Air pollution in Tbilisi

Poverty and distributional consequences

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Contents

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 because of residential sorting, limited access to health care, and financial constraints. This report comprehensively assesses the negative effects of air pollution in Tbilisi, the Georgian capital, including from a distributional point of view, by leveraging multiple data sources: administrative data, surveys, satellite imagery, first-hand real-time data from outdoor, indoor, and portable monitors collected for this study, and government monitors.

In Tbilisi, outdoor air pollution levels exceed international standards. The average monthly particulate matter ($PM_{2.5}$) concentration is 20 μg/m^3, which is four times higher than the annual recommended limit set by the World Health Organization (WHO) and surpasses the levels in other cities in the region. The concentration of outdoor air pollution is highest in the city center, where wealthier individuals reside and the elevation is lower. However, the poor and less well educated are likely to be more exposed because they tend to work outdoors, do so for longer periods, and are typically in areas with more polluted air. Anthropogenic emissions from traffic congestion and industry significantly drive outdoor air pollution both near and downwind from the sources. Weather patterns, including thermal inversions and wind, influence the distribution of outdoor air pollution concentrations. In line with the literature, this analysis shows that outdoor air pollution adversely affects health, especially respiratory and mental health, productivity, and economic outcomes in Tbilisi. Tackling outdoor air pollution is thus likely to yield high benefits in Tbilisi, particularly among the poor and vulnerable.

Reducing outdoor air pollution can be achieved by strengthening air quality monitoring and regulating traffic and industrial emissions. Advancing existing initiatives by exercising more control over car imports and speeding up the implementation of the technical inspection reform could substantially lower outdoor air pollution in Tbilisi. Incentivizing electric vehicle use and enforcing fuel standards could also reduce traffic-related emissions, while preparing Georgia for the green transition. Addressing industrial emissions is also crucial for reducing Tbilisi's outdoor air pollution. In January 2023, the government submitted a new Industrial Emissions Law to Parliament, aiming to prevent industrial spills into the environment and reduce waste generation. Enforcing regulations on filtration and emission control equipment in the industrial sector could be an effective way to curb industrial emissions further. Additionally, introducing carbon pricing, a policy instrument tackling greenhouse gas (GHG) emissions, could markedly improve local air quality by reducing overall emissions.

Indoor air pollution is another major issue in Tbilisi. Air pollution levels are higher indoors than outdoors on average. Cooking, smoking, and building insulation are significant drivers of indoor air pollution in the capital. The taxation of tobacco and polluting cooking fuels could therefore be effective policy tools. Despite the high exposure to indoor air pollution, adaptation is low, and poorer and less well educated households exhibit lower adaptive capacity. Hence, policies should prioritize support among less well educated and poorer households, which, on average, are more highly exposed and vulnerable.

Targeted information campaigns or incentives for adopting information devices, such as monitors, would likely reduce population exposure to air pollution and improve health outcomes. This analysis shows that providing households with information on the levels of air pollution in neighborhoods and homes, along with information on protective actions, increases knowledge about air pollution and its impacts. This new knowledge translates into behavioral change among informed households, which then disproportionately engage in protective actions related to the air pollution information they receive, such as avoiding going out when outdoor air pollution is high. Notably, 35 percent of households receiving live indoor air pollution information reduced indoor smoking as a consequence. This change in behavior led to substantial reductions in adverse health impacts.

Introduction

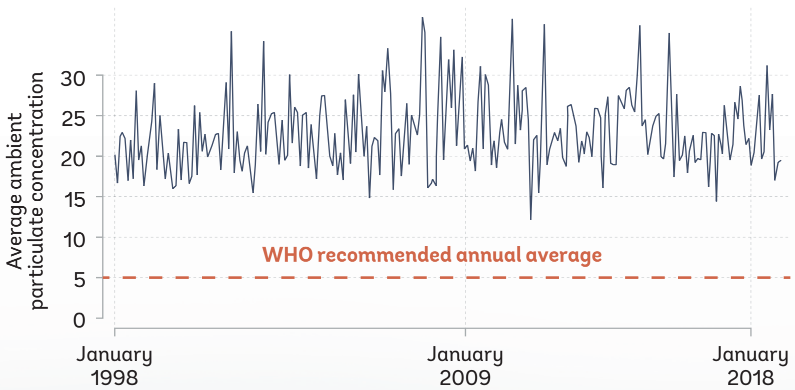
Air pollution levels in Georgia's capital, Tbilisi, exceed international standards and are higher than in other capitals in the region (figure 1). The average monthly particulate matter ($PM_{2.5}$) concentration is above 20 μg/m³, four times the annual average recommended by the World Health Organization (WHO). Between 2017 and 2021, air pollution levels were worse in Tbilisi than in Istanbul (Turkey), Baku (Azerbaijan), and Kyiv (Ukraine). Tbilisi's inhabitants are aware of the issue and rank the problem high on the list of priorities for the city. In a 2017 survey, 42 percent of Tbilisi inhabitants reported air pollution as the most important infrastructural issue (CRRC 2018). More recently, 11 percent of interviewees in Tbilisi considered air pollution one of the capital's most important issues (CRRC 2021).

Air pollution significantly impacts various dimensions of welfare, from mortality to morbidity, 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). Substantial adverse impacts on mortality have been documented in China (Ebenstein et al. 2017), India (Greenstone and Hanna 2014), Indonesia (Jayachandran 2008), and the United States (Deryugina et al. 2016). Welfare is further impacted by air pollution due to 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 (Currie et al. 2015; Davis 2011). Although the impacts of air pollution have been studied in

Figure 1

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

a. Time series, 1998–2018



b. Ranking of cities based on air pollution levels

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

Exceeds WHO guidelines by: 3 to 5 times | 5 to 7 times

Sources: Panel a: World Bank calculations based on data of van Donkelaar et al. 2021. Panel b: data from IQAir 2022.
Note: Panel a: $PM_{2.5}$ concentration is expressed in μg/m³. It represents the average of reanalysis data from van Donkelaar et al. (2021) across the urban area of Tbilisi. The line in orange represents the WHO-recommended threshold. Panel b: IQAir's ranking of most polluted cities in the world based on a comparison of annual average $PM_{2.5}$ concentrations in 2017–21.

other countries, the estimates presented in this report seem to be the first to evaluate the adverse effects on health, real estate values, cognitive performance, and productivity in Tbilisi.

The burden of air pollution is unequally distributed. Inequalities are present at all spatial scales. Across countries, low- and middle-income countries suffer more than high-income countries from air pollution issues (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 NO_2 concentrations and income in the United States, Hsiang, Oliva, and Walker (2017) show that, across metropolitan areas, the richest locations (cities) are more highly polluted. However, they find that within metropolitan areas, the poor are more highly exposed. The poor may live in more polluted neighborhoods or spend more time outdoors or in less well insulated buildings. Even if they are exposed to similar average levels of air pollution, poor households are likely to suffer more than wealthier households. This higher vulnerability stems from several factors, including lower access to health care, credit constraints that prevent defensive 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 policies tackling air pollution in Tbilisi, the capital of Georgia, that may, under identified conditions, benefit the poorest households and be progressive. The resulting evidence could support the engagement of the government of Georgia in committing to green investments in line with the Green Deal of the European Union. Internally, this project also contributes to Objective 3.3 of the current World Bank–Georgia Country Partnership Framework to enhance the 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 data on air pollution in Tbilisi. These include official monitoring stations, satellite imagery, and outdoor and indoor air pollution monitors installed for this project. The second section assesses whether poor people are more exposed to air pollution. This involves 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 relies on natural experiments to provide the first causal estimates of air pollution impacts on health, productivity, and economic outcomes in Tbilisi. Sections 5–7 use the project's surveys and air pollution data collected from indoor, outdoor, and portable monitors to identify causes and consequences at the individual level. The fifth section examines household-level drivers of indoor and outdoor air pollution and the differences in drivers by income and educational attainment. Section 6 uses household-level survey and air pollution data collected during the project to deepen an analysis of the distributional consequences of exposure to air pollution on health, economic outcomes, and cognitive performance. The last sections evaluate two of the many potential approaches to tackle air pollution: information sharing among individuals and nationwide carbon pricing. Section 8 leverages a randomized controlled trial (RCT) to assess the impact of sharing air pollution information on the exposure, protective behaviors, and welfare of individuals. Section 9 quantifies the benefits of carbon pricing in terms of air pollution reduction. The report concludes with a summary of policy recommendations.

CHAPTER 1

Measuring air pollution in Tbilisi

Throughout this report, air pollution is measured by the concentration of ground-level fine particulate matter ($PM_{2.5}$). The report relies on three main data sources, as follows:

- *Tbilisi's official air pollution monitors.*[1] Four high-quality monitors have been reporting on daily concentrations of $PM_{2.5}$ since August 2016. Their location is presented in map 1, panel b.
- *Reanalysis data combining station data, satellite measurements, and a chemical transport model* (van Donkelaar et al. 2021). This dataset provides modeled estimates of monthly $PM_{2.5}$ pollution from 1998 to 2020 on a 0.01 x 0.01 decimal degree grid. It has been used widely in the literature because of its global spatial coverage and long time series. It is used in the section relying on natural experiments to maximize the temporal and geographic range of the panel data constructed through the project.
- *Data collected by outdoor, indoor, and individual monitors acquired and installed for this project.* The project has dramatically increased the number of air pollution monitors in Tbilisi by providing for the installation of 41 outdoor monitors throughout the city. These monitors are represented in map 1, panel c, by the circles without borders. Monitors were installed in public schools or households in randomized districts selected through stratified randomization based 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 monitor measurements, the project also provided for the distribution of indoor air monitors among 145 randomly selected households for the randomized controlled trial (RCT) described in appendix B. Moreover, a total of 43 enumerators also measured air pollution throughout the city using individual monitors, while conducting the surveys.

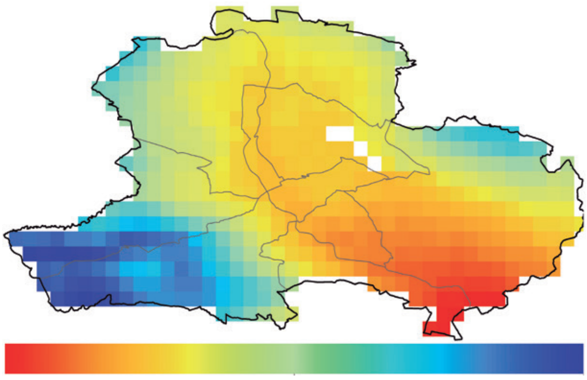
This report relies on each data source; the advantages and disadvantages of each are weighed. Although government data depend on a few monitoring stations, these are sophisticated and precise. They are used here to calibrate and validate the project's collected data. These monitors can also distinguish pollutants, which is necessary to deepen the understanding of mechanisms from source to effect. For the analysis that follows, the impact of specific pollutant concentrations have been explored whenever outcome data were collected near these monitors. The reanalysis from satellite imagery provides global monthly estimates of $PM_{2.5}$ concentrations. The main advantage of this dataset is its long time span and expansive geographic coverage, allowing balanced panel data to be built to facilitate natural experiments. However, the reanalysis is not calibrated to Tbilisi and is often less accurate than ground-based monitors. The data collected during this project rely on PurpleAir monitors. Although these monitors do not distinguish specific pollutants, they are reliable, represent good value for money, and allow collection at high time frequency because data are collected every minute. Their accuracy is sufficient for research studies (Burke et al. 2022; Krebs et al. 2021; Liang et al. 2021), and their relatively accessible price allowed the project to increase the spatial coverage of air pollution monitoring in Tbilisi significantly. These data are used to complement the other two sources and infer individual daily and weekly exposure among the surveyed households.

1 See Air Quality Portal, National Environmental Agency, Tbilisi, Georgia (accessed April 19, 2023), https://air.gov.ge/en/.

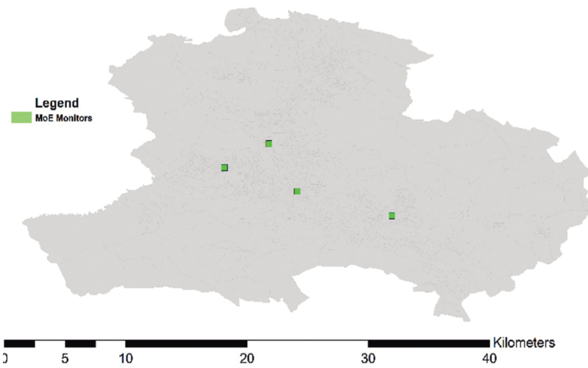
Map 1

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

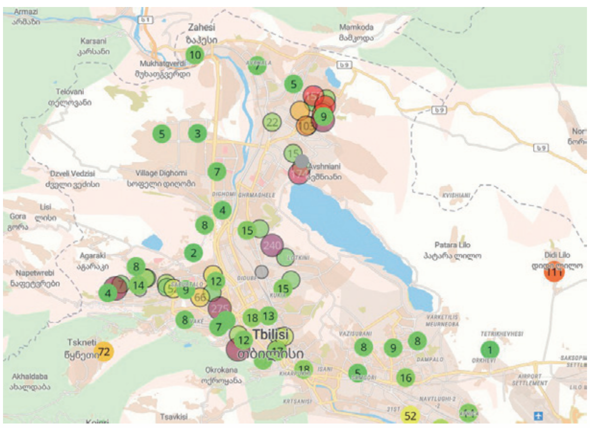
a. Satellite imagery reanalysis (monthly, 1998–2020)



b. NEA monitors (daily, 2016–22)



c. Project outdoor and indoor monitors (every minute, March–May 2023)



Sources: Panel a: van Donkelaar et al. 2021. Panel b: Air Quality Portal, National Environmental Agency, Tbilisi, Georgia (accessed April 19, 2023), https://air.gov.ge/en/. Panel c: Snapshot taken on March 27, 2023, Real-Time Map of data from installed PurpleAir monitors.

