of Georgia, 2023). In 2018, the government launched the nationwide vehicles' Periodic Technical Inspection reform (Ministry of Economy and Sustainable Development of Georgia, 2019). However, implementation could be accelerated, and enforcement strengthened. Additional policies to consider are incentivizing fuel-quality improvements and local traffic restrictions in hot spots. Developing public transport is essential to ensure that these reforms do not have disproportionate income effects on Tbilisi inhabitants and the poorest. There has been progress on that front in the last five years in Tbilisi, including the creation of bus lanes and pedestrian crossings, for instance, but more remains to be done.

Emissions from industrial sites located in the Southeast of Tbilisi negatively impact air pollution. Using data on industrial emissions from the Ministry of Environmental Protection and Agriculture of Georgia (2023), we proxy air pollution emissions by the reported emissions of greenhouse gases. Although the correspondence between the emission of PM2.5 pollutants and greenhouse gases (GHG) is not perfect, they share many of the same sources. The biggest five industrial sources of emissions around Tbilisi are metallurgical production, the manufacture of construction materials, food production, and to a lesser extent, wood processing, and waste management. Figure 10B shows the location of all industrial emitters of greenhouse gases. The most important sources are in the Southeast, where PM2.5 concentration and its variation are also the highest (Figure 10A). Results in Figure 10C show that emissions from industrial sites significantly affect air quality in the district where they are located. An industrial site emitting 10 000 tons of greenhouse gases a year increases monthly PM2.5 concentration in its district by 0.1 µg/m3. In Tbilisi, two industrial sites reported GHG emissions higher than 10

000 tons between 2016 and 2021. This result suggests that industrial sites with high GHG emissions increase air pollution levels in their district as much as recurrent traffic jams (more than 20 days per month). Dust emissions also significantly increase air pollution, and Tbilisi hosts two industrial sites emitting more than 100 tons of dust between 2016 and 2021. Their emissions increase monthly PM2.5 concentration in their district by 0.26 µg/m3. Therefore, tackling dust sources is also critical to decrease air pollution in the capital.

Figure 10

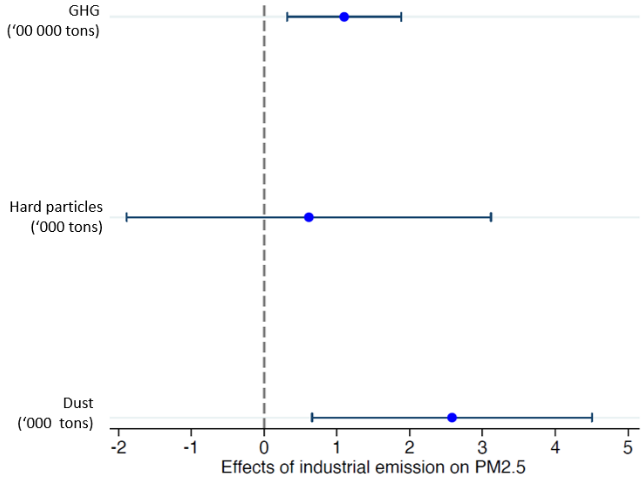
Air pollution and its seasonal variation are highest where emissions from industrial sites are also the highest.



A. Air pollution and its seasonal variation are highest in the Southeast (red)

B. Where total emissions from industrial sites are also the highest (bigger circles).

C. Emissions from industrial sites increase air pollution levels in Tbilisi

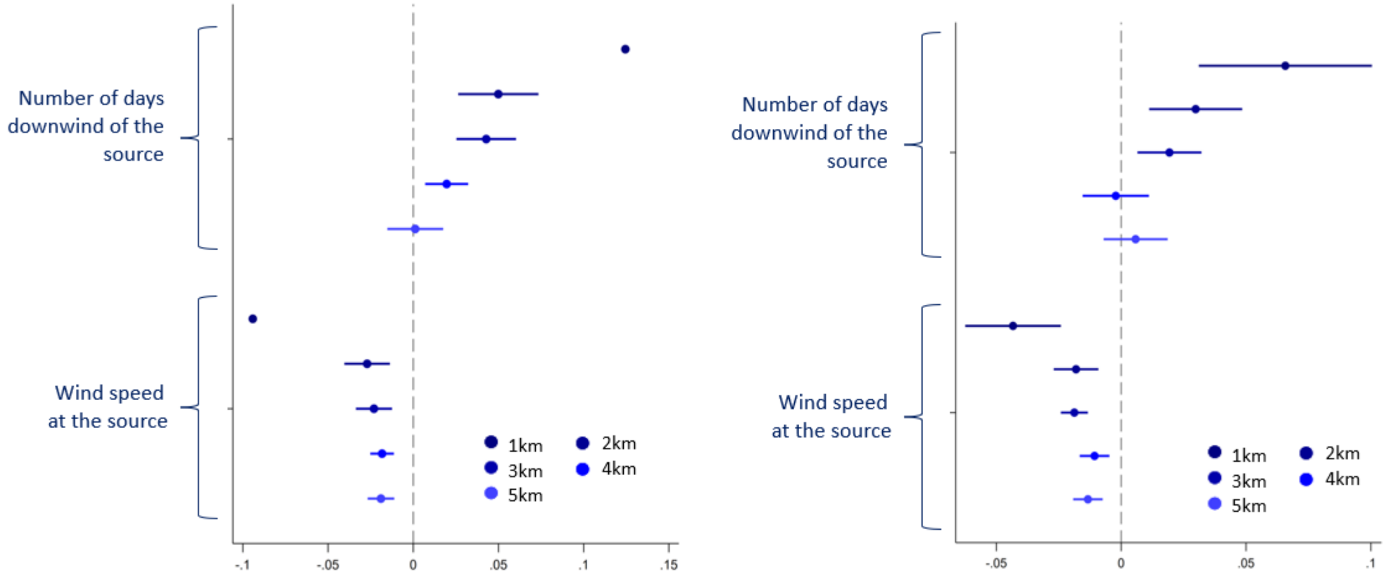


Notes and sources: Authors' calculation. Panel A shows the average pollution level across Tbilisi census blocks in each 2018 quarter. Pollution is measured in µg/m^3 and uses van Donkelaar *et al.*, (2021). Data on emissions in tons per year and covers organizations based in Tbilisi from 2016 to 2021. It was collected by the The Ministry of Environmental Protection and Agriculture of Georgia, Environment and Climate Change Department. In Panel B, the size of the red circle represents the 2018 total GHG emissions emitted by industrial activities located at the centroid of the circle. Data is from the Ministry of Environmental Protection and Agriculture of Georgia, Environment and Climate Change Department.

Pollution from emitting industrial sites severely impacts air quality in downwind districts. The four most important industrial sources of greenhouse gases in Tbilisi are sites for metallurgical production, construction material manufacturing, and food production. In the following analysis, we call *downwind* the alignment between wind at the source and the direction of the considered district. Figure 11 shows the impact of GHG emissions on downwind districts by source (panel) and distance (blue shades). Our results are lower bounds because of measurement error. Indeed, wind patterns further away from the source also influence whether a district receives air molecules emitted by the source. Further work using an atmospheric model would be needed to calculate the exact location of downwind districts and reduce measurement error. Within 1km of the source, PM2.5 concentration increases by up to 0.2 µg/m3 on average with each additional downwind day (Figure 11C). For districts further away from industrial sites, the increase is about 0.05 µg/m3 by downwind day. The impact of industrial emissions also decreases further away from the source, but effects on air pollution are still significant 3 to 5 kilometers away, suggesting widespread effects on air pollution. This strong effect is mitigated by wind speed at the source since strong winds disperse emissions non-linearly.