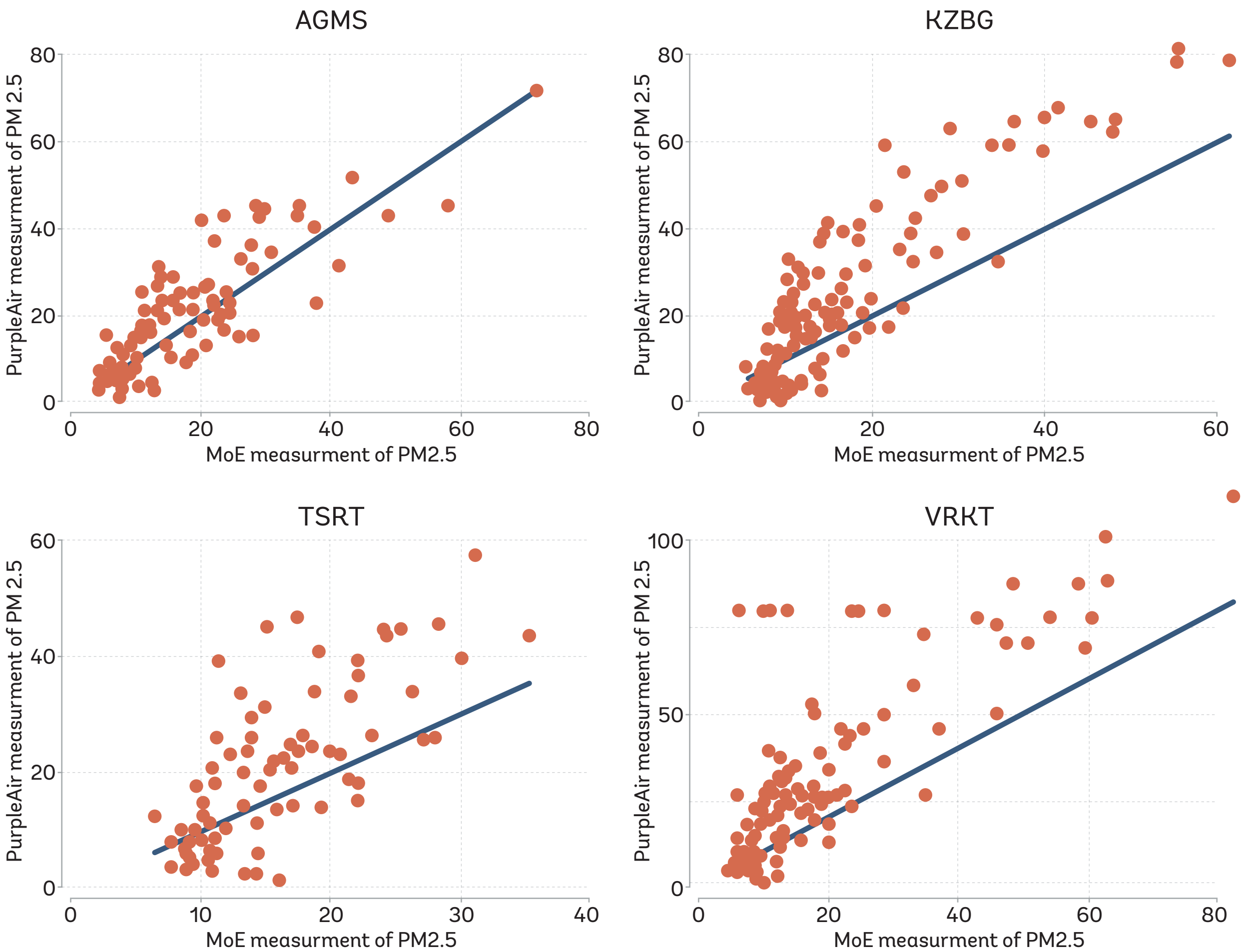
Note: Panel a represents a global estimate for November 2013. Panel c: Circles with black borders are indoor air pollution monitors, and circles without borders are outdoor monitors. NEA = National Environmental Agency.

The measurements of $PM_{2.5}$ concentrations by the PurpleAir monitors are highly correlated with those provided by the monitors of the National Environmental Agency (NEA). Figure 2 presents the correlation of the readings of monitor stations operated by NEA with the daily readings of the nearest PurpleAir monitors. Each panel corresponds to a different NEA monitor, named AGMS, KZBG, TSRT, and VRKT. The correlation between the NEA data and the PurpleAir data is between 0.71 and 0.9. The PurpleAir monitors slightly overestimate pollution levels relative to the NEA monitors, particularly at higher pollution levels (figure 2). The discrepancy is relatively small and may derive from the spatial mismatch between the locations of the monitors. Indeed, the NEA monitor with the closest corresponding PurpleAir monitor (AGMS) exhibits the smallest bias. This alignment between the measurements of the high-quality NEA monitors and the PurpleAir monitors confirms that these are reliable data sources.

Pollution levels are relatively stable throughout the year and within a week and are consistently higher than the recommended WHO air pollution thresholds. Satellite data were used to examine the trends by month over 1998–2020. Pollution is slightly elevated in the late summer and early fall relative to the rest of the year (figure 3, panel a). However, seasonal variation is limited; the full range only amounts to approximately 40 percent of the mean. Weather patterns may explain part of the slight summer increase. Wind speed, which disperses pollutants, is lower between July and November relative to the rest of the year, and precipitation, which reduces pollution by diluting or settling pollutants to the ground, decreases in June and July. This pattern also suggests a limited role for residential heating in the winter compared with other emission sources. Data from the installed PurpleAir monitors were used to examine how pollution levels vary over the days of the week from January 2023 to April 2023 (figure 3, panel b). Average daily pollution is relatively stable, around 25 μg/m^3, with no notable spikes on the weekends. However, the maximum and minimum daily values, represented in grey in figure 3, panel b, show that the variation in air pollution is greater on weekends. Air pollution levels reach nearly 300 μg/m^3 on Fridays and Saturdays in some locations. Average and peaks are higher than the WHO guideline for daily air pollution: average $PM_{2.5}$ exposure should not exceed 15 μg/m^3 for more than three or four days a year.

Figure 2

The measurements of the National Environmental Agency and PurpleAir are highly correlated



Source: Calculations based on data of Air Quality Portal, National Environmental Agency, Tbilisi, Georgia (accessed April 19, 2023), https://air.gov.ge/en/; and World Bank calculations based on data collected by installed PurpleAir monitors.
Note: Each panel represents the data from one of the four monitors operated in Tbilisi by the National Environmental Agency (NEA). The name of the monitor is at the top of each panel. The data reflect PM2.5 daily measurements from January 1, 2023, to April 30, 2023. For each monitor operated by the NEA, the average daily reading of the nearest PurpleAir monitor is used as a comparison.

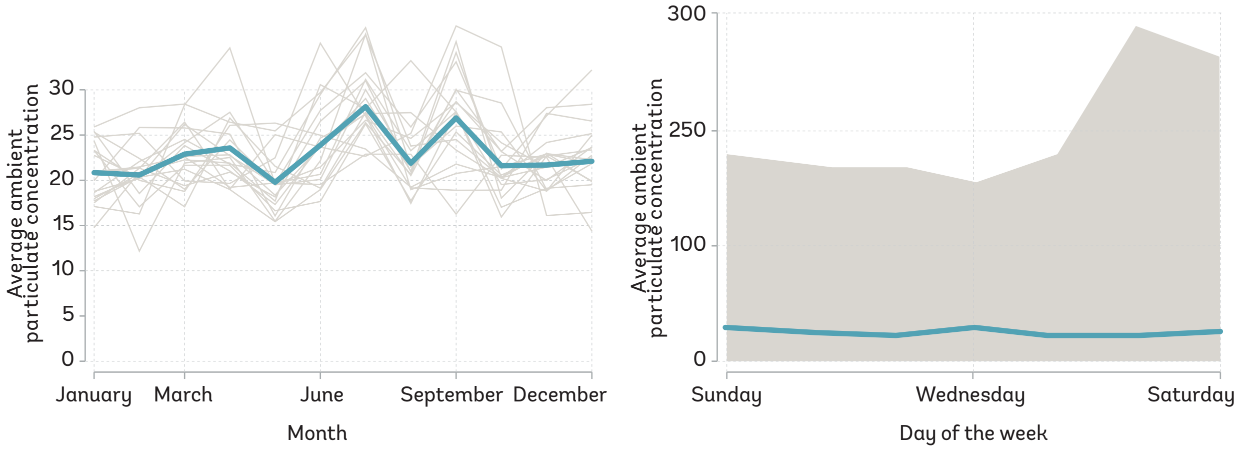
On average, indoor air pollution levels are higher than outdoor pollution levels and only 8.6 percent of households own an air purifier. Average indoor $PM_{2.5}$ concentrations measured during the survey were 33 μg/m³ higher than outdoor $PM_{2.5}$ concentrations. In addition to the data collected by enumerators during the survey, the project installed 145 indoor air monitors in randomly selected households. The resulting data show that indoor air pollution was higher on weekends than on weekdays, 53.7 vs. 50.6 μg/m³ (figure 4). While morning (6–12 am) pollution levels are relatively similar, weekend afternoon (12–6 pm) and after midnight pollution levels are higher. This suggests that some household activities performed in the evening and on weekends could generate an increase in indoor air pollution. The survey results also show that the adaptive capacity is low in Tbilisi, where only 8.6 percent of households own an air purifier compared with 25 percent in the United States (Daily 2020). Sections 6 and 7 explore other potential sources of indoor air pollution and the barriers to adaptation.

Figure 3

Monthly and weekly trends in outdoor air pollution in Tbilisi

a. Monthly pollution trends, 1998–2020

b. Weekly trends, January 2023–April 2023



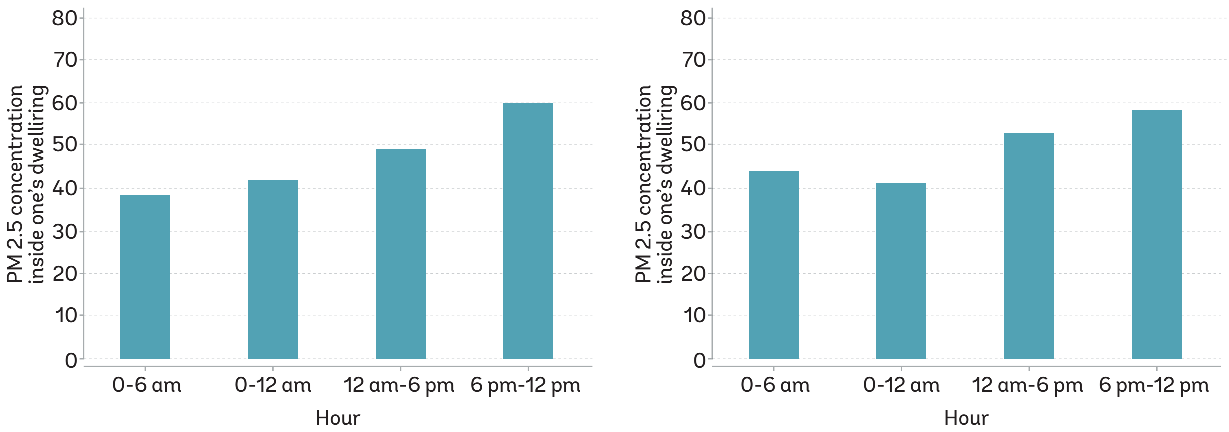
Sources: Panel a: van Donkelaar et al. 2021. Panel b: World Bank calculations based on data collected by installed PurpleAir monitors.
Note: Panel a: Monthly average pollution for the full sample is shown in blue. Grey lines indicate pollution by month in each year in 2000–20. Panel b: Daily averages in January 2023–April 2023. The grey area indicates the maximum and minimum of the daily average across all monitors in Tbilisi over the period.

Figure 4

Within-day trends in indoor air pollution in Tbilisi during weekdays and week-ends

a. Variations in air pollution, weekdays

b. Variations in air pollution, weekends



Source: World Bank calculations based on data collected by installed PurpleAir monitors.
Note: The figure shows the data derived from indoor monitors installed in randomly selected households during the first survey.

CHAPTER 2

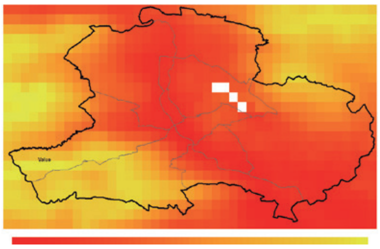
The spatial distribution of air pollution and wealth in Tbilisi

Pollution is concentrated in the city center, which is also lowest in elevation and home to the wealthiest individuals. Map 2, panel a, shows that pollution is greater in the center, likely because of the low elevation, the weather patterns, and the geography of urban development. The center is at a lower altitude than the suburbs, and air pollution is trapped by the surrounding high hills (map 2, panel b). Wealthier households are also disproportionately located in the center because of residential sorting (map 2, panel c). As a result, pollution is strongly correlated with wealth, negatively correlated with elevation, and negatively correlated with distance from the city center. The correlation with wealth disappears once elevation and distance from the center are included as control variables (map 2, panel d). This suggests that these two factors may drive the relationship between wealth and pollution at the district level.

Map 2

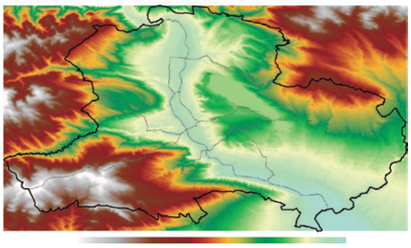
In Tbilisi, PM2.5 concentration is negatively correlated with elevation and positively correlated with wealth

a. Pollution is concentrated in the center (red = highly polluted)



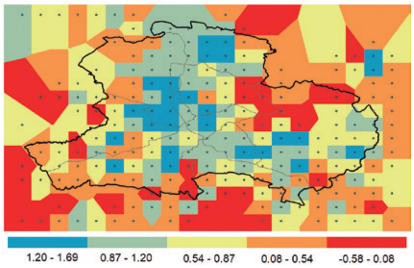
Average PM2.5 concentration (ug/m3)

b. Elevation is higher in the suburbs (brown = higher)



Elevation in meters

c. Wealthier people tend to live in the center (blue = wealthier)



Relative wealth index

d. Positive correlation between PM2.5 concentration and the relative wealth index

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

Sources: Panel a: World Bank calculations. Panel b: data of ASTER GDEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer, Global Digital Elevation Model) version 3, Earthdata, National Aeronautics and Space Administration, Washington, DC, https://search.earthdata.nasa.gov/. Panels c and d: for wealth, see Chi et al. 2022.
Note: Panel a shows the average level of pollution across Tbilisi averaged over the full sample in 1998–2018. White indicates cells for which there is no estimate. Pollution is measured in μg/m³. Panel b plots the elevation of the city measured in meters. Panel c plots the grid-cell level estimates of wealth, a relative wealth index. 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 PM2.5 concentration in the grid-cell for which the relative wealth index is observed. All regressions include month and year FE. CBD = central business district. N = number of observations. *p < .10 ** p < .05 *** p < .01

The positive correlation between outdoor air pollution and wealth holds at the neighborhood level, but at the individual level, the wealthiest households are located in buildings that are less exposed to outdoor air pollution. The project has involved a survey of 880 households and the measurement of outdoor air pollution levels using 41 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 results outlined above hold at the neighborhood level. Outdoor air pollution is greatest in neighborhoods in which the wealthiest households are located (figure 5, panel a), likely in the city center. However, this relationship changes if one considers the results of measurements of outdoor air pollution by enumerators using portable monitors outside the dwellings following the survey. Despite their residence in the most highly polluted neighborhoods, the wealthiest 8 percent of the population reside in dwellings in places in which instantaneous measurement of outdoor pollution is lower relative to the places of the dwellings of other income groups (figure 5, panel b). While these instantaneous measurements may not be accurate reflections of long-term average exposure levels this suggests that two competing drivers of urban sorting are at play. Wealthier households are located in more central, more highly polluted neighborhoods. However, within the polluted neighborhoods, the wealthier individuals may select dwellings less affected by outdoor air pollution. This selection may be based on proxies of air pollution, such as living close to parks or avoiding dwellings next to busy streets. This sorting is consistent with results showing that real estate values drop as air pollution rises, indicating that clean air is a valued amenity. This is consistent with the findings of Hsiang, Oliva, and Walker (2017) showing that wealthy urban areas are more exposed to air pollution, but that, within these areas, the poorer households are more highly exposed.

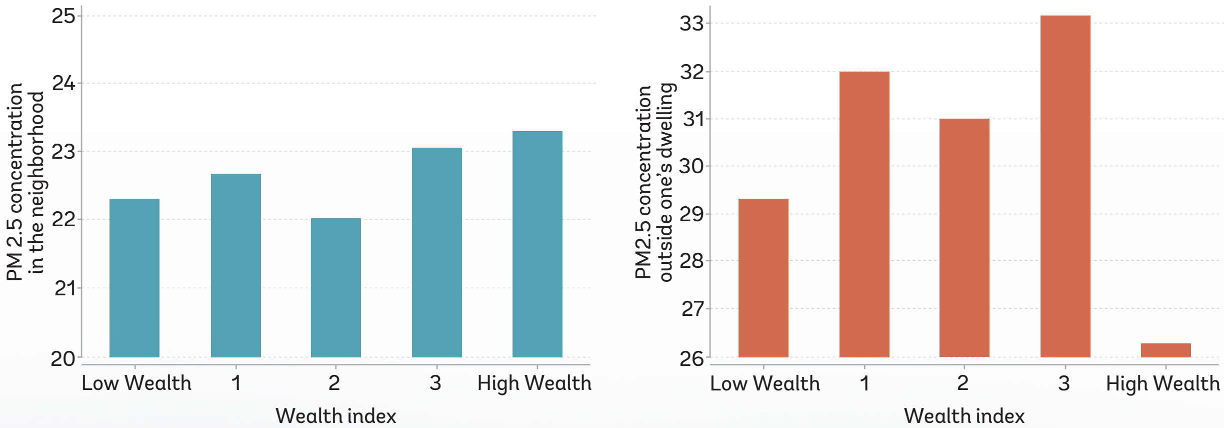
Poorer households are more exposed to indoor air pollution and more vulnerable to air pollution because they are less likely to own protection devices. Project results based on an exploration of differences by wealth status suggest that poor households are disproportionately exposed to indoor air pollution. The average indoor air pollution concentration in the dwellings of these households during the survey was 68 $\mu g/m^3$, compared with 60 $\mu g/m^3$ in high-wealth households. Poor households are also less likely to own devices to mitigate air pollution. Only 4 percent of low-wealth households own an air purifier, compared with 16 percent of high-wealth households.

Figure 5

Wealthier neighborhoods are associated with higher air pollution, but, within these neighborhoods, the wealthiest individuals live in buildings characterized by lower instantaneous outdoor air pollution

a. The wealthiest households are in neighborhoods with the highest outdoor air pollution

b. Outdoor air pollution is lower outside the housing of the wealthiest individuals



Sources: World Bank calculations based on project survey data and authors' calculations based on data collected by installed PurpleAir monitors.

Note: Panel a: outdoor air pollution levels are the average measured from January 2023 to April 2023. Panel b: outdoor air pollution was measured by project enumerators outside the interviewee dwellings at the time of the survey.

CHAPTER 3

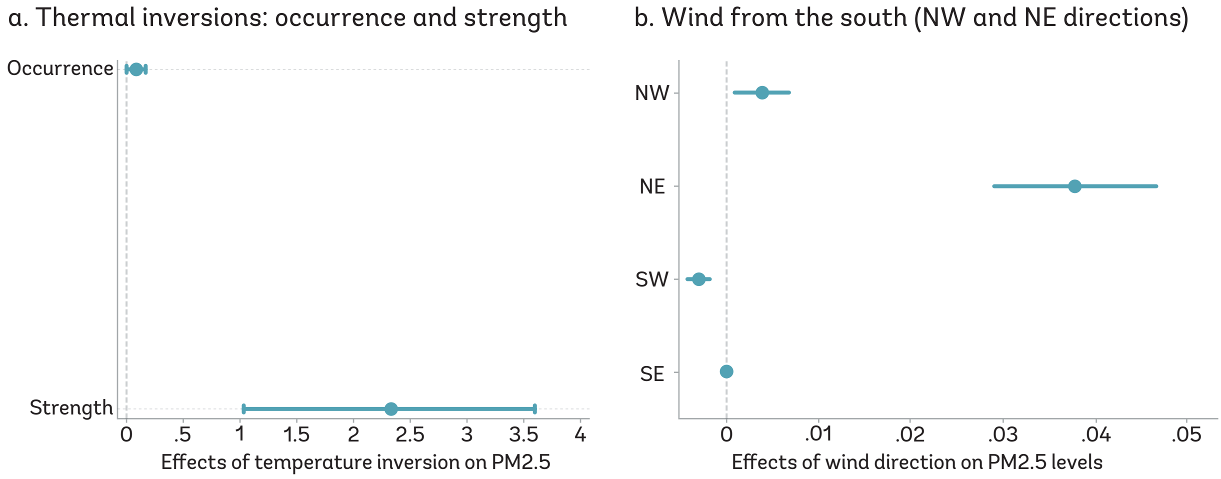
Sources of variation in outdoor air pollution in Tbilisi

This section sheds light on the influence of weather on the distribution of outdoor air pollution in Tbilisi (Lagidze et al., 2015). It also examines two of the main sources of air pollution in the city: traffic and industrial emissions (Davitashvili, 2013; IQAir, 2024)[2].

Thermal inversions and winds from the south raise $PM_{2.5}$ concentrations in Tbilisi. On a typical day, the air at the surface is hotter than the upper atmosphere. As a result, polluted surface air moves up before cooling and redescending, 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 because of meteorological conditions. In this situation, the cold, polluted air at the surface is trapped, resulting in higher air pollution. On average, thermal inversions occur three times per month per district and greatly boost monthly

Figure 6

Thermal inversions and wind from the south increase PM2.5 concentrations in Tbilisi



Sources: World Bank calculations based on ERA5 (ECMWF Reanalysis v5), Copernicus Climate Change Service, European Centre for Medium-Range Weather Forecasts, Reading, UK, https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5#:~:text=ERA5%20is%20produced%20by%20the,to%20a%20height%20of%2080km; ERA5 Hourly Data on Single Levels from 1940 to Present, Climate Data Store, Copernicus Climate Change Service, European Centre for Medium-Range Weather Forecasts, Reading, UK, https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview; van Donkelaar et al. 2021.

Note: Thermal inversion occurs when the air temperature rises with height in layers of the atmosphere. Because the warm air is higher, the air under the inversion cannot escape because it is cooler. As a result, pollutants become 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 if the wind vector is in this direction. For instance, Northeast (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 standard errors are clustered at the district level. The method is described in Baquié et al. (2023).

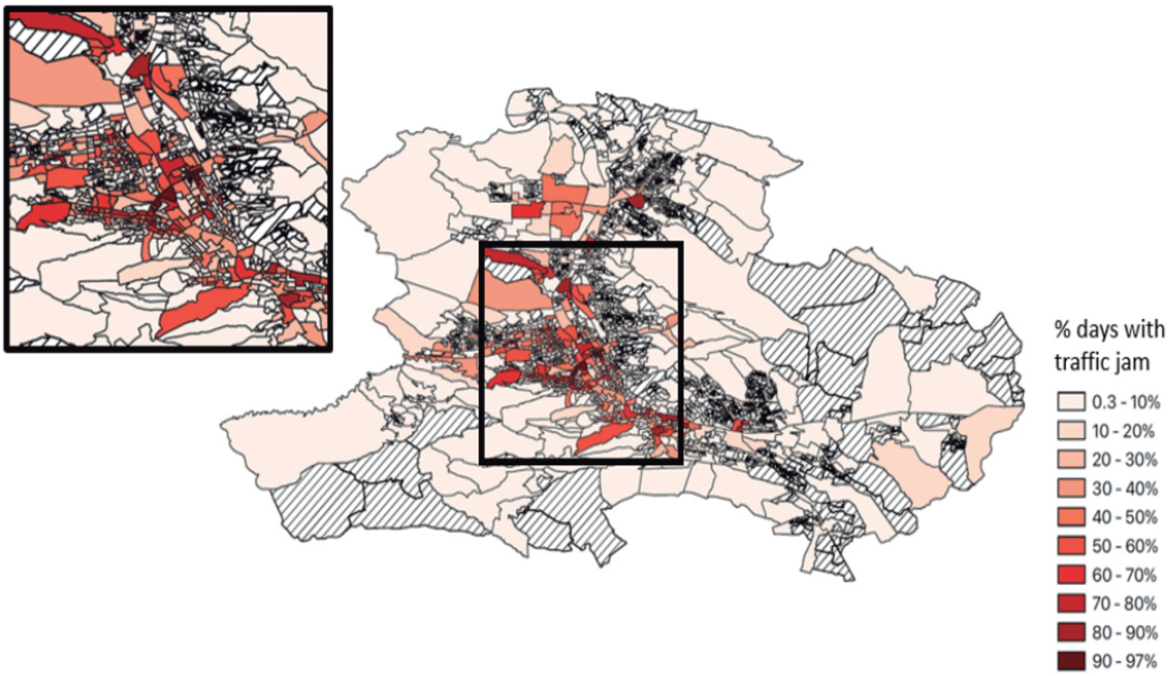
2 Other sources of outdoor air pollution mentioned in the literature, but not investigated in the context of this report include agriculture and the energy sector (Lagidze et al. 2015).

$PM_{2.5}$ concentrations (figure 6, panel a). The higher the temperature gradient (that is, the stronger the inversion), the higher the rise in the $PM_{2.5}$. Air pollution also increases when the wind blows from the south (figure 6, panel b). This is likely caused by emitting industries to the southeast and the fact that many districts are located to the northeast of high traffic areas. The results highlight the need for adaptation to mitigate the effects when atmospheric conditions are expected to augment air pollution. Wind patterns and thermal inversions are exogenous sources of variation in air pollution that are used in the project as instruments to study the impact of air pollution on health and economic outcomes (Chen et al. 2018; Deryugina et al. 2016; see section 4).

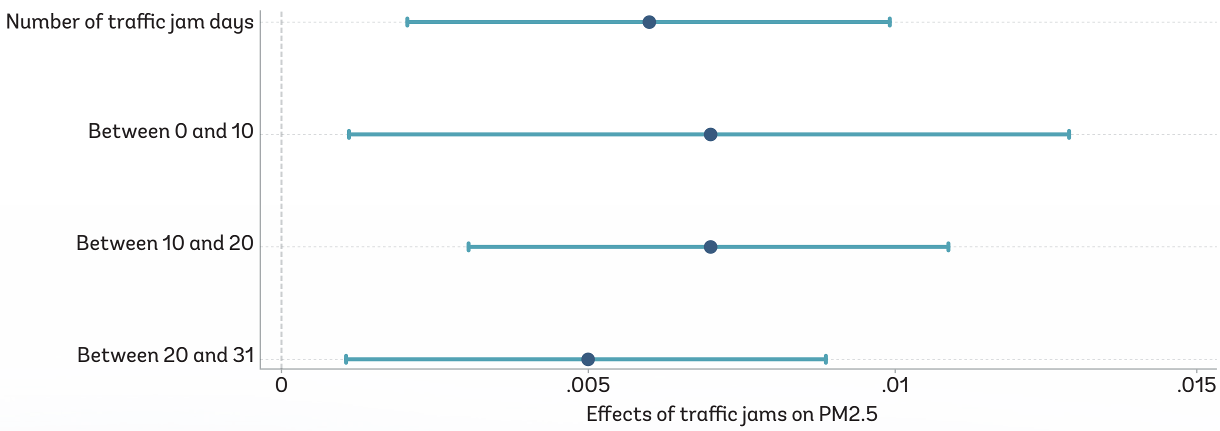
Map 3

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 a district's monthly PM2.5 concentration by 0.006 μg/m³



Sources: World Bank calculations based on ERA5 (ECMWF Reanalysis v5), Copernicus Climate Change Service, European Centre for Medium-Range Weather Forecasts, Reading, UK, https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5#:~:text=ERA5%20is%20produced%20by%20the,to%20a%20height%20of%2080km; van Donkelaar et al. 2021; Traffic Data, Mapbox, San Francisco, https://www.mapbox.com/traffic-data.
Note: A traffic jam in a district is defined as an observed traffic speed lower than 5 km/h on one of the district's roads at any point during the day. Robust standard errors are clustered at the district level. The data and method are described in Baquié et al. (2023).