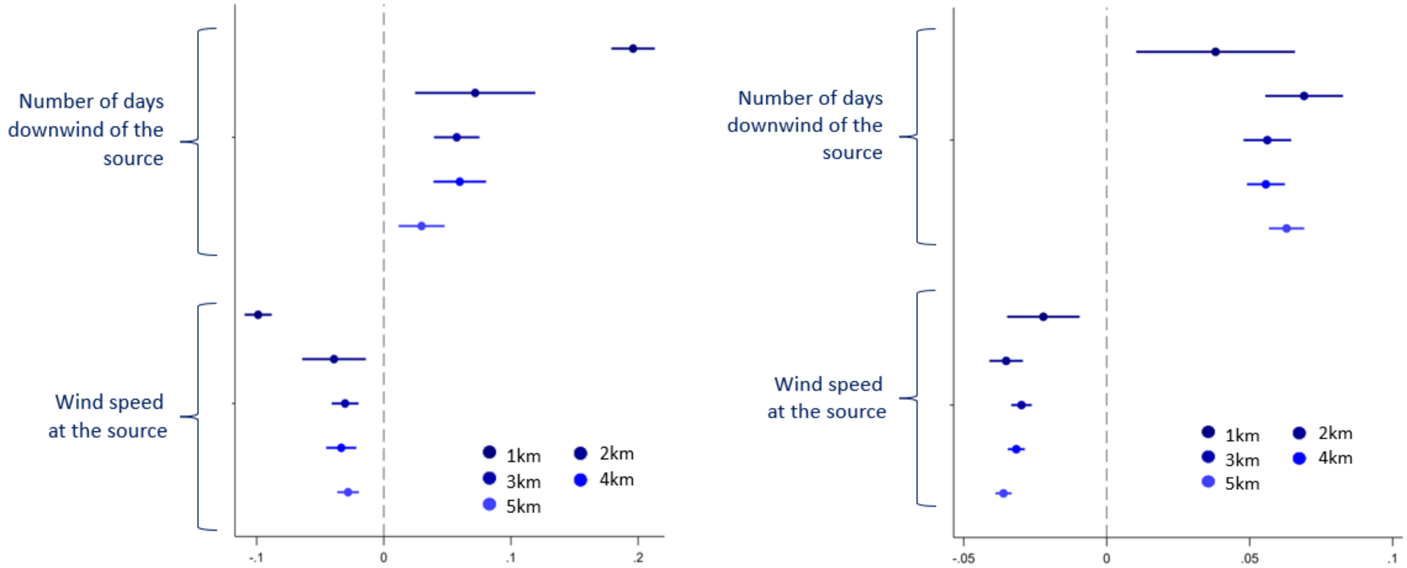
Figure 11

Emissions from industrial sites significantly increase air pollution levels in downwind districts.



A. Impact of being downwind from the most polluting industrial site (Metallurgical production)

B. Impact of being downwind from the second most polluting industrial site (Manufacture of construction materials)



C. Impact of being downwind from the third most polluting industrial site (Food production)

D. Impact of being downwind from the fourth most polluting industrial site (Food production)

Notes and sources: Authors’ calculation. Each panel corresponds to a different emission source among the four biggest emitters of GHG emissions in Tbilisi (Ministry of Environmental Protection and Agriculture, Environment and Climate Change Department). The dependent variable is monthly PM2.5 concentration measured in µg/m3 using(van Donkelaar *et al.*, (2021) and ERA5 for wind direction, wind speed, temperature and precipitation (Hersbach *et al.*, 2023). The regressions main independent variables are dummy for being downwind from the source and measures of wind speed at the source. We restrict the regressions to districts surrounding the source, within 1,2,3,4, and 5 km. Regressions include year, month and district fixed effects, district-level controls for wind speed, direction, temperature, and precipitation. Wind speed is dropped in the regression within 1km of the source because they are multicollinear to the wind speed at the source. Standard errors are clustered at the district level.

Regulating industrial emissions could yield significant health benefits in Tbilisi, particularly in districts downwind from the most polluting industrial sites. (Luechinger, 2014) shows that the mandated desulfurization of German power plants decreased SO2 concentration, which lowered the infant mortality rate. Similarly, (Lavaine and Neidell, 2013) provide evidence that strikes in French oil refineries decreased SO2 concentration in surrounding areas and increased birth weight and newborns’ gestational age. Under the EU-Georgia Association Agreement, Georgia has committed to aligning its regulations on industrial pollution with the EU legislation (2010/75/EU Directive on Industrial Emission). In this process, the authorities have submitted to the Parliament a new Law on Industrial Emissions (Trigger 1.II) that aims to prevent emissions into ambient air, water and land as a result of industrial activities or, where it is practically impossible, to reduce and control emissions, as well as to prevent the generation of waste. This law stipulates the obligation to have an integrated permit for industrial activities with the potential for significant impacts on the environment and human health. According to the draft law, an integrated environmental system and a compliance monitoring and control mechanism should be introduced in 2026. Given the high impact of industrial emissions on air pollution, enforcing this law and accelerating its implementation is essential to curb industrial emissions further.

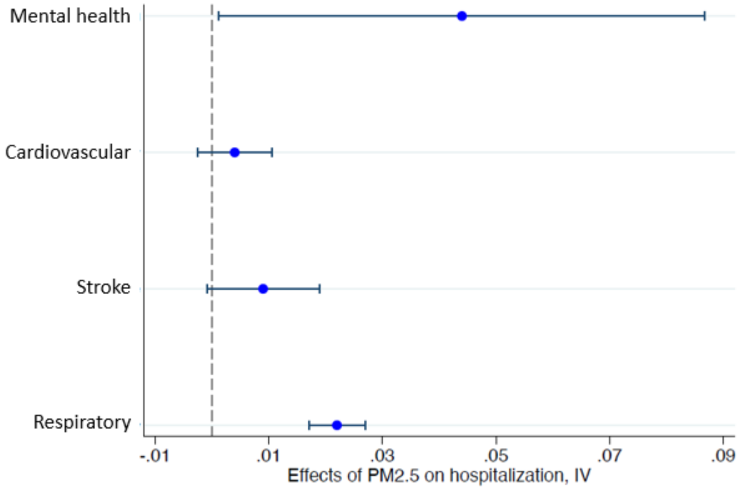
4 Impacts of air pollution in Tbilisi: health and real estate values

This section presents causal estimates of the impacts of air pollution and assesses their heterogeneity in income. Following the literature, we use an instrumental variable strategy to isolate exogenous variations in air pollution. As mentioned above, thermal inversions and wind patterns are relevant and exogenous instruments for air pollution. This method differs from another widespread method of estimating air pollution impacts on health by combining exposure measures with relative risk functions to estimate mortality and morbidity attributable to air pollution (WHO, 2016). Our method is agnostic about the form and intensity of the exposure-heath relationship and can be used to calibrate relative risk functions in the second method.

In Tbilisi, air pollution significantly increases hospitalizations for mental health and respiratory diseases. Our analysis combines daily data on hospital discharges from the National Center for Disease Control (The National Center for Disease Control and Public Health (NCDC), 2022) with air pollution data (van Donkelaar *et al.*, 2021) to build monthly panel data of air pollution levels at each hospital location. Figure 12 shows the coefficients in the instrumented regressions of hospitalizations by type on average monthly PM2.5 concentration at the hospital location. In Tbilisi, a 1 µg/m3 increase in PM2.5 concentration significantly increases hospitalizations for respiratory diseases by up to 2.2% and hospitalizations for mental health by up to 4.4%. Results for stroke-related hospitalizations are less accurate, but the point estimate indicates a potential increase of up to 0.9%. Moreover, these significant effects of air pollution on health are likely to be a lower bound of the true effect. Indeed, there is some measurement error as the analysis uses the hospital location to calculate PM2.5 exposure, not the patients' addresses. The high magnitude of the effects is in line with the adverse health consequences shown in other countries where air pollution adversely impacts infant mortality (Greenstone and Hanna, 2014; Barrows, Garg and Jha, 2018), adult deaths (Heft-Neal *et al.*, 2018), life expectancy (Ebenstein *et al.*, 2017), and mental health (Chen *et al.*, 2018).

Figure 12

Air pollution significantly increases hospitalizations for mental health and respiratory diseases in Tbilisi.

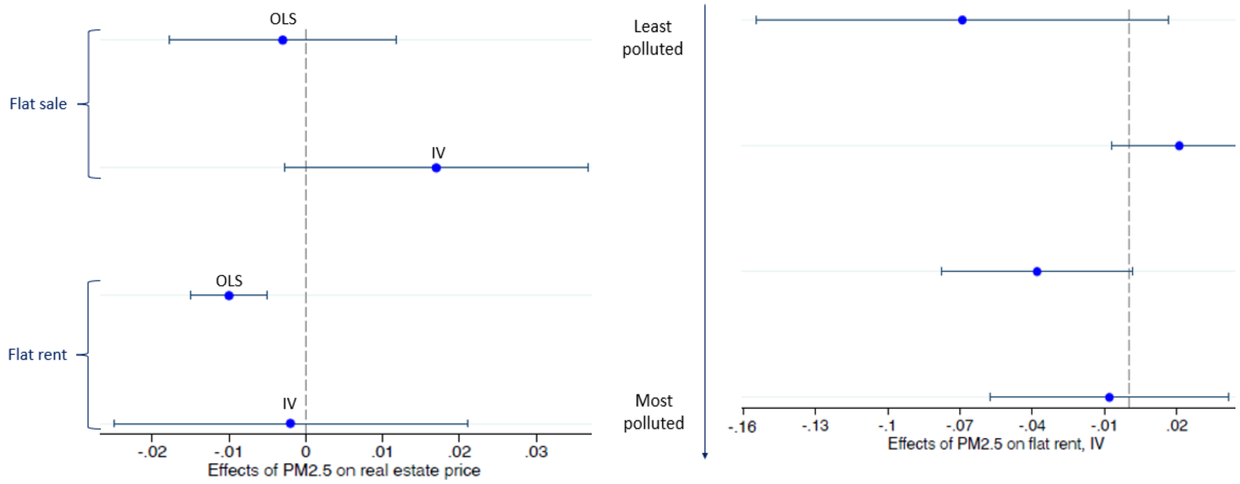


Notes and sources: Authors calculation using (van Donkelaar *et al.*, 2021) and hospitalization data from The National Center for Disease Control and Public Health (2022). PM2.5 is predicted in the first stage using wind patterns and thermal inversions as instruments, weather, and year, month, and hospital fixed effects. Robust standards errors are clustered at the district level.

Air pollution negatively affects real estate values in Tbilisi, and clean air is an important amenity. To investigate the impact of air pollution on real estate values, we merge van Donkelaar et al.'s pollution data (2021) to the complete universe of Tbilisi's sale and rent advertisements posted on a major real estate website, LIVO, between January 2019 and June 2021. LIVO is one of the main real estate agencies in Georgia, and monthly data includes 30,000 - 60,000 observations (depending on a month) on the listings of real estate for sale, rent, and exchanges in Georgia. In Tbilisi, a 1μg/m3 increase in PM2.5 is associated with up to a 1% decrease in rent (Figure 13). This result is consistent with evidence from the US, where neighborhoods within 2 miles of power plants-major sources of air pollution-experienced a 3% to 7% decrease in housing values and rents (Davis, 2011). Unfortunately, the limited number of house transactions in the LIVO dataset prevents us from accurately estimating the effect on flat sales and private houses. The drop in flat value related to air pollution is stronger for flats located in areas with clean air. In the 25% least polluted areas, a 1μg/m3 increase in PM2.5 decreases average flat rent by almost 8%. This suggests that clean air is considered an important amenity for people buying in less polluted areas.

Figure 13

Air pollution significantly decreases flat rent prices in Tbilisi in a non-homogenous way.



A. Air pollution decreases flat rent prices in Tbilisi.

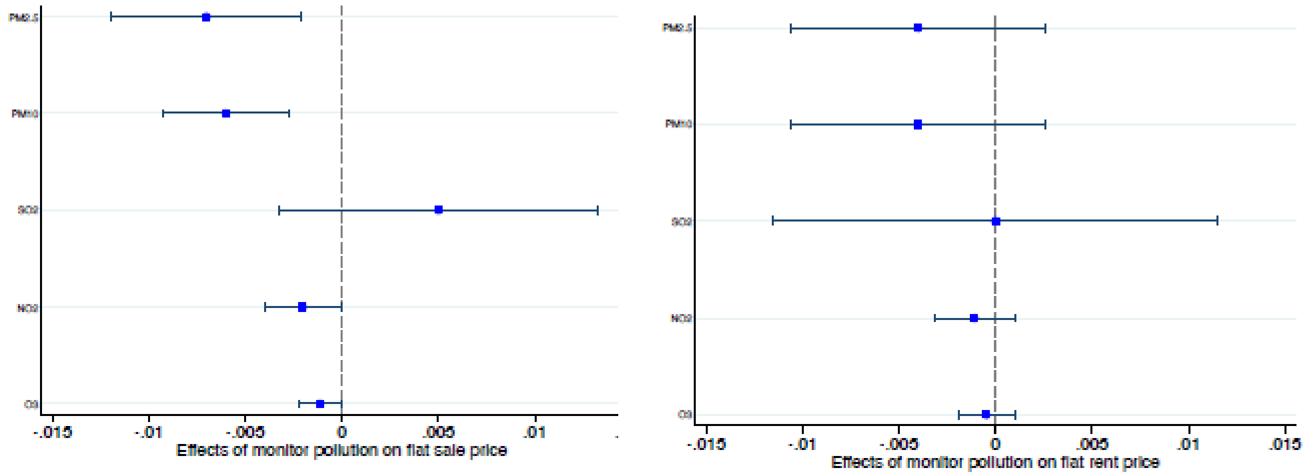
B. The marginal effect is higher in less polluted areas

Notes and sources: Authors calculation using(van Donkelaar *et al.*, 2021) and the complete universe of Tbilisi's sale and rent advertisements posted on a major real estate website, LIVO, between January 2019 and June 2021 (LIVO, 2023). . Monthly data on listings of real estate for sale, rent, and exchange in Georgia between January 2019 to June 2021 (30 months) are included in the LIVO data. Number of observations ranges from 30,000 - 60,000 depending on the month. The regressions include year-month and house/flat fixed effects. In the IV specification PM2.5 is predicted in the first stage using wind patterns and thermal inversions as instruments, weather, and year, month, and hospital fixed effects.

The highest effect on real estate values stems from PM2.5, PM10, and NO2 and O3 pollutants. PM10 and PM2.5 refer to all inhalable particles with a diameter smaller than 10 and 2.5 micrometers, respectively. They are emitted by a large range of sources, such as construction sites, fires, industries, power plants, or vehicles. Figure 14 shows that NO2 and O3 also have an adverse effect on flat prices, particularly flat sales. A 1μg/m3 increase in NO2 decreases average flat sales by 0.2%. This drop in real estate prices reflects the high value of an environment free of NO2 and O3 pollution for Tbilisi inhabitants. Once in the atmosphere, capturing these pollutants is impossible. Therefore, policies need to tackle emissions of NO2 and O3 to increase the welfare of people in Tbilisi. Nitrogen dioxide (NO2) forms when fossil fuel is burned at high temperatures, which is common for vehicles and power plants. Cars, power plants, and some industrial processes also emit ground-level ozone (O3). Policies recommendations tackling traffic and industrial emissions, such as the ones discussed in Section 3 are likely to be reflected in real estate values due to the importance of clean air as an amenity.

Figure 14

Increase in PM2.5, PM10, NO2 and O3 concentrations decreases flat sale and rent prices in Tbilisi.



A. Impact of pollutants on flat sale prices

B. Impact of pollutants on flat rent prices

Notes and sources: Authors calculation using Tbilisi's official air pollution monitors (Ministry of Environment Protection and Agriculture of Georgia, 2018) and the universe of LIVO advertisements (LIVO, 2023) with an address within 5 miles of an official monitor. Monthly data on listings of real estate for sale, rent, and exchange in Georgia between January 2019 to June 2021 (30 months) are included in the LIVO data. Number of observations ranges from 30,000 - 60,000 depending on the month. We separately regress flat sale price (left) or flat rent price (right) on each air pollutant and report estimated coefficients and 95% confidence intervals in the figures. The regressions include year-month and house/flat fixed effects, as such the variation comes from the 138,303 real estates (out of 165,533) for which we observe at least two ads during the sample period.