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 (2024), but quantitative estimates of the relationship are scarce. The project relies on Mapbox for daily road traffic data to help quantify the impact on air pollution in Tbilisi.[3] Mapbox provides daily speed and delay times for all Tbilisi roads. In the project, each road segment is matched to its district, and traffic intensity is quantified by the number of days with traffic jams in each district in each month. A traffic jam in a district is defined as an observed traffic speed lower than 5 km/h on one of the district's roads at any point during the day. Map 3, panel a, shows that congestion is an important issue in the city center. In this area, most districts experience traffic jam days during more than half the year, and some experience traffic jams on 90 percent of all days.

Traffic congestion significantly increases air pollution. The analysis shows that each additional day with a traffic jam raises monthly air pollution by 0.006 μg/m³ in a district (map 3, panel b). As in most districts in the city center, 10 traffic jam days per month increase the $PM_{2.5}$ concentration by 0.06 μg/m³. The relatively small magnitude of this estimate is likely due to the spatial averaging of air pollution. This analysis relies on a districtwide measure of the air pollution generated by a traffic jam, but only a small part of the district is impacted, which implies much larger increases in pollution in areas near the traffic jam. The relationship that is documented is significant and linear; the marginal effect of one traffic jam day on air pollution is constant and does not depend on the cumulative number of traffic jam days in a month. Reducing the number of traffic jam days would therefore yield the same decrease in $PM_{2.5}$ concentration no matter the location. However, because impacts on health worsen with higher $PM_{2.5}$ concentrations, a policy tackling traffic in highly congested areas would likely yield health benefits. Traffic management would also benefit areas downwind of traffic hotspots. Indeed, wind decreases the concentration of pollutants in heavy traffic areas, but displaces them to downwind districts.

Policies to reduce traffic, such as regulating car imports and accelerating the implementation of reforms in technical inspections, could decrease outdoor air pollution in Tbilisi. Some countries have significantly improved health outcomes by lowering traffic-related air pollution. In India, the regulation on mandated catalytic converters substantially decreased $PM_{2.5}$ and NO_2 concentrations and infant mortality rates (Greenstone and Hanna 2014). Recent work also suggests that exposure to road traffic pollution is highly localized but also damaging to health (Bassi et al. 2022). To reduce traffic emissions in Georgia, the government is considering introducing a mandatory Euro 5 emissions standard thereby limiting imports of old cars that would not meet the standard (Press Service 2023). In 2018, the government launched the nationwide vehicle periodic technical inspection reform.[4] 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 ensuring that these reforms do not have disproportionate income effects on Tbilisi inhabitants and the poorest. There has been progress on this front in Tbilisi in the last five years, including the creation of bus lanes and pedestrian crossings, for instance, but more needs to be done.

Emissions from industrial sites located in southeast Tbilisi negatively affect air pollution. Data on industrial emissions (Ministry of Environmental Protection and Agriculture of Georgia, 2023) are used to proxy air pollution emissions through reported greenhouse gas (GHG) emissions.[5] Although the correlation between the emissions of $PM_{2.5}$ pollutants and GHGs is not perfect, they share many 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. Map 4, panel b, shows the location of all industrial GHG emitters. The most important sources are in southeast Tbilisi, where $PM_{2.5}$ concentrations and variations are also the greatest

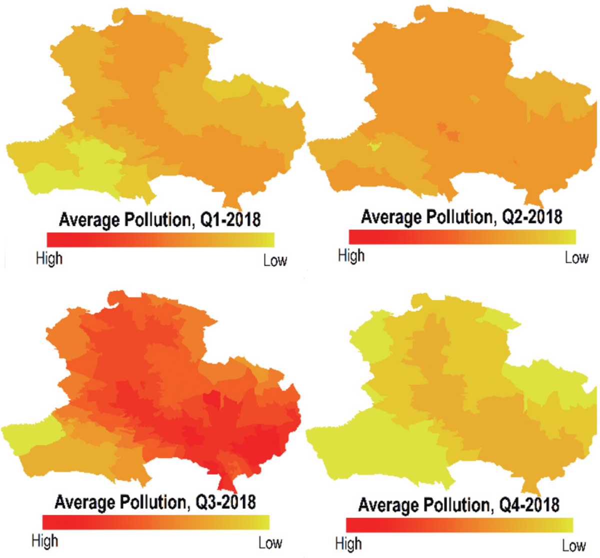
3 See Traffic Data, Mapbox, San Francisco (accessed: May 8, 2023), https://www.mapbox.com/traffic-data.
4 Periodic Technical Inspection of Vehicles (web page), Ministry of Economy and Sustainable Development of Georgia, Tbilisi, Georgia (accessed May 23, 2023), https://www.economy.ge/?page=economy&s=126&lang=en.
5 For the data, see Air Quality Portal, National Environmental Agency (accessed April 19, 2023), Tbilisi, Georgia, https://air.gov.ge/en/.

(map 4, panel a). Map 4, panel c, illustrates that emissions from industrial sites significantly affect air quality in the districts where they are located. An industrial site emitting 10,000 tons of GHG per year in a district increases monthly $PM_{2.5}$ concentrations in the district by 0.1 µg/m³. In Tbilisi, two industrial sites reported GHG emissions at more than 10,000 tons in 2016–21. This suggests that industrial sites with high GHG emissions raise air pollution levels in a district as much as recurring traffic jams of more than 20 days per month. Dust emissions also significantly increase air pollution, and Tbilisi hosts two industrial sites that emitted more than 100 tons of dust in 2016–21. These emissions increased monthly $PM_{2.5}$ concentrations in the respective districts by 0.26 µg/m³. Tackling sources of dust is therefore also critical to the effort to lower air pollution in the capital.

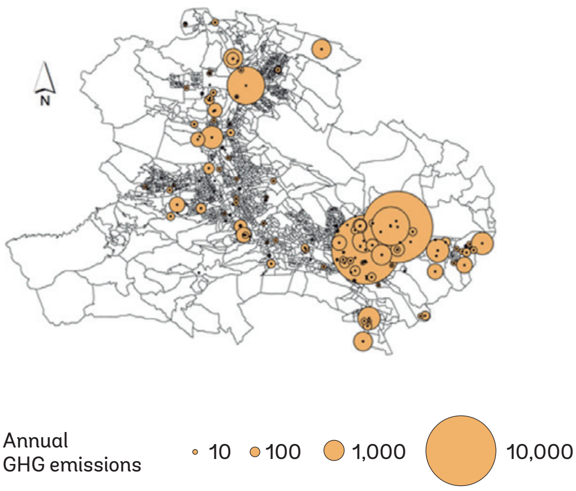
Map 4

Air pollution and seasonal variations are greatest in areas where industrial site emissions are also greatest, Tbilisi

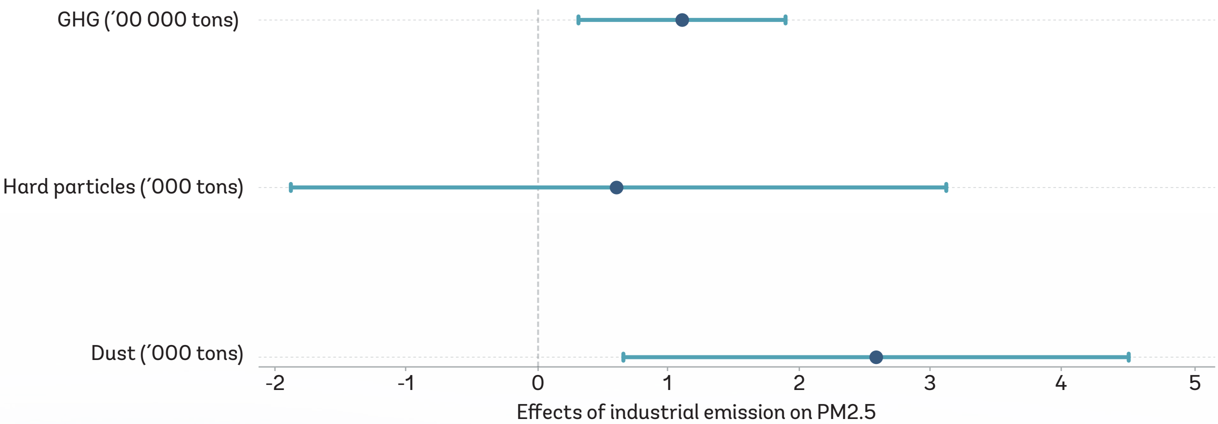
a. Pollution is greatest in southeast Tbilisi (red)



b. Industrial site emissions in southeast Tbilisi (larger circles)



c. Industrial site emissions increase air pollution in Tbilisi

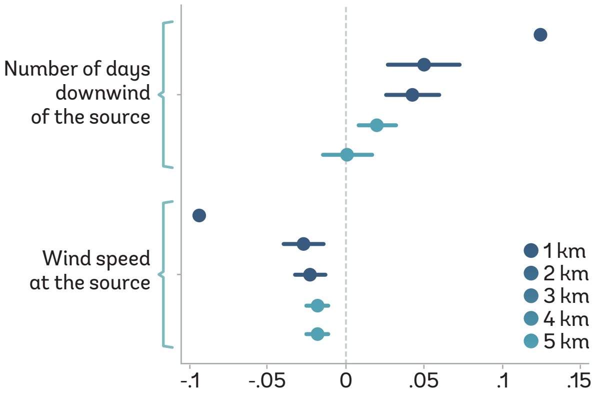


Sources: World Bank calculations based on data of Air Quality Portal, National Environmental Agency (accessed April 19, 2023), Tbilisi, Georgia, https://air.gov.ge/en/; van Donkelaar et al. 2021.
Note: Panel a: average pollution levels across Tbilisi census blocks in each quarter of 2018. 2018 data were used as an example of a recent pre-COVID year. Pollution is measured in µg/m³. Data on emissions are in tons per year and cover entities based in Tbilisi in 2016–21. Panel b: the size of the circles represents the 2018 total GHG emissions emitted by industrial activities located at the centroids of the circles. The data and method are described in Baquié et al. (2023).

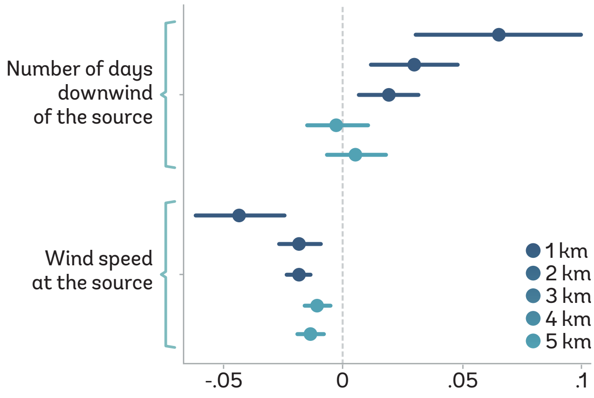
Figure 7

Emissions from industrial sites significantly increase air pollution in downwind districts

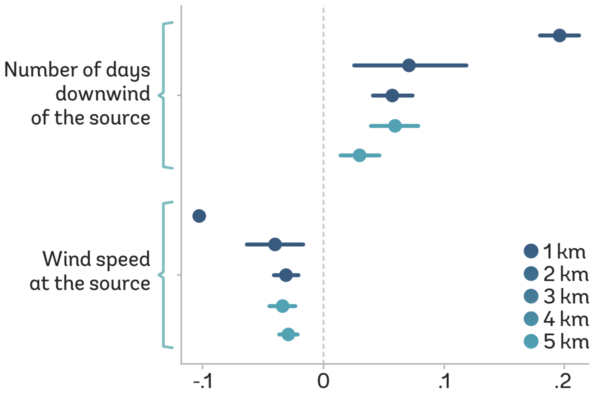
a. Impact downwind of the most polluting site (metallurgical production)



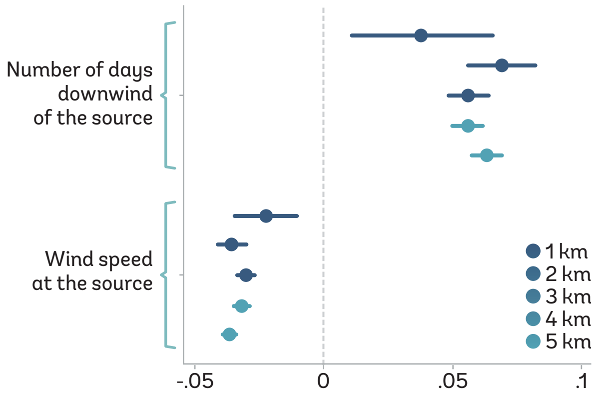
b. Impact downwind of the second-most polluting site (manufacture of construction materials)



c. Impact downwind of the third-most polluting site (food production)



d. Impact downwind of the fourth-most polluting site (food production)



Sources: World Bank calculations based on data of Air Quality Portal, National Environmental Agency (accessed April 19, 2023), Tbilisi, Georgia, https://air.gov.ge/en/; ERA5 (ECMWF Reanalysis v5), Copernicus Climate Change Service, European Centre for Medium-Range Weather Forecasts, Reading, UK, https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5#:~:text=ERA5%20is%20produced%20by%20the,to%20a%20height%20of%2080km; van Donkelaar et al. 2021.
Note: Each panel corresponds to a different emission source among the biggest emitters of GHG emissions in Tbilisi. The dependent variable is monthly PM2.5 concentration measured in μg/m³ using data on wind direction, wind speed, temperature, and precipitation. The main independent variables in the regressions are a dummy for the location downwind of the source and measures of wind speed at the source. The regressions are restricted to districts surrounding the source and within 1, 2, 3, 4, and 5 kilometers. 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 1 kilometer of the source because it is multicollinear with the wind speed at the source. Standard errors are clustered at the district level. The data and method are described in Baquié et al. (2023).