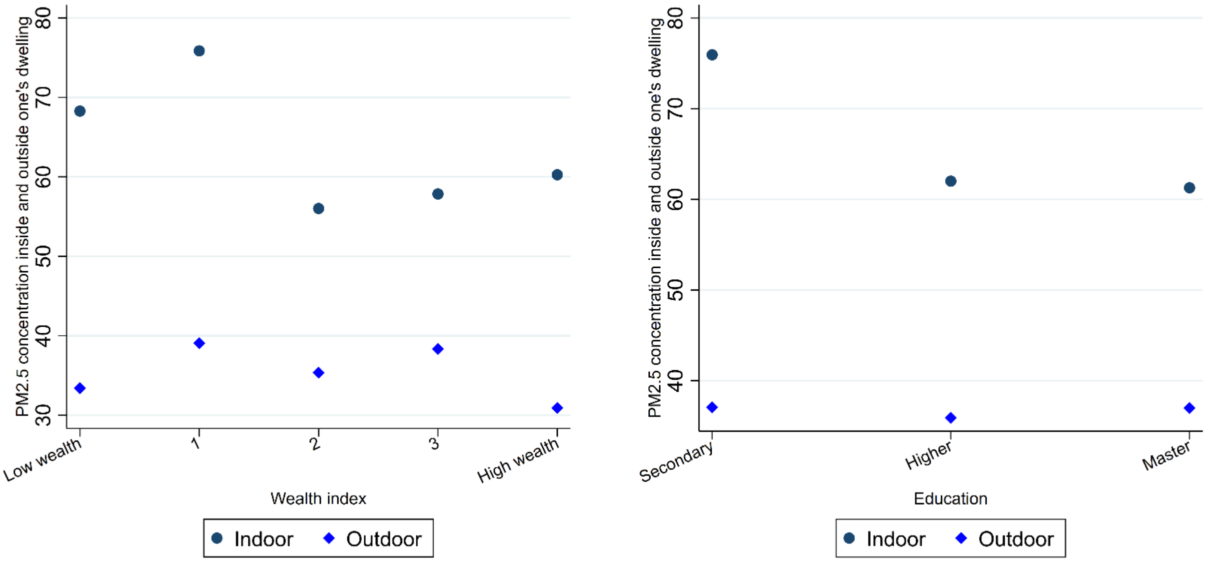
The high impact of outdoor air pollution on health and real estate values in Tbilisi highlights the need to regulate important sources of emissions. As mentioned above, policies reducing traffic and industrial emissions could substantially reduce ambient air pollution in Tbilisi. The resulting health benefits could be significant, as the above analysis suggests. These benefits are likely higher for the most vulnerable people, including children, the elderly, pregnant women, people with weakened health, and the poorest. Indeed, air pollution causes illnesses but also worsens the effect of other diseases, such as influenza (Graff Zivin *et al.*, 2020). As such, policies tackling air pollution are likely to highly benefits the most vulnerable. However, some policies could also impact the poor's income disproportionately, such as increasing car prices, for instance. Ex-ante policy evaluation should be conducted case-by-case to assess policies' progressiveness.

5 Individual exposure to air pollution and its drivers

The wealthiest and most educated households are exposed to lower PM2.5 concentrations inside and outside their dwellings. Figure 15 shows the distribution of measured outdoor and indoor pollution levels during the survey across wealth (Panel A) and education groups (Panel B). As highlighted in Section 2, even though wealth is associated with living in a central location and more pollution, the wealthiest live in housing less exposed to outdoor air pollution. Indoor air pollution levels are also lower in medium to high-wealth groups. Wealth is positively correlated to education, with a 28% correlation between the asset and education indexes. As such, the variation across education groups could drive some variation across wealth groups. Although outdoor pollution outside one's dwelling is constant across education groups, indoor air pollution levels are much lower for higher education households. This suggests that more educated households may live in better-insulated buildings and/or have a higher capacity to adapt to air pollution and decrease indoor air pollution.

Figure 15

Indoor and outdoor air pollution measured at the time of the survey, by wealth and education



A. Low-wealth households are more exposed to indoor air pollution and high-wealth households are less exposed to outdoor pollution

B. Outdoor air pollution is constant across groups, but indoor air pollution is much lower in the dwellings of educated households

Notes and sources: Authors calculation based on collected survey data. Outdoor and indoor air pollution levels are the ones measured by the enumerator's portable monitor at the time of the survey.

Time spent outside is similar across households; less wealthy and educated households spend more time working outdoors, while more educated and affluent people spend more time exercising outdoors. Figure 16A shows that respondents from wealthy households spend less time working outside on average. Across the first four groups, the intensive and extensive margins are at play. More wealth is associated with a lower likelihood of working outside, for shorter periods of outdoor work, and in slightly less polluted areas. The wealthiest bin has fewer observations and fewer active people, making estimates more imprecise. On the other hand, the wealthier the household, the more the respondent spends time exercising outdoors. Again, both the intensive and extensive margins count. More affluent households are more likely to do outdoor exercise and for a longer duration. Moreover, across the first four groups, higher wealth is also associated with exercising in areas with cleaner air. These relationships are even stronger when considering education. More educated households are less likely to work outdoors but spend more time exercising outdoors (Figure 16B).

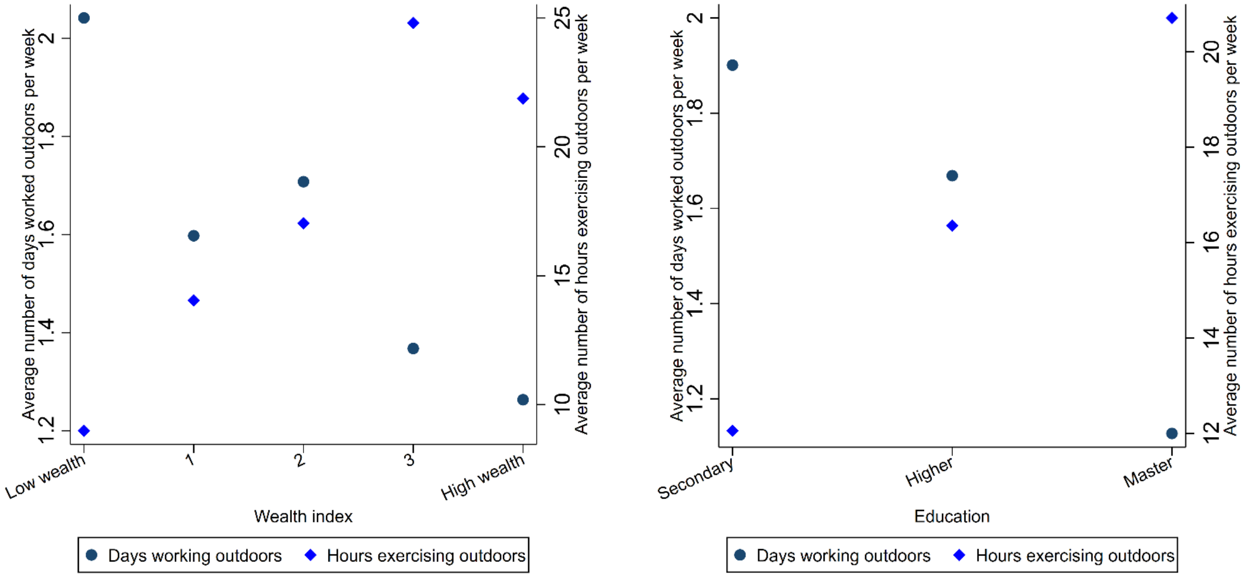


Figure 16

Indoor and outdoor air pollution measured at the time of the survey, by wealth and education

A. Low-wealth households are more exposed to indoor air pollution and high-wealth households are less exposed to outdoor pollution

B. Outdoor air pollution is constant across groups, but indoor air pollution is much lower in the dwellings of educated households

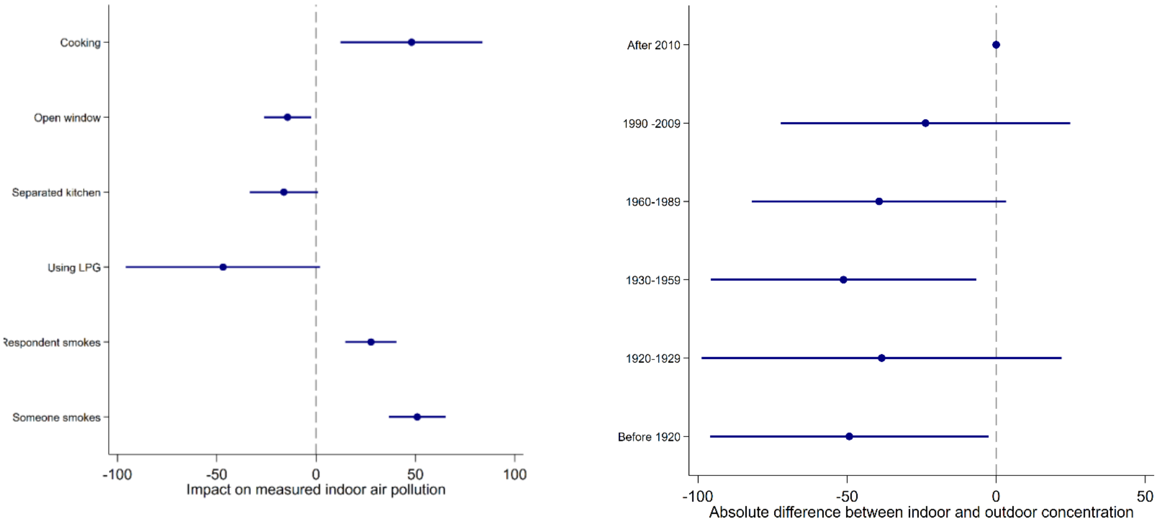
Notes and sources: Authors calculation based on collected survey data. Outdoor and indoor air pollution levels are the ones measured by the enumerator's portable monitor at the time of the survey.