Pollution from industrial site emissions severely affects air quality in downwind districts. The most important industrial sources of GHGs in Tbilisi are sites for metallurgical production, the manufacture of construction materials, and food production. In the following analysis, downwind refers to an alignment between the wind at a source and the direction of the district under consideration. Figure 7 shows the impact of GHG emissions on downwind districts by source (panel a) and distance (blue shading). Within 1 kilometer of a source, the $PM_{2.5}$ concentration increases by up to 0.2 μg/m³ on average with each additional downwind day (figure 7, panel c). Among districts more distant from an industrial site, the increase is about 0.05 μg/m³ per downwind day. The impact of industrial emissions also decreases as distance increases from the source, but the effects on air pollution are still significant 3 to 5 kilometers away, suggesting that the effect is widespread. The strong effect is mitigated by wind speed at the source because strong winds disperse emissions nonlinearly. These results represent lower bounds because of measurement error. Indeed, wind patterns farther away from a source also influence whether a district receives air molecules emitted by the source. Additional work with atmospheric models would be needed to calculate the exact location of downwind districts and reduce measurement error.

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 power plants in Germany decreased SO_2 concentration, which lowered the infant mortality rate. Similarly, Lavaine and Neidell (2013) provide evidence that labor strikes in French oil refineries decreased SO_2 concentrations in surrounding areas and increased birthweight and the gestational age of newborns. Under the European Union–Georgia Association Agreement, Georgia has committed to aligning its regulations on industrial pollution with the relevant European Union legislation (2010/75/European Union Directive on Industrial Emission). In this process, the authorities have submitted to 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 this is not practicable, to reduce and control emissions, as well as prevent the generation of waste. The draft law stipulates the obligation to possess an integrated permit for industrial activities that have the potential for significant environmental and human health effects. According to the draft law, an integrated environmental system and a compliance monitoring and control mechanism should be introduced in 2026. Given the substantial impact of industrial emissions on air pollution, enforcing this law and accelerating its implementation are essential to curbing industrial emissions.

CHAPTER 4

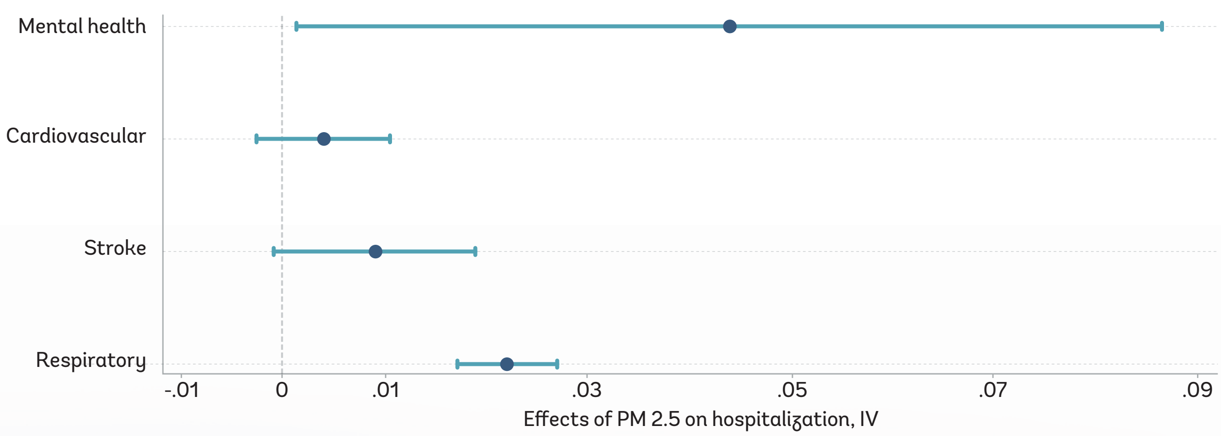
The impacts of outdoor air pollution in Tbilisi

This section presents causal estimates of the impacts of air pollution and assesses their heterogeneity with income. Following the literature, the analysis relies on an instrumental variable strategy to isolate exogenous variations in air pollution. Thermal inversions and wind patterns are relevant and exogenous instruments for air pollution. The method differs from another widespread method of estimating the effects of air pollution on health by combining measures of exposure with relative risk functions to estimate the mortality and morbidity attributable to air pollution (WHO 2016). The method is agnostic about the form and intensity of the exposure-health relationship and focuses on the impact of short-term variations in air pollution for which causal estimates can be recovered. It can be used to calibrate the relative risk functions in the latter method or health capital models for assessing long-term impacts. Similarly, the results here speak to the short-term impacts on real estate values, but could be used to calibrate urban models for estimating the level of air pollution to establish the level of clean air as an amenity.

In Tbilisi, air pollution significantly increases hospitalizations for mental health problems and respiratory diseases. The analysis combines data on daily hospital discharges with air pollution data to build monthly panel data on air pollution levels at each hospital location. Figure 8 shows the coefficients in the instrumented regressions of hospitalizations by type on average monthly $PM_{2.5}$ concentrations at the hospital locations.

Figure 8

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



Sources: World Bank calculations based on data on hospitalizations from NCDC (National Center for Disease Control and Public Health, Georgia), Global Health Data Exchange, Institute for Health Metrics and Evaluation, University of Washington, Seattle, https://ghdx.healthdata.org/organizations/national-center-disease-control-and-public-health-georgia and data on air pollution from van Donkelaar et al. (2021).
Note: PM2.5 concentration 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. The data and method are described in Baquié et al. (2023).

In Tbilisi, a 1 μg/m³ increase in $PM_{2.5}$ concentration increases hospitalizations for respiratory diseases by up to 2.2 percent and hospitalizations for mental health by up to 4.4 percent. The results on stroke-related hospitalizations are less accurate, but the point estimate indicates a potential rise by up to 0.9 percent. 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 because the analysis uses the hospital location to calculate $PM_{2.5}$ exposure, not the patient addresses. The high magnitude of the effects is in line with the adverse health consequences found in other countries where air pollution adversely impacts infant mortality (Barrows, Garg, and Jha 2019; Greenstone and Hanna 2014), adult deaths (Heft-Neal et al. 2018), life expectancy (Ebenstein et al. 2017), and mental health (Chen et al. 2018).[6]

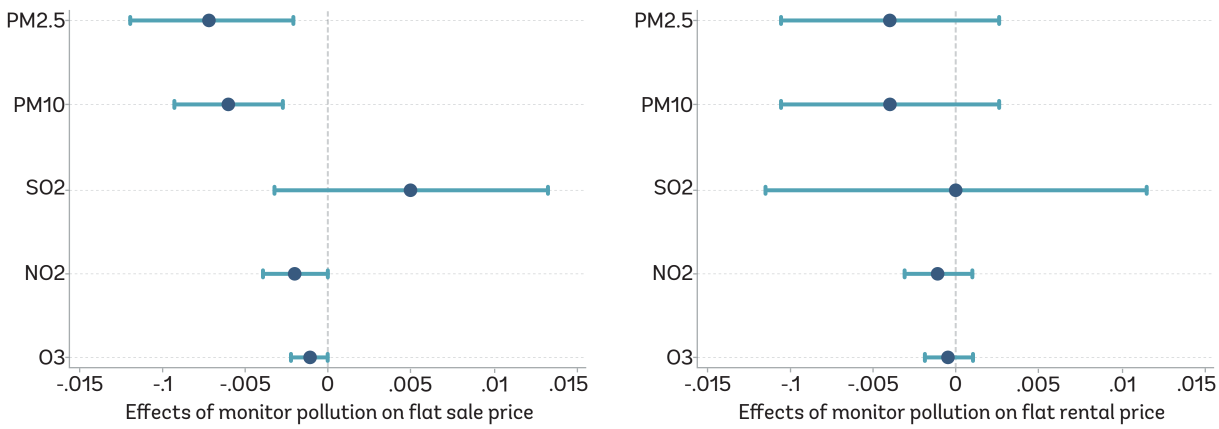
Air pollution negatively affects real estate values in Tbilisi, and clean air is an important amenity. The analysis investigates the impact of air pollution on real estate values by using the complete universe of daily Tbilisi sales and rental advertisements posted on a major real estate website, LIVO, between January 2019 and June 2021.[7] LIVO is one of the main real estate agencies in Georgia. The monthly data include 30,000–60,000 notices (depending on the month) on real estate listings for sale, rent, or exchange in Georgia. Based on these notices and data from the NEA monitors, one may conclude that both $PM_{2.5}$ and PM_{10} reduce apartment sales prices (figure 9). This is consistent with evidence from the United States, where neighborhoods within 2 miles of power plants—major sources of air pollution—experienced a 3 percent to 7 percent decrease in housing values and rents (Davis 2011). However, these real estate data only cover a short time period in which pollution may have been more salient for buyers. Further analysis with more comprehensive data should be carried out because it may reveal a lower impact of pollution on buyer behavior.

Figure 9

Increases in $PM_{2.5}$, PM_{10}, NO_2 and O_3 concentrations decrease apartment sale and rental prices in Tbilisi

a. Impact on apartment sale prices

b. Impact on apartment rental prices



Sources: World Bank calculations based on data of Air Quality Portal, National Environmental Agency (accessed April 19, 2023), Tbilisi, Georgia, https://air.gov.ge/en/; LIVO (Real Estate Website, Georgia), https://livo.ge/ [In Georgian].
Note: The LIVO advertisements used involve properties with an address within five miles of an NEA monitor. Monthly data on real estate listings for sale, rent, or exchange in Georgia between January 2019 and June 2021 (30 months) are included. The number of observations ranges from 30,000 to 60,000 depending on the month. The apartment sales price (panel a) or apartment rental price (panel b) is regressed separately on each air pollutant, and the estimated coefficients and 95% confidence intervals are reported in the figures. The regressions include year-month and house/apartment fixed effects. This means any variations arise from the 138,303 properties (out of 165,533) on which there were at least two ads during the sample period. The data and method are described in Baquié et al. (2023). The ordinary least squares regression likely underestimates the impact because of omitted variables, such as economic activity that increases both prices and air pollution.

6 Although, because of problems in data availability, the focus here is on hospitalization risk rather than mortality risk, the substantial mortality effects of pollution exposure are well documented in the literature and are likely to represent a significant portion of the welfare burden of pollution exposure. Long-term exposure may be particularly harmful in terms of mortality (Deryugina and Reif 2023).
7 See LIVO (Real Estate Website, Georgia), https://livo.ge/. [In Georgian.]

The greatest effect on real estate values stems from $PM_{2.5}$, PM_{10}, NO_2, and O_3 pollutants. PM_{10} and $PM_{2.5}$ 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, industry, power plants, and vehicles. Figure 9 shows that NO_2 and O_3 also have an adverse effect on apartment prices, particularly apartment sales prices. A 1 μg/m^3 increase in NO_2 decreases average apartment sales by 0.2 percent. This drop in real estate prices reflects the higher value attached by Tbilisi inhabitants to an environment free of NO_2 and O_3 pollution. Once in the atmosphere, capturing these pollutants is impossible. Policies therefore need to tackle NO_2 and O_3 emissions to boost the welfare of Tbilisi residents. Nitrogen dioxide (NO_2) forms when fossil fuel is burned at high temperatures, which is common in vehicles and power plants. Cars, power plants, and some industrial processes also emit ground-level ozone (O_3). Policies tackling traffic and industrial emissions, such as the ones discussed in section 3, are likely to be reflected in real estate values because of the importance of clean air as an amenity.

In Tbilisi, higher air pollution is associated with lower productivity (measured by examination performance), although the association is not significant. Reasearch shows that air pollution has adverse effects on cognition and productivity, including short-term memory and mathematical reasoning (La Nauze and Severnini 2021; Qiu, Yang, and Lai 2019; Zhang, Chen, and Zhang 2018). To assess this relationship, the analysis included the measurement of student performance using student grades on the national unified entry examinations. The data span 2011 to 2017 and cover 29 subjects and 338 examination centers. Individual grades are matched with the air pollution level measured in the census block of the examination center in the month preceding the examination (van Donkelaar et al. 2021). Annex D, figure D.2 reports on the estimates, according to which, on average, a 1 percent increase in monthly $PM_{2.5}$ concentrations decreases the test scores by 0.12 percent. This effect is consistent with existing work on air pollution and examination scores, but the estimates are not statistically significant. The results also suggest that the magnitude of the impact may differ across subjects. Mathematics, physics, and geography may be the most affected. The results likely represent a lower bound of the true impact of air pollution on test scores because of the measurement error linked with the assumption that students take the national unified entry examinations in their schools. Moreover, the effect of air pollution on the examination day may be greater than the one observed in the preceding month. Nonetheless, the negative relationship between air pollution and student test scores suggests a potential impact on cognition and, in turn, productivity, even though the estimates are imprecise.

The high impact of outdoor air pollution on health, real estate values, and test scores in Tbilisi highlights the need to regulate important sources of emissions. Policies aimed at 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 greater among the most vulnerable, including children, the elderly, pregnant women, people with weakened health, and the poorest. Indeed, air pollution causes illness, but also worsens the effects of other diseases, such as influenza (Graff Zivin et al. 2020). Policies tackling air pollution are likely to benefit the most vulnerable. However, some policies may also affect the incomes of the poor disproportionately by, for example, raising car prices. Ex ante policy evaluation should be conducted case by case to assess the progressivity of the policies.

CHAPTER 5

The benefits of carbon pricing: reductions in outdoor air pollution

The government of Georgia officially approved the Paris Agreement in May 2017, showcasing a firm commitment to worldwide climate action. This dedication has been consistent with the government's active and influential participation in subsequent meetings of the Conference of the Parties, emphasizing the government's determination to tackle climate challenges nationally and globally. Meanwhile, the European Union and the governments of neighboring countries have implemented carbon pricing measures, including carbon taxes and emissions trading schemes (ETSs), as part of their efforts to meet emissions reduction targets.

Climate mitigation policies, such as carbon pricing, have the potential to reduce air pollution. Section 3 demonstrates the substantial impact of vehicle traffic and industrial emissions on outdoor air pollution in Tbilisi. Policies aimed at reducing emissions from these sources are likely to yield considerable benefits in terms of both public health and economic outcomes. This section explores the potential of carbon pricing, a climate mitigation policy designed to curtail GHG emissions. It shows that such policies are likely not only to reduce GHG emissions, but also to improve air quality throughout Georgia, yielding significant welfare benefits.

Carbon pricing improves air quality by creating incentives for transitioning to cleaner energy sources and adopting more sustainable practices. The analysis covers the effects of three distinct carbon pricing policies:

- *A carbon tax that sets the price of carbon at US$25 per metric ton of CO_2 equivalent by 2030:* This policy aligns with the proposed emissions reduction target for low-income countries, as outlined by Chateau, Jaumotte and Schwerhoff (2022).
- *A carbon tax that sets the price of carbon at US$75 per metric ton of CO_2 equivalent by 2030:* This corresponds to the proposed emissions reduction target for high-income countries.
- *An ETS with a 19 percent emissions reduction target by 2030:* This target corresponds to a carbon price of US$90 by 2030, the 2023 carbon price in the European Union.

The air pollution-related benefits of these carbon pricing policies are estimated in the analysis by combining projections derived using the climate policy assessment tool (CPAT) with estimates of the impacts of air pollution (IMF, 2022; Baquie et al., 2023; World Bank, 2023a).[8] A spreadsheet-based model, the CPAT is a valuable resource for policy makers in evaluating and designing climate mitigation measures. It facilitates quick assessments of the consequences of climate mitigation, encompassing aspects such as effects on energy demand and pricing, carbon dioxide (CO_2) and other GHG emissions, fiscal revenues, gross domestic product (GDP), and welfare.[9] The approach likely provides the lower bounds of the impacts of air pollution. Indeed, some dimensions have not yet been evaluated, including mortality, and the above estimates correspond to the short-term impacts of air pollution, which underestimate the long-run consequences of cumulative exposure. Still, they suggest the potentially large benefits of carbon pricing in terms of health and real estate values.

8 See CPAT (Climate Policy Assessment Tool), International Monetary Fund and World Bank, Washington, DC, https://www.imf.org/en/Topics/climate-change/CPAT; CPAT (Climate Policy Assessment Tool) Documentation, International Monetary Fund and World Bank, Washington, DC (status: January 24, 2024), https://cpmodel.github.io/cpat_public/.

9 The assumptions behind the calculations in this section are explained in Baquié et al. (2023); they include a 5 percent GDP growth rate and no population growth in the CPAT assessment.

The scenarios mentioned above would reduce vehicle traffic from 7.8 percent to 25.0 percent by 2030. Figure 10 illustrates the estimated effects of the three carbon pricing policies on transportation. Introducing a US$25 carbon tax (light blue curve) would lead to a notable reduction of 1.3 percent in miles traveled by 2025 and ultimately result in a substantial 7.8 percent reduction by 2036. In contrast, the US$75 carbon tax produces a much more significant effect: an estimated 22 percent reduction in traffic by 2036. The ETS, designed to reach an equivalent carbon price of US$90 by 2030, promises the most substantial projected impact, a 25 percent reduction in vehicular distance.

The expected declines in vehicular transportation are likely to improve air quality. In the first scenario, where a US$25 carbon tax leads to a 7.82 percent reduction in traffic congestion by 2036, the CPAT tool projects a consequential decrease in ambient pollution levels by 0.35 µg/m³. In the second and third scenarios involving a US$75 carbon tax and the ETS, the reductions in air pollution attributed to traffic are even more substantial, amounting to 1.00 µg/m³ and 1.14 µg/m³, respectively, by 2036. These forecasts are generated by extending the TM5–fast Scenario Screening Tool model, a source-receptor model of the relationships between emissions and concentrations (Van Dingenen et al. 2018). In this model, the decline in traffic-related air pollution primarily results from reduced vehicular use because of rising fuel prices. The estimates in section 3 also suggest that eliminating traffic jams by adopting carbon pricing to reduce the number of vehicles used, incentivizing public transport, or improving urban planning could reduce air pollution by up to 0.18 µg/m³.

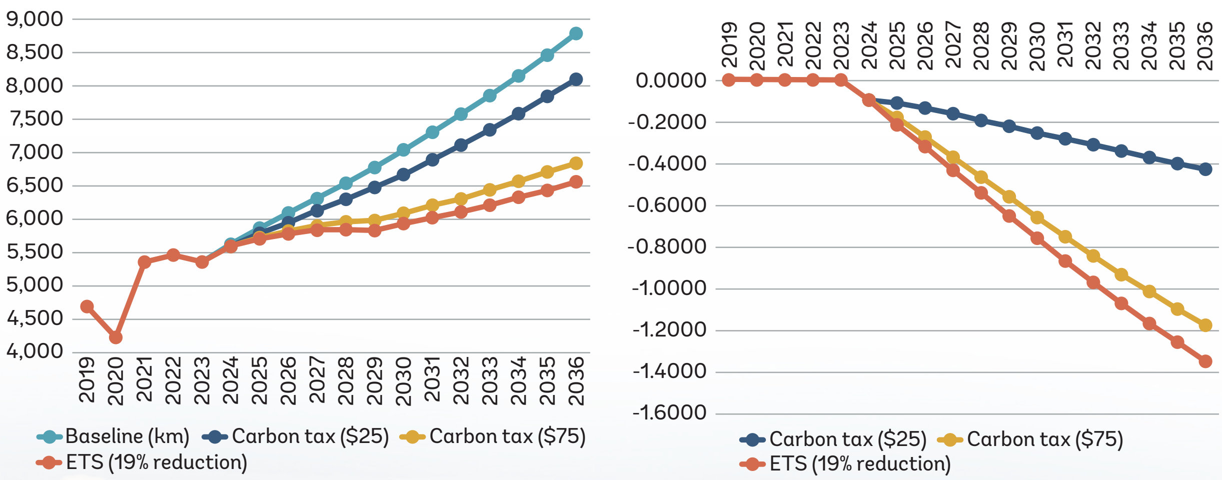
Carbon pricing regulations are expected to decrease $PM_{2.5}$ concentrations by up to 1.35 µg/m³ by 2036. Figure 10, panel b, shows the trajectories of pollution reduction in the three carbon pricing scenarios under consideration. The US$25 carbon tax results in a 0.43 µg/m³ reduction in air pollution by 2036, while the US$75 carbon tax achieves a more substantial decrease of 1.18 µg/m³ over the same time frame. These expected enhancements in air quality underscore the advantages of carbon pricing. The reduction in air pollution is predominantly attributed to changes in transportation (81 percent–85 percent). The next most influential sources of air pollution are the residential, services, and construction sectors (8.7 percent–9.5 percent), followed by the industrial sector (5.3 percent–7.5 percent). This aligns with the estimates in section 3, highlighting the significant impact of industrial emissions on air quality in downwind areas.

Figure 10

Carbon pricing could decrease traffic by up to 25% by 2030 and yield improvements in air quality

a. Traffic is reduced by carbon pricing policies (millions of vehicle-kilometers)

b. PM2.5 concentration declines(µg/m³)



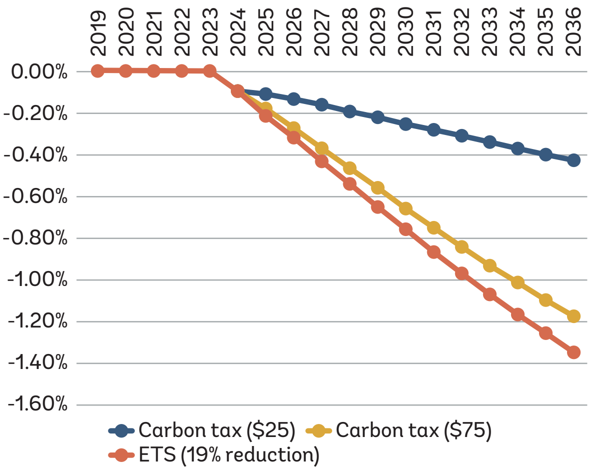
Source: World Bank calculation.
Note: The panels illustrate the application of the CPAT to three carbon pricing scenarios. The data and method are described in Baquié et al. (2023).

Carbon pricing policies could yield significant benefits in public health. The analysis relies on the estimates of improvements in air quality deriving from carbon pricing scenarios to assess the magnitude of the benefits in health (figure 11). With the 0.43 μg/m³ reduction in $PM_{2.5}$ levels resulting from the US$25 per ton carbon tax, a 0.44 percent decrease in hospitalizations per district-day is anticipated by 2036. Such outcomes underscore the diversity of the advantages linked to enhanced air quality by implementing carbon pricing. In the case of the adoption of the recommended ETS, the corresponding reduction in hospitalizations is projected to reach 1.38 percent by 2036. Consequently, the results emphasize the potentially substantial benefits of carbon pricing policies through the corresponding improvements in air quality.

Figure 11

The estimated benefits of carbon pricing in health

Decrease in the incidence of respiratory infections (%)



Source: World Bank calculation.
Note: The panels illustrate the application of the CPAT to three carbon pricing scenarios. The data and method are described in Baquié et al. (2023).

CHAPTER 6

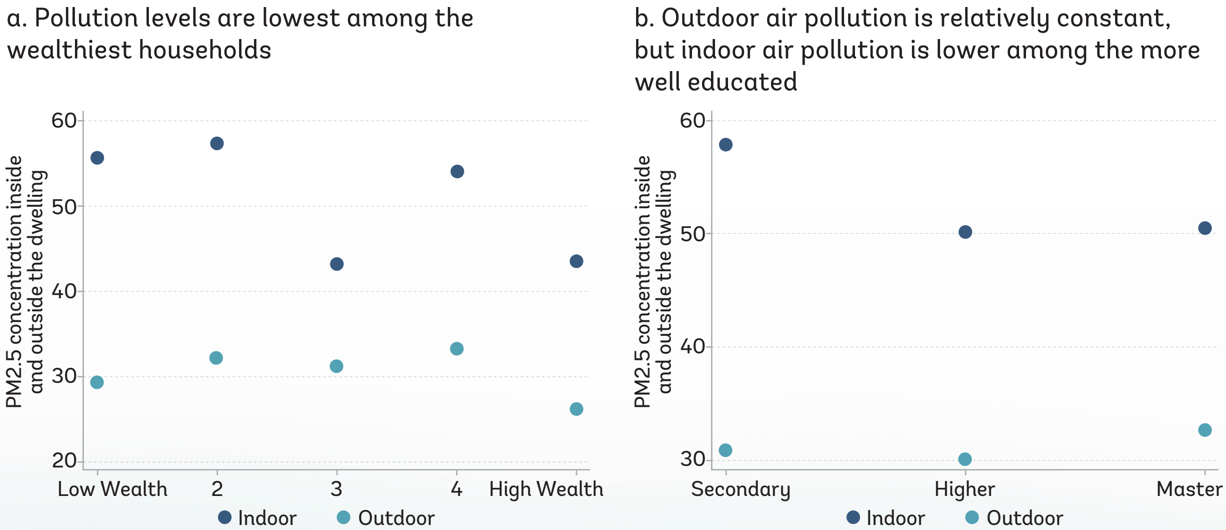
The exposure of individuals to air pollution and the associated drivers

The wealthiest households are exposed to lower instantaneous $PM_{2.5}$ concentrations inside and outside their dwellings. Figure 12 shows the distribution of measured outdoor and indoor pollution levels during the survey across wealth status (panel a) and educational attainment (panel b). Although wealth is associated with residence in a central location and more pollution, the wealthiest may live in housing that is less exposed to outdoor air pollution (see section 2). Indoor air pollution levels are also lower in the case of medium- to high-wealth groups. Wealth is positively correlated with greater educational attainment: there is a 28 percent correlation between the asset and education indexes. The variations across groups identified by educational attainment may therefore drive some variations by wealth groups. Although outdoor pollution outside one's dwelling is slightly higher among the most well educated households, indoor air pollution levels are much lower among households that have attained higher education. This suggests that more well educated households may be located in more well insulated buildings or have a greater capacity to adapt to air pollution and reduce indoor air pollution.

Time spent outside varies by socioeconomic status; less wealthy and less well educated households spend more time working outdoors, while more well educated and affluent people spend more time exercising outdoors. Project survey respondents in wealthy households spent less time working outside on average, up to almost a day of difference relative to others (figure 13, panel a). Across the first four groups, the intensive

Figure 12

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



Source: World Bank calculations based on project survey data.
Note: The outdoor and indoor air pollution levels have been measured by the enumerators using portable monitors at the time of the survey.

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 areas with cleaner air. There are fewer observations and fewer active people in the wealthiest bin, making the associated estimates more imprecise. Still, the evidence suggests that the wealthiest are as likely to work outside as the median wealth group, but for shorter periods and in areas with cleaner air. In addition, the wealthier the household, the more the respondent spends time exercising outdoors, up to a 10-hour difference. Both the intensive and extensive margins count. More affluent households are more likely to undertake exercise outdoors and for a longer duration. However, more wealth is not associated with exercising in areas with cleaner air, likely reflecting the finding that wealthier households tend to be located in relatively more highly polluted neighborhoods. These relationships are even stronger in the case of educational attainment. More well educated households are less likely to work outdoors and more likely to do so for shorter periods and in areas with cleaner air. At the same time, these households spend more time exercising outdoors, for longer periods, and in more highly polluted areas (figure 13, panel b).