Policies should support less educated and poorer households disproportionately working in more polluted areas. The above results suggest that respondents spend almost the same time outdoors, either exercising or working, no matter their education or wealth levels. However, policies should support less educated and poorer households, who disproportionately work in areas with polluted air, and who cannot mitigate their exposure, unlike more affluent households that stay outdoors for leisure. Having companies provide protective equipment against air pollution when needed would be a progressive policy. When it comes to exercising outdoors, wealthy and educated groups are the most exposed but already exercise in areas with cleaner air. Nevertheless, further information on the consequences of air pollution on health could decrease exposure. Future work will test the effectiveness of different interventions with the Randomized Control Trial (RCT) described in Annex 2.

Cooking, smoking, and building insulation are three important drivers of indoor air pollution. Figure 17A presents some of the significant drivers of the indoor air pollution level measured by the enumerator during the survey. Cooking and having a smoker in the dwelling are associated with an increase in indoor air pollution levels of approximately 50 µg/m3. Although very high, these levels are temporary, and the air pollution levels are significantly lower when a window is open during measurement, for instance. Given the importance of cooking for air pollution, having a separate kitchen or using LPG are associated with lower indoor air pollution. Education is important for these drivers. The probability of living with a smoker is much lower for highly educated respondents (14%) compared to other groups (23%).

Figure 17

Cooking, smoking and lack of insulation explain variations in indoor air pollution


A. Cooking and smoking are two main drivers of indoor air pollution

B. Newer buildings are better insulated

Notes and sources: Authors calculation based on collected survey data. Outdoor and indoor air pollution levels are the ones measured by the enumerator's portable monitor at the time of the survey.

Taxation of tobacco and polluting cooking fuels could be effective and progressive policy tools. Figure 17 shows that smoking and not using LPG are two important drivers of indoor air pollution. Taxation can decrease the demand for tobacco and polluting cooking fuels by increasing prices, which would likely yield high health benefits. With an extended Cost Benefit Analysis, (Fuchs and Gonzalez Icaza, 2020) show that the long-term net distributional effects of increasing cigarette taxation are likely progressive in Georgia. Poorer households reduce their consumption more intensely when faced with higher tobacco prices, which improves their health. Price instruments could also be used to incentivize households to switch to less polluting cooking fuels. Further work would need to be conducted to assess the effectiveness and progressiveness of a tax or subsidy, but the long-term health gains will likely compensate for the direct costs for households.

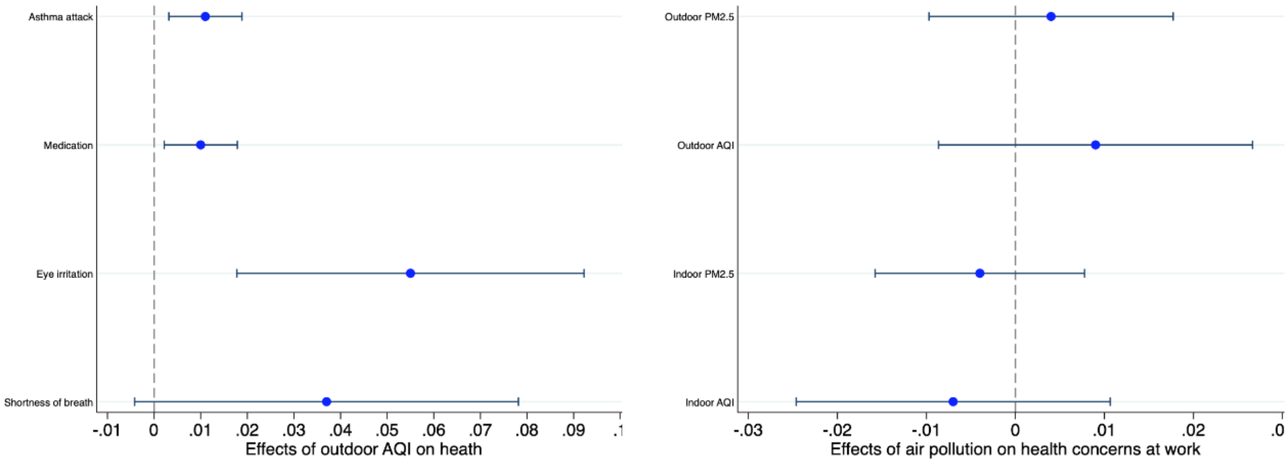
Building characteristics, such as their age, also influence indoor air pollution levels. Figure 17B shows that the age of the dwelling also impacts indoor air pollution levels compared to outdoor ones. On average, newer buildings are better insulated, meaning the difference between indoor and outdoor air pollution is higher. However, since indoor air pollution is higher than outdoor one in 62% of observations, ventilation may have a cleaning effect on indoor air. Wealthy and educated households disproportionately live in newer buildings, with 8% of respondents with a master's degree living in a building built after 1990, compared to 4% only in other education groups. Sources of heating are not significantly associated with levels of indoor air pollution at the time of the survey, maybe because the survey was conducted in May and not in the winter months. Nevertheless, point estimates indicate that firewood is associated with increased indoor and outdoor air pollution, but only 1.4% of Tbilisi's households use it for heating.

6 Impacts of air pollution at the individual level

Air pollution negatively impacts health. We use the survey results to further estimate the effect of air pollution on a large range of health symptoms. As shown in Figure 18A, worsened outdoor air pollution, measured by an increase in the air quality Index (AQI), leads to significant health issues, especially respiratory diseases. For every 1% increase in AQI, the probability of experiencing an asthma attack increases by 1.1%. Similarly, the probabilities of seeking medication, experiencing eye irritation, and having shortness of breath also increase by 1%, 5.5%, and 3.7%, respectively. This impact on health translates into missed days of work, which in turn affect productivity and income. According to our survey results, outdoor AQI and PM2.5 are associated with a 0.9% and 0.4% increase in health concerns affecting work (Figure 18B). The effect is strongest for the least educated group, for which a 1 percent increase in outdoor pollution increases the probability of having work patterns affected by health issues by 1.2%-1.9%. These estimates suggest that outdoor air pollution not only decreases efficiency but may also exacerbate income inequality.

Figure 18

Air pollution adversely impacts health and economics outcomes.



A. Effects of outdoor air pollution on health

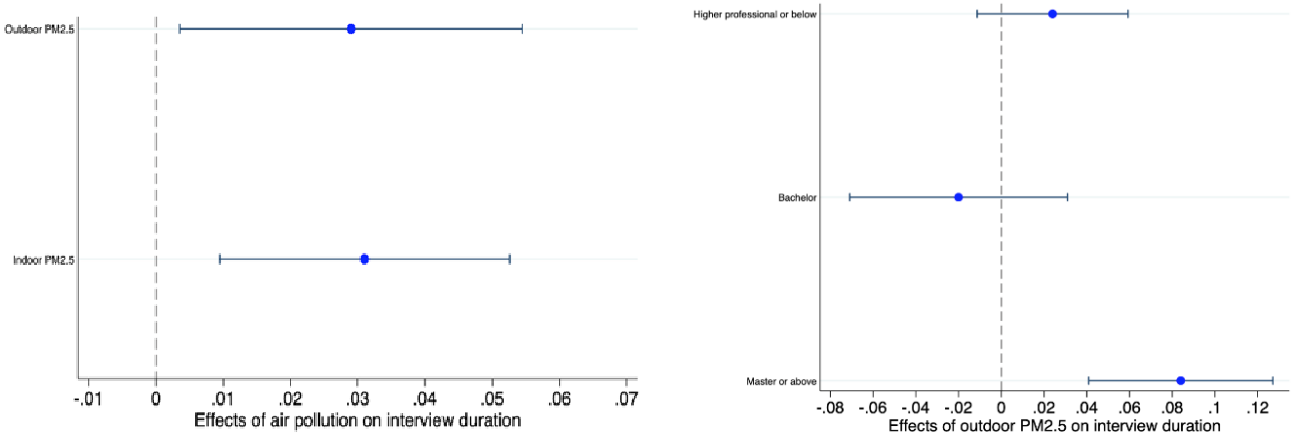
B. Effects of indoor air pollution on normal work patterns

Notes and sources: Authors calculation based on collected survey data. Outdoor and indoor air pollution levels are the ones measured by the enumerator's portable monitor at the time of the survey. Controls include gender, age quadratic terms, treatment group dummies, and housing type dummies.

Indoor and outdoor air pollution adversely affect productivity. We use interview duration as a proxy for productivity to estimate air pollution impacts. Figure 19A shows that a one percent rise in indoor PM2.5 concentration increases interview duration by 2.5%. The effect size is similar for outdoor PM2.5, increasing duration by 2.7%. We further study the pollution-productivity relationship by interviewee's education. Figure 19B shows that the effect is most severe for the high-education group, which includes interviewees with a master's degree, Doctorate, or equivalent. For them, a 1% increase in outdoor PM2.5 is associated with an 8.4% increase in interview duration. Similar effects are observed for indoor pollution, but the magnitude is smaller, resulting in a 5.6% increase in interview durations. Effects on interviewees in other education groups are imprecise.

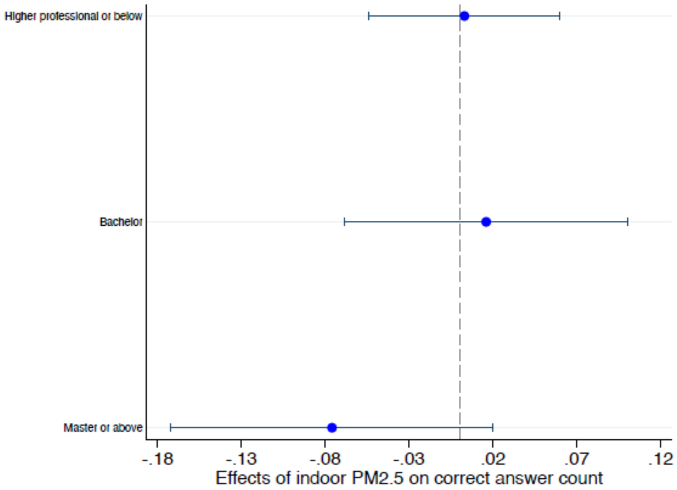
Figure 19

Air pollution is associated with higher interview duration, particularly for the most educated.



A. Effects of air pollution on interview duration **B. Effect by education**

C. Effects of air pollution on cognition, by education



Notes and sources: Authors calculation based on collected survey data. Outdoor and indoor air pollution levels are the ones measured by the enumerator's portable monitor at the time of the survey. Controls include gender, age quadratic terms, treatment group dummies, and housing type dummies.

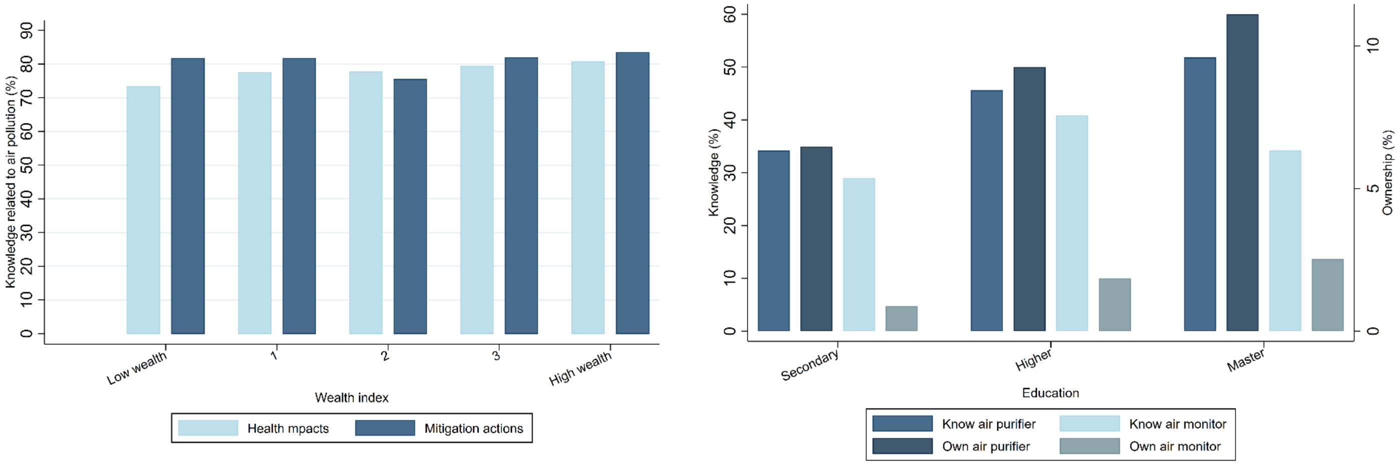
Air pollution further impacts productivity by hampering cognition. Our survey used Raven's test to assess the interviewee's cognitive performance. We define performance by the number of correct answers and the test duration. Estimates are imprecise but will be improved with the second wave of the survey, allowing us to compare the responses of the same person over time. Nevertheless, the point estimates indicate that a 1% increase in indoor air pollution is associated with a 0.6-1.4% decrease in correct answers and a 5.4-7.6% increase in test duration. Figure 19C presents the results by education group; the highest impact of air pollution is on the most educated. Finally, the effect on cognition is more pronounced when examining indoor air pollution than with outdoor air pollution, which aligns with the higher exposure to indoor pollution during the interview process.

7 Individual adaptation to air pollution

More educated and wealthy households have a higher capacity to adapt to air pollution, with higher knowledge, access to information, and ownership of information or defensive devices. We use survey results to investigate households' knowledge about air pollution and their adaptive capacity by wealth and education. Figure 20A shows that the more educated the respondent, the more knowledge they have on the impacts of air pollution on health. Educated households also have a higher capacity to adapt to air pollution because they are more likely to know and own protective devices (Figure 20B). They are more likely to own information devices, like air pollution monitors. This result suggests that providing information, air pollution monitors, or protection devices could disproportionately help the most vulnerable. The project's RCT will further assess the efficiency of such interventions.

Figure 20

Knowledge of air pollution impacts and adaptive capacity increase are higher for more educated and wealthy households.



A. Wealthier households know better the health impacts of air pollution

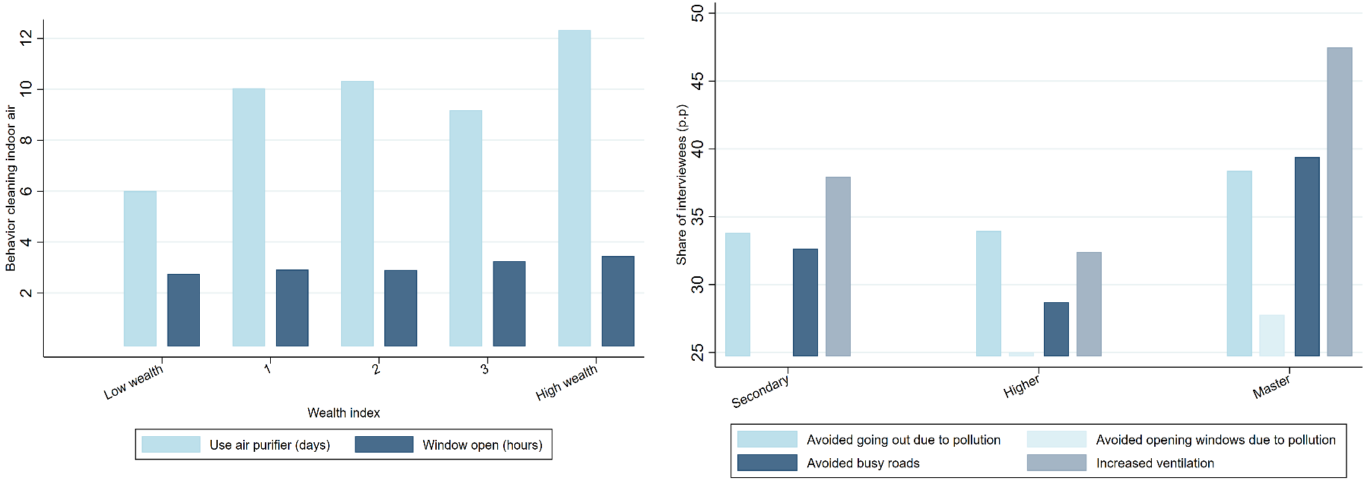
B. More educated households are more likely to own defensive and information devices, such as air purifiers and indoor air monitors.