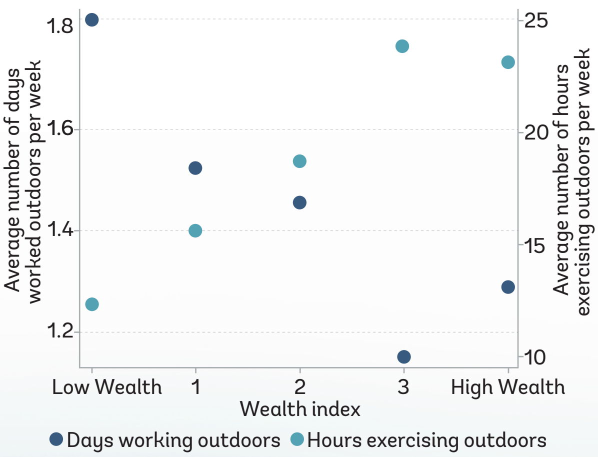
Policies should support less well educated and poorer households that disproportionately work in more polluted areas. The above results suggest that exposure to outdoor air pollution because of work or exercise varies by wealth and education status. Policies should support less well educated and poorer households, which disproportionately work in areas with polluted air and cannot mitigate their exposure. Obliging companies to provide protective equipment against air pollution would be a progressive policy. Wealthy and educated groups are the most highly exposed to air pollution because of outdoor exercise. Increasing their knowledge of the consequences of air pollution on health and the link with outdoor activities could allow them to adapt their leisure activities. However, the project RCT suggests that this behavioral shift cannot be realized by distributing leaflets to households or sending out text messages on outdoor air pollution levels.

Cooking, smoking, and building insulation are three important drivers of indoor air pollution. Figure 14, panel a exhibits some of the significant drivers of the indoor air pollution level measured by enumerators during the survey. Cooking and the presence of a smoker in a dwelling are associated with an increase in indoor air pollution levels of approximately 32 μg/m³. Although high, these levels are transitory; the levels become substantially lower if a window is open during measurement, for instance. Given the importance of cooking in air pollution, the availability of a separate kitchen

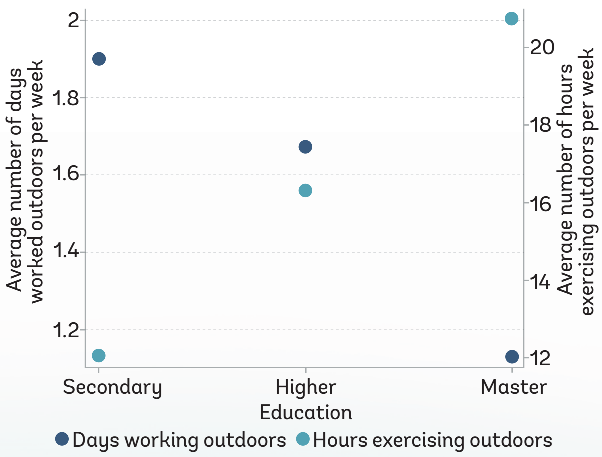
Figure 13

Number of days working outdoors and hours exercising outdoors, by wealth and education status

a. Low-wealth households are more likely to work outdoors and less likely to exercise outdoors



b. More well educated households tend to work indoors and exercise outdoors



Source: World Bank calculations based on project survey data.
Note: The outdoor and indoor air pollution levels have been measured by the enumerators using portable monitors at the time of the survey.

or the use of liquefied petroleum gas is associated with lower indoor air pollution. Moreover, these drivers of indoor air pollution vary greatly across education groups. The probability that a household member is a smoker is much lower among highly educated respondents (13 percent) compared with other groups (23 percent).

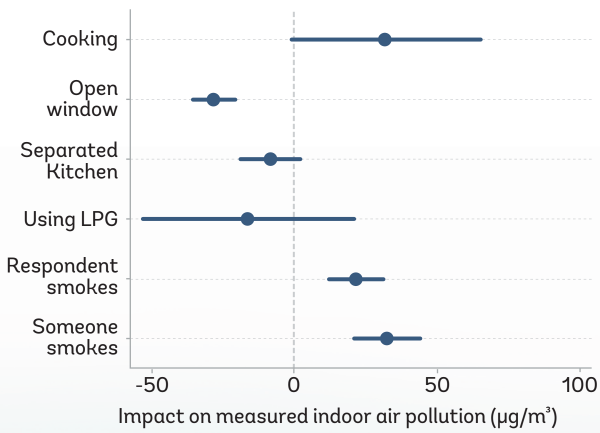
Taxation of tobacco and polluting cooking fuels may be effective and progressive policy tools. Figure 14 shows that smoking and cooking are two important drivers of indoor air pollution. Taxation can decrease the demand for tobacco and polluting cooking fuels by increasing prices, which would likely yield substantial health benefits. Using an extended cost-benefit analysis, Fuchs and González Icaza (2020) show that the long-term net distributional effects of increasing cigarette taxation are likely to be progressive in Georgia. Poorer households reduce their consumption more intensively if they are faced with higher tobacco prices, which improves their health. The project survey suggests that providing households with an indoor air pollution monitor could also be effective in reducing smoking. Indeed, 30 percent of the respondents who were smokers and who received indoor air pollution monitors declared that they reduced smoking because of the feedback provided by the monitors. Price instruments could also be used to incentivize households to switch to less polluting cooking fuels. More research needs to be conducted to assess the effectiveness and progressiveness of a tax or subsidy, but the long-term health gains would likely offset the direct costs to households.

Building characteristics, such as building age, also influence indoor air pollution levels. Figure 14, panel b, shows that the age of the dwelling also impacts indoor air pollution levels relative to outdoor levels. On average, newer buildings are more well insulated, meaning that the difference between indoor and outdoor air pollution levels is greater. However, because indoor air pollution is relatively greater in 58 percent of the observations, ventilation may have a cleaning effect on indoor air. The wealthy and more well educated disproportionately reside in newer buildings: 8 percent of survey respondents with a master's degree reside in buildings constructed after 1990, compared with only 4 percent among other education groups. Heating sources were not significantly associated with levels of indoor air pollution at the time of the survey, possibly because the survey was conducted after the winter months. Nonetheless, point estimates indicate that firewood and fan heaters are linked to increases in average indoor air pollution exceeding 10 μg/m³, but only 2 percent of Tbilisi households use one of these methods as a primary heating source.

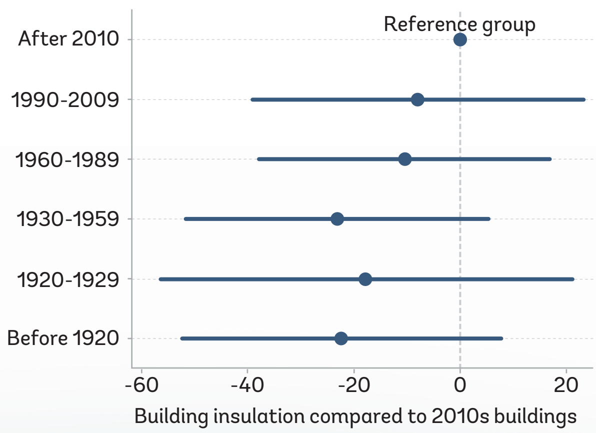
Figure 14

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 more well insulated



Source: World Bank calculations based on project survey data.
Note: Insulation is measured as the absolute difference between indoor and outdoor air pollution concentrations. A higher value indicates better insulation. The reference group consists of buildings constructed in the 2010s. Compared with buildings constructed in 2010, older buildings exhibit lower absolute differences in outdoor and indoor concentrations and, hence, lower insulation.

CHAPTER 7

The impacts of air pollution on individuals

Air pollution negatively affects the health of Tbilisi inhabitants. The analysis relies on the project survey results to estimate the effect of air pollution on a wide range of health issues, including asthma, eye irritation, sore throat, headache, cough, wheezing, blocked sinuses, and shortness of breath. The two survey rounds have facilitated the identification of the causal impact of outdoor air pollution on health based on a difference-in-differences strategy. The results show that cumulative exposure to rising outdoor air pollution leads to significant health issues (figure 15). For every 3 percent increase in average outdoor $PM_{2.5}$ concentrations over the two weeks preceding the survey, households experienced one additional symptom. The probability of experiencing a sore throat and blocked sinuses rose significantly, by 6.8 percent. The results associated with headache, cough, and wheezing were less precise, but indicate a substantial increases of 10.6 percent, 4.7 percent, and 3.6 percent, respectively (figure 15, panel b). This impact on health translates into missed days of work and school, which are likely to affect productivity and income. According to the survey, a 1 percent rise in $PM_{2.5}$ is associated with an 8.8 percent increase in missed workdays. The estimates, though imprecise, suggest that the effect on school days may be even greater, a rise of 13.8 percent on average (figure 15, panel c). The specification estimates of the effects of short-term changes in pollution levels are likely lower bounds of the long-term changes in pollution that take into account cumulative exposure.

Indoor and outdoor air pollution adversely affect productivity. The analysis relied on interview duration as a proxy for productivity to estimate the impact of air pollution Figure 16, panel a, shows that a 1 percent rise in indoor $PM_{2.5}$ concentrations at the time of the survey increases interview duration

Figure 15

Air pollution adversely affects health in Tbilisi and the number of missed work and school days

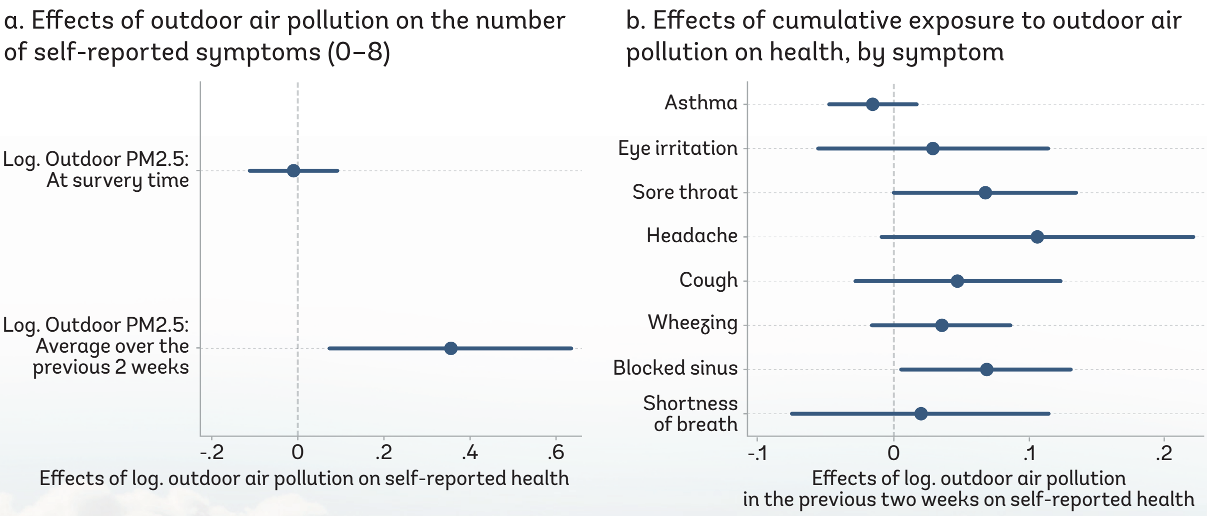
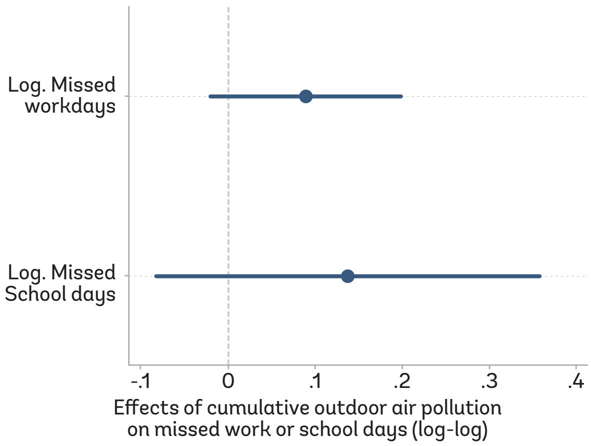


Figure 15 (continue)

c. Health effects of cumulative exposure to outdoor air pollution on missed work and school days



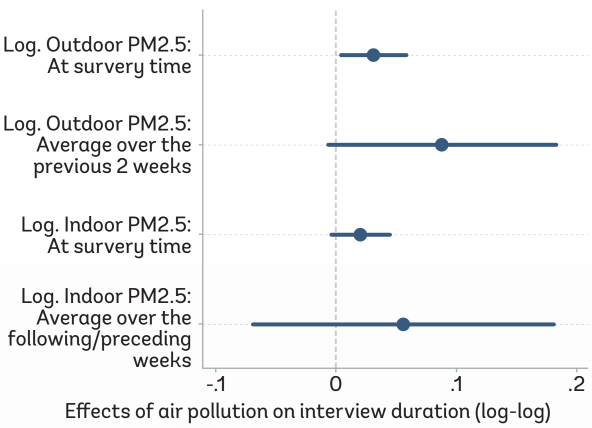
Source: World Bank calculations based on project survey data.
Note: Outdoor air pollution levels were measured during the survey by the enumerators using portable monitors. The average outdoor air pollution level was measured in the neighborhoods of survey households two weeks before the survey by averaging the values for the closest outdoor air pollution monitors. The corresponding regression is the number of self-reported symptoms (panel a) and the dummy variable of the reported symptom (panel b) on the log of measured air pollution levels. In panel c, the dependent variable is the logarithm of the number of missed workdays or school days, respectively. Household and survey round fixed effects are included, and standard errors are clustered at the block level.

by 2.1 percent. The size of the effect was similar for outdoor $PM_{2.5}$ at the time of the survey, increasing duration by 3.1 percent. The effect may be much larger if one considers cumulative exposure to air pollution. Based on information from the project outdoor and indoor air pollution monitors, the analysis concluded that a 1 percent rise in outdoor $PM_{2.5}$ concentration two weeks before the survey expands interview duration by 8.8 percent. The same rise in indoor $PM_{2.5}$ concentration in the weeks around the survey time increases interview duration by 5.6 percent. This estimate is less precise because only 18 percent of the surveyed households received an indoor air pollution monitor. The analysis also assesses the pollution-productivity relationship with the educational attainment of the interviewees. Although outdoor air pollution at the time of the survey had a homogenous impact across groups, cumulative exposure disproportionately affects the members of less well educated households. Figure 16, panel b shows that, among these people, a 1 percent rise in outdoor $PM_{2.5}$ is, on average, associated with an 18 percent increase in interview duration. The findings on the effects on interviewees in other groups sorted by educational attainment and in the case of indoor air pollution are imprecise.