Notes and sources: Authors calculation based on collected survey data. Outdoor and indoor air pollution levels are the ones measured by the enumerator's portable monitor at the time of the survey.

More wealthy households are more likely to take action to mitigate indoor air pollution. Figure 21A shows that the wealthier the respondent, the longer they use their air purifier and leave their window open for ventilation. These behaviors are conducive to decreasing indoor air pollution. The results suggest that information campaigns targeted by income could effectively mitigate the disproportionate exposure of poorer households to indoor air pollution. Figure 21B indicates that the pattern is not as clear when it comes to outdoor air pollution. Having a master's or doctorate is associated with performing more mitigation actions regarding outdoor air pollution, but patterns for less educated groups are not as clear. Again, information could be needed to support less educated households and decrease their exposure to air pollution. The project's RCT will further assess the effectiveness of such interventions.

Figure 21

More educated households are more likely to take actions to mitigate indoor air pollution.



A. More educated households are more likely to take actions mitigating indoor air pollution.

B. Having a master's degree or doctorate is associated with more mitigation actions regarding outdoor air pollution.

Notes and sources: Authors calculation based on collected survey data. Outdoor and indoor air pollution levels are the ones measured by the enumerator's portable monitor at the time of the survey.

Policy recommendations and future work

Progress has been made, but challenges remain to reduce air pollution levels and their impacts in Tbilisi. In 2020, Georgia adopted the Improved Ambient Air Quality Monitoring Law, which is major progress in tackling air pollution in the country. However, the initiation of zonal air quality management plans has been delayed, and institutional capacity needs to be strengthened to support the successful implementation of the legislation.

Decreasing emissions from transportation should be a priority. Emissions in the transport sector are projected to increase by about 71 percent by 2030 (Government of Georgia, 2021). In the meantime, passenger activity is expected to increase by almost 60 percent and freight activity by 240 percent compared to 2015 (World Bank, 2023). Building on current efforts by further regulating car imports and accelerating the implementation of technical inspection reform could further decrease outdoor air pollution in Tbilisi. Incentivizing the use of electric vehicles could also reduce traffic-related emissions while preparing Georgia for the green transition. Georgia has excise taxes on oil products and cars, but the incentives need to be better aligned and stronger to shift the paradigm and promote less-emitting vehicles, whose current share is negligible. Finally, while the authorities in Tbilisi are expanding the offering of public transportation services, there is scope further to increase the percentage of public transport in mobility.

Regulating industrial emissions is also important to tackle air pollution in Tbilisi and support the green transition. The authorities submitted a new Law on Industrial Emissions to Parliament in January 2023 to prevent spillage from industrial activities into the environment and waste generation. While this law is expected to support the adoption of more efficient and cleaner technology, it does not specifically aim to reduce emissions. Enforced regulations on filtration and monitoring systems in the industrial sector could be an effective way to curb industrial emissions further.

Increasing information on air pollution risks and mitigation actions could allow households to self-protect and is likely to be progressive. As highlighted in the analysis, in Tbilisi, the less well-off and educated are disproportionately impacted by higher indoor pollution levels. Poor and less educated households also have a lower capacity to adapt as they are less likely to adopt mitigating behaviors or own defensive equipment. Our analysis also confirmed that pollution has a significant impact on health - especially on mental health and respiratory diseases - but also on cognitive ability and labor productivity. Therefore, improving households' knowledge of air pollution and supporting the most vulnerable with the acquisition of protective and information devices could yield substantial benefits for economic development and shared prosperity. Targeted information campaigns or incentives for adopting information and protective devices, such as monitors or air purifiers, could be effective. Future work for this project will evaluate the effectiveness of providing information to households in several ways that could support the design of information campaigns.

Some interventions providing information on air pollution levels and their impact to households will be tested in the project's Randomized Control Trial. Sections 5 to 7 of the current version rely on data from the first wave of surveys, but the project includes a second round and a Randomized Control Trial (RCT) described in Annex 2. Results from the RCT will assess the cost and benefits of providing leaflets on air pollution, information on outdoor levels, and indoor air monitors and highlight the most efficient policies to tackle information constraints. Comparing households over time will also increase the precision of our estimates. The project team is also exploring the opportunity to access standardized test results to complement its analysis of the effects of air pollution on human capital by including education outcomes in Section 4.

A.1 Annex 1 – Natural experiments: Data and methods

Relative Wealth Index

The Relative Wealth Index (RWI), used in Section 2, is an indicator developed by a collaboration between UC Berkeley's Center for Effective Global Action and Facebook's Data for Good (Chi *et al.*, 2022). This index predicts the relative standard of living within a country using nontraditional data sources, including satellite imagery and deidentified Facebook connectivity data. It has been validated using ground truth measurements from the Demographic and Health Surveys. Data is available for over 100+ low- and middle-income countries, including Georgia, at a 2.4 km resolution. The datasets are publicly accessible and have been used, for example, by World Bank projects in Togo and Nigeria. The rank correlation between the RWI score and World Bank poverty measures is significant and approximately 0.4 [t-stat> 2.96].

Weather

We use ERA5 for data on wind direction, wind speed, temperature and precipitation (Hersbach *et al.*, 2023). Variables are mainly introduced as bins in regressions to account for the potential non-linearity of weather effects.

Traffic

Traffic data on Tbilisi's roads comes from Mapbox (Mapbox, 2023). Data is presented as the daily speed and delay time for all Tbilisi roads. We match each road segment to its district and quantify traffic intensity by the number of days with traffic jams within a month in each district. A traffic jam in a district is defined as an observed traffic speed lower than 5km/h on one of the district's roads at any point during the day.

Industrial emissions

Data is an inventory of industrial emissions by type and year, provided by the Ministry of Environmental Protection and Agriculture, Environment and Climate Change Department. The data contains emissions in tons per year for industrial sites based in Tbilisi and it covers 2016-2021.

Health

We use daily data on hospitalizations for given ICD-10 codes associated with air pollution provided by the National Center for Disease Control and Public Health (NCDC). The data is available for March 2014 to August 31 and includes variables of organization code, name, and addresses. Hospitals were geolocated using Google maps.

Real estate values

Raw data was shared by the real estate agency Livo.ge - one of the main real estate websites in Georgia (LIVO, 2023). It was processed into a conventional/spreadsheet format by the Private Sector Development Center of ISET Policy Institute. The data contains the complete universe of listings of real estate for sale, rent, and exchange in Georgia from Jan 2019 to June 2021 (30 months).

Natural experiments

We use temperature inversion (existence and strength) and four wind directions interacted with municipality id to instrument air pollution. The first stage regression, whose results are discussed in Section 3's part on weather patterns, is specified as:

$$PM_{it} = Inversion_{it} + InversionStrength_{it} + I(WindDirection_{it} = d) \times I(Municipality_i = m) + Weather_{it} + \tau_t + \gamma_i + \varepsilon_{it}$$

where PM_{it} represents monthly PM2.5 pollution in district i in month t, sourced from (van Donkelaar *et al.*, 2021). On the right-hand side, variables are as follows:

- $Inversion_{it}$ is the occurrence indicator for temperature inversion in district i in month.
- $InversionStrength_{it}$represents the strength of the inversion, both obtained from ERA5 data (Hersbach *et al.*, 2023).
- $I(WindDirection_{it} = d) \times I(Municipality_i = m)$: We include municipality-specific wind direction indicators as supplementary variables. Specifically, we categorize the wind direction in district i in month t into four groups - northeast, northwest, southwest, and southeast - and encode them as dummies, denoted as $I(WindDirection_{it} = d)$. We then interact these four dummies with municipality fixed effects to account for varying pollution levels around each municipality, denoted as $I(Municipality_i = m)$. This accounts for the fact that pollution from the same direction may differ depending on the industrial structure of neighboring areas.
- $Weather_{it}$: We include wind speed, precipitation, and temperature as control variables.
- τ_t represents year-month fixed effects, and γ_i denotes district fixed effects. To address within-district across-time serial correlation, we cluster the standard errors at the district level.

All other regressions in Section 3 follow a similar specification, except that they include additional variables on traffic or the source of emissions.

In Section 4, we use OLS and IV regressions to study the impact of air pollution on health and real estate values. Specifications are similar and the one for real estate is as follows:

$$ln(P_{it}) = \widehat{PM_{it}} + Characteristics_{it} + \tau_t + \gamma_i + \varepsilon_{it}$$

where $\widehat{PM_{it}}$ is the district-month level PM2.5 concentration instrumented using wind directions and inversions. In the OLS equivalent, we use the satellite measure (PM_{it}) directly in the above specification. $Characteristics_{it}$ includes housing characteristics and distance to school/store/hospital. $\tau_t$includes year-month fixed effects and γ_i captures district fixed effects.

A.2 Annex 2 – Randomized Control Trial

The project includes a Randomized Control Trial on the effectiveness of interventions providing information on air pollution. The goal of this experiment is to answer the following questions:

- Do households benefit from receiving information on air pollution? We will assess whether it impacts the respondent's knowledge of air pollution's impact, avoidance behaviors, exposure to air pollution, health, economic and cognitive outcomes.
- Which type of information is the most effective and efficient among receiving a booklet, daily information on outdoor pollution, and an indoor air pollution monitor?
- Do benefits differ by income level? Are some of the interventions more progressive than others?

Treatment groups

Each treatment group receives different information on air pollution:

- T1: Households receive a leaflet containing information on the health-related risks related to air pollution and information on avoidance behavior, such as reducing one's outdoor activities or the frequency of opening windows when outdoor air pollution is high or using an air purifier.
- T2: On top of the leaflet, households receive information on outdoor air pollution level once a day by text message. The measure is given by the project's PurpleAir monitor that is the closest to their location. Households receive the average level in the morning (8am-10am) preceding the text message sent at noon. This measure is correlated with pollution levels later in the day and, therefore, likely to inform future pollution levels.
- T3: In addition to the leaflet and information on outdoor air pollution levels, the household receives an indoor air pollution monitor. The average indoor air pollution level over the last 24 hours is added to the text message. In addition, the indoor air pollution monitor provides live feedback on the indoor air pollution level as its color changes from green (good) to red (bad) depending on the level.

The groups and their respective interventions are summarized in in Table 1:

Table 1

RCT's treatment groups receiving different information on air pollution

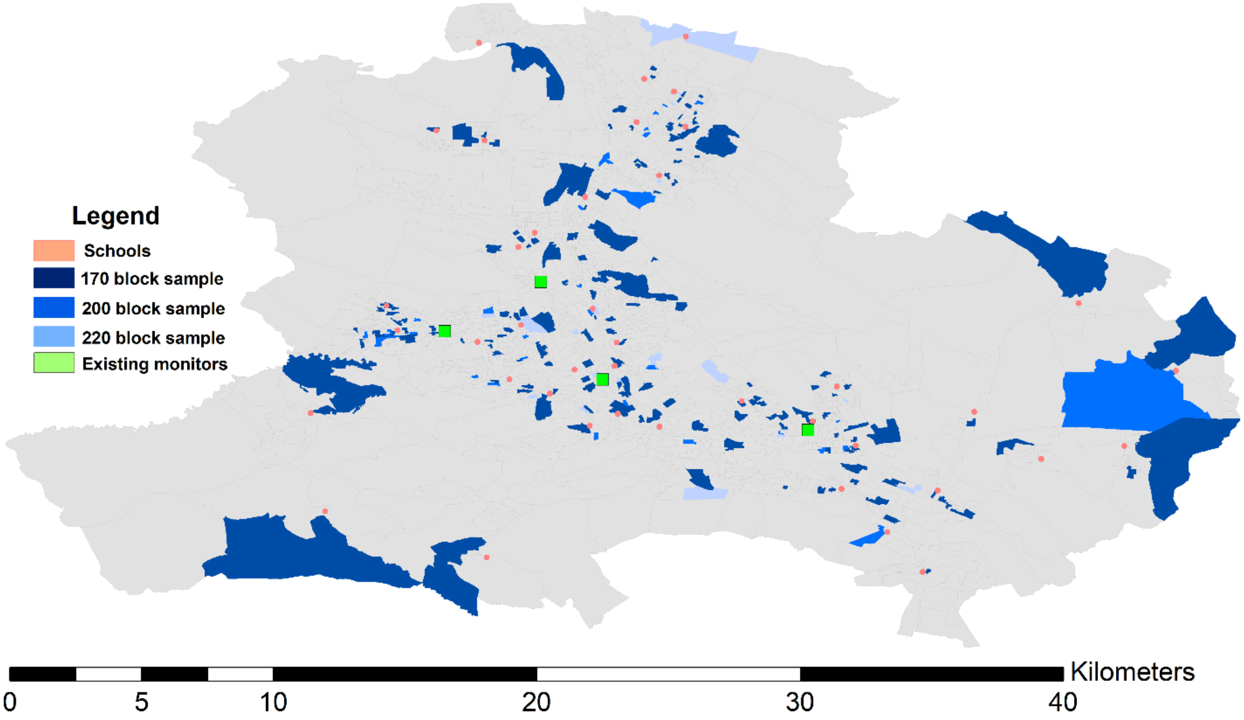
Type of Information	Control	Treatment Groups		
	C1	T1	T2	T3
Indoor air pollution				**X**
Outdoor air pollution			**X**	**X**
Leaflet		**X**	**X**	**X**
Number of HHs	220	220	220	170

Sampling

The survey and RCT rely on stratified sampling of 220 census blocks in Tbilisi. Strata are by income and elevation with the same number of blocks in each. In each selected block, three or four households were randomly selected to be assigned to different control/treatment groups and surveyed. We also installed outdoor air pollution monitors in or near schools nearby the selected blocks. Figure 22presents the map of the selected census blocks (light blue).

Figure 22

Selected census blocks for surveying and installation of outdoor monitors.



Notes and sources: Authors calculation. Selected blocks are in light blue.

A.3 Annex 3 – Field Work

The project involves the collection of survey data on sources of air pollution, exposure, health and economic outcomes, cognition, and knowledge and behaviors with respect to air pollution. 862 households were interviewed in 220 census blocks randomly drawn in four strata based on elevation and income. In each block, 3 to 4 households are interviewed and allocated to different RCT treatment/control groups.

Two rounds of surveys will be conducted to test for the impact of the RCT treatments by comparing the first and second wave results across groups. The two waves will also be used to build panel data of households over time. The first wave was in March-April 2023, and the second will start in May 2023. The survey was collected through face-to-face interviews using Computer Assisted Personal Interviewing (CAPI). The interview lasted 20 minutes on average. The current version of the report relies on the results from the first wave only.

Questionnaire

The first-wave questionnaire includes eight different sections:

- Household demographics
- Sources of air pollution
- Profile of the respondent
- Exposure of air pollution, including the measurement of air pollution inside and outside at the time of the interview
- Health outcomes
- Economics outcomes
- Cognitive test
- Knowledge of air pollution and avoidance behaviors
- Willingness to pay for protective devices

The second-wave questionnaire kept sections that were likely to change over time: exposure to air pollution, outcomes, cognitive test, knowledge and avoidance behavior and willingness to pay. We also included questions aimed at understanding the impact of the treatments and inquiring on potential spillovers between households.

Field Work

The project's team collaborated with CRRC Georgia for this activity. They recruited 22 enumerators, two supervisor and one technical assistant for installing indoor air monitors. CRRC conducted two four-hour training before the start of the fieldwork. During the trainings, interviewers practiced the questionnaire, sampling instructions, familiarized themselves with the maps and recording air quality with the help of the portable air monitors. They also discussed possible problems or challenges that might arise during the fieldwork.

The training covered the following topics:

- Sampling instructions
- Becoming familiarized with maps
- Indoor monitor installment procedure
- Usage of portable air monitors

- Respondent selection
- Overview of the questionnaire with special attention to problematic questions
- Conducting test interviews

Trainings were provided by CRRC staff. Before the actual fieldwork, all enumerators were provided with tablets, maps for every cluster, letter to the respondent explaining the aim of the project, name tags and portable air monitors that they had to carry with them during the whole fieldwork. The technical assistant received indoor monitors and detailed manual of instalment.

Random Walk Procedure

To select households within districts, interviewers followed a random walk process. Starting points were marked on all maps and trainers instructed them on the direction of the random walk. Depending on the number of apartment blocks and houses to be sampled, interviewers were instructed to conduct interviews in different buildings or if there were only one building in the sampled block, they were asked to use different entrances. All enumerators had to follow instructions provided by CRRC and a back check was conducted to ensure quality.

Air pollution measurement

Enumerators carried a portable air pollution monitor during the interviews. For each interview, they recorded air pollution level outside of the building and inside the room where the interview was conducted. This information is the one that has been used in the current analysis of Sections 5 to 7.

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