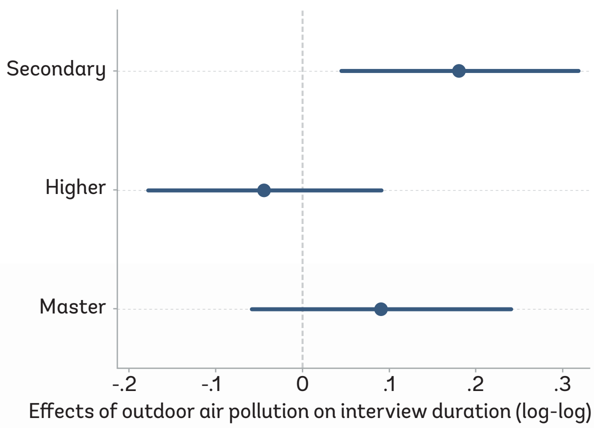
Figure 16

Air pollution is associated with higher interview duration, particularly among the most well educated

a. Effects of air pollution on interview duration



b. Effects of air pollution on interview duration, by educational attainment



Source: World Bank calculations based on project survey data.
Note: Outdoor air pollution levels were measured during the survey by the enumerators using portable monitors. The average outdoor air pollution level was measured in the neighborhoods of survey households two weeks before the survey by averaging the values for the closest outdoor air pollution monitors. The analysis also relied on the data on indoor air pollution measured by indoor air pollution monitors to examine households in the corresponding group of the randomized controlled trial (RCT). Among these households, the average indoor air pollution was measured two weeks after the first survey and one week before the second interview. The regression is the log of interview duration in minutes on the log measured air pollution levels. Household and survey round fixed effects are included, and standard errors are clustered at the block level. The estimates on outdoor air pollution are causal, while the estimates on indoor air pollution may suffer from omitted variable bias.

CHAPTER 8

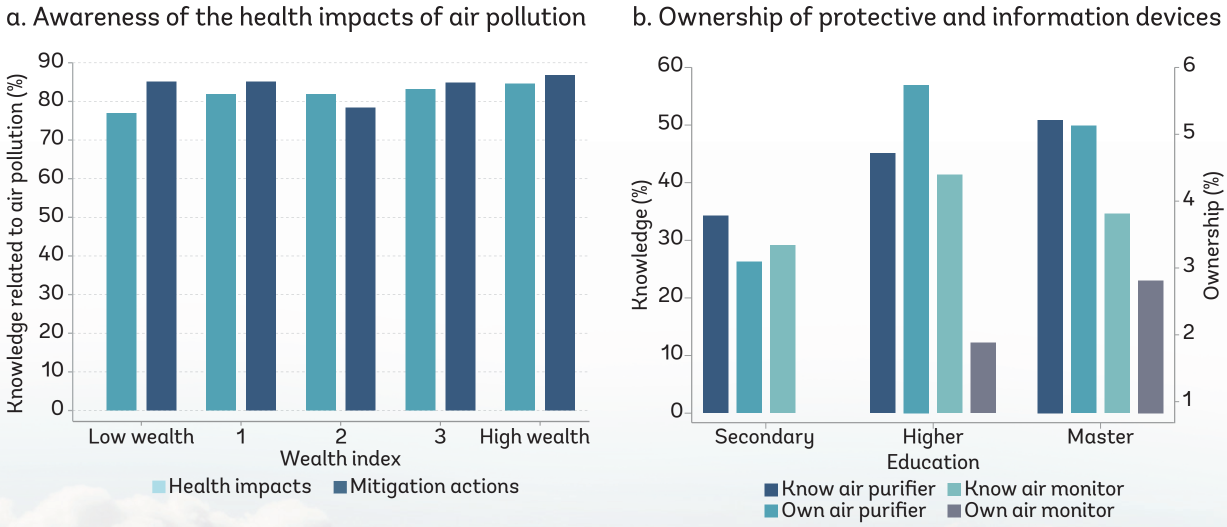
The adaptation of individuals to air pollution

More well educated and wealthier households enjoy a higher capacity to adapt to air pollution because of greater knowledge, more access to information, and ownership of information or protective devices. The analysis relies on the first project survey to measure household knowledge about air pollution and household adaptive capacity before the intervention. Figure 17 illustrates the results by wealth and education status. The more well educated the respondents, the more knowledge they have on the impacts of air pollution on health (figure 17, panel a). More well educated households also have greater capacity to adapt to air pollution because they are more likely to know about and own air pollution monitors or protective devices (figure 17, panel b). This suggests that providing information, monitors, or protective devices may disproportionately help the most vulnerable. The results of the RCT support this interpretation (see section 9). They show that providing information on outdoor air pollution levels through text messages or indoor air pollution monitors increases household knowledge on the impacts of air pollution and protective actions.

Wealthier households are more likely to take action to mitigate indoor air pollution. The wealthier the respondents, the longer they use air purifiers and leave windows open for ventilation (figure 18, panel a). Both behaviors are conducive to a decline in indoor air pollution. The results suggest that information campaigns targeted by income may effectively mitigate the disproportionate exposure of poorer households to indoor air pollution. This interpretation is supported by the results presented in section 9, which shows that sharing information on air pollution is effective in shifting household behavior toward more protective actions. The distributional pattern is not as

Figure 17

Awareness of impacts and adaptive capacity are greater among more well educated and wealthier households

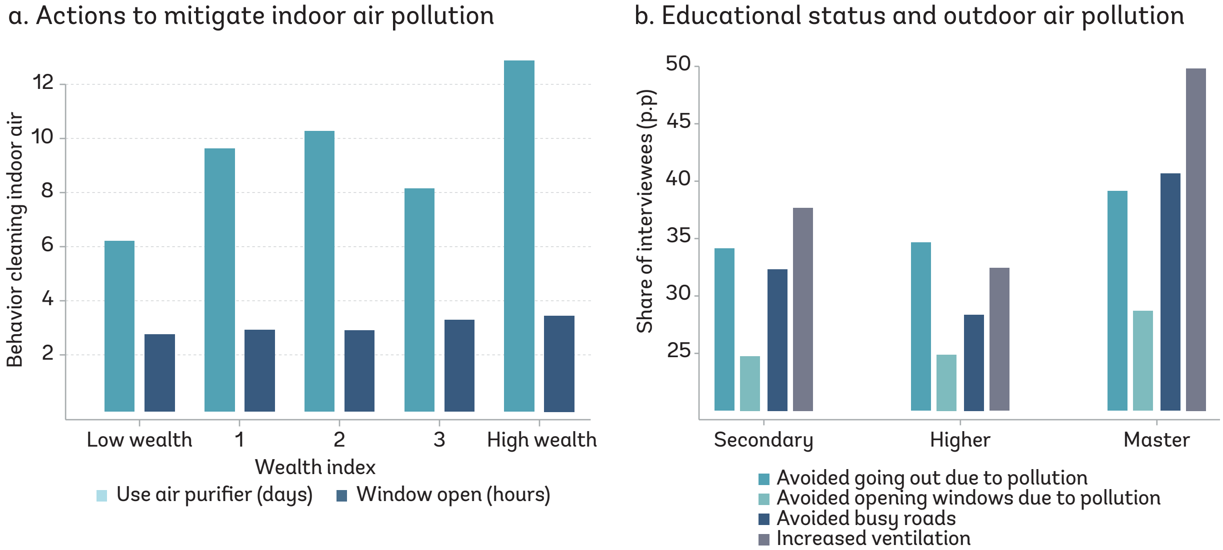


Source: World Bank calculations based on survey data collected at baseline.

apparent in the case of outdoor air pollution (figure 18, panel b). Educational attainment measured by possession of a master's or doctorate is associated with the application of more mitigation actions against outdoor air pollution. The patterns among the less well educated are not as clear.

Figure 18

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



Source: World Bank calculations based on survey data collected at baseline.

CHAPTER 9
The impact of information sharing on exposure, behavior, and welfare

This section presents the results of the RCT undertaken to test the effectiveness of providing information on air pollution in reducing the exposure of individuals to air pollution and enhancing protective behavior and welfare. The experiment evaluates the impact of three separate interventions, as follows:

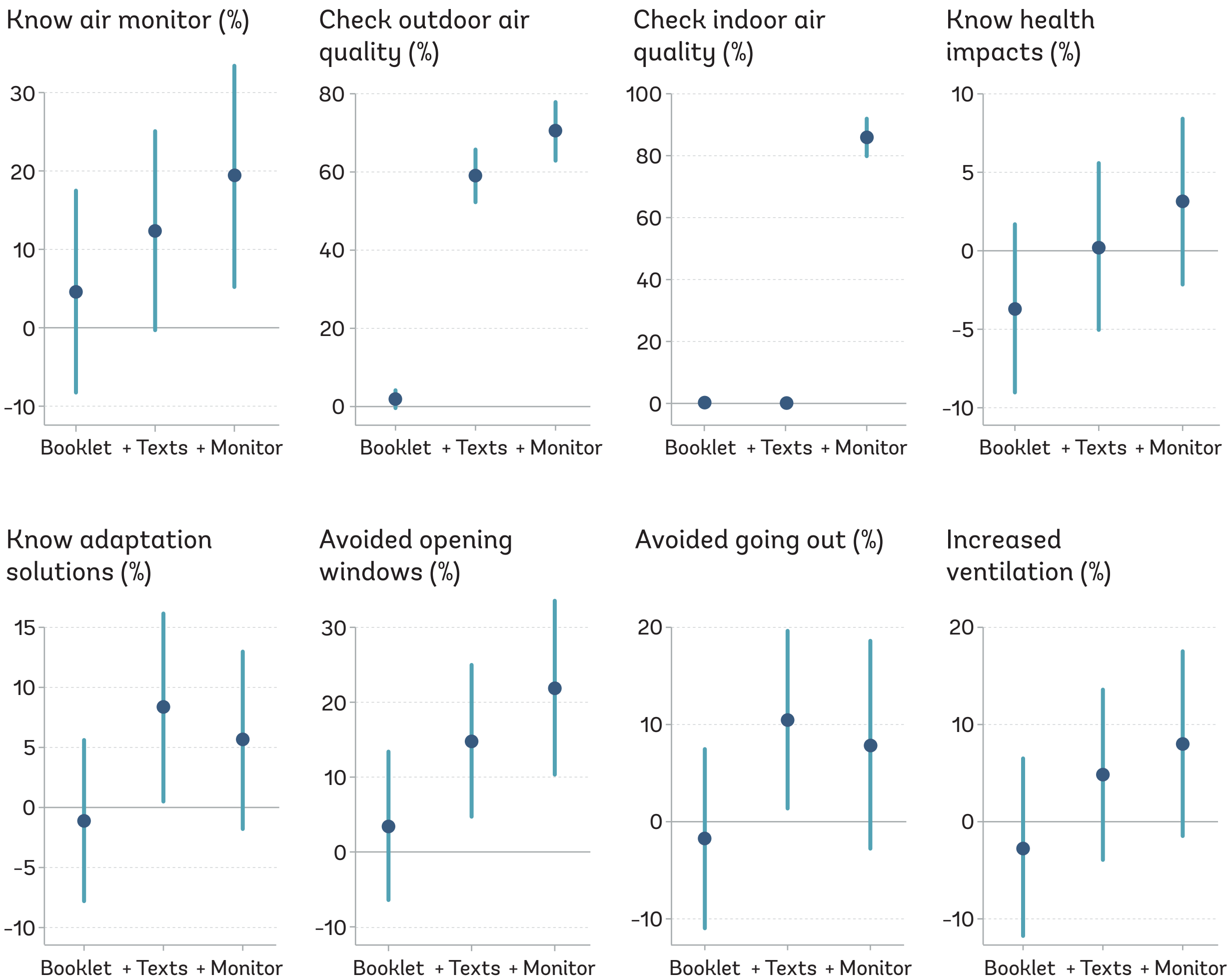
- *Providing households with a booklet on air pollution's adverse effects and on protective actions.* The booklet details the negative impacts of exposure to air pollution on respiratory and cardiovascular health and offers examples of protective actions. The booklet also refers to a website with live public information on outdoor air pollution levels. It explains the health effects of each pollution level and proposes the adoption of relevant protective action, including staying indoors during periods of high pollution and increasing the ventilation in the home. Households also received a refrigerator magnet with a quick-response code leading to a website exhibiting the information in the booklet.
- *Providing the booklet and daily text messages with information on the level of outdoor air pollution in the neighborhood.* Besides the booklet, households received text messages on the level of outdoor air pollution in the local neighborhood each day at 10 am. The project's outdoor monitor closest to the household is used to provide accurate outdoor air pollution information. The measure sent each day is the average air pollution level between 8 am and 10 am because this is a good predictor of air pollution levels during the rest of the day.
- *Households are provided with an indoor air pollution monitor that changes color according to the measured air pollution level.* In addition to the booklet and messages provided by the second intervention, the daily text messages sent through the third intervention also include information about the level of indoor pollution in the household during the previous 24 hours. Households are also supplied with an indoor air pollution monitor that changes color depending on the measured level of indoor air pollution.

Households were randomly assigned to each intervention: 220 were surveyed without any of the interventions; 220 were the focus of the first intervention; 220 the second; and 140 the third. Appendix B supplies additional details on the RCT, including sampling, the measurement of air pollution using the monitors, and the survey data collection process.

Providing indoor air pollution monitors or daily text messages indicating outdoor air pollution levels effectively increases the knowledge of households on air quality and the related health impact. Households treated with the second or third intervention knew about the air pollution monitors and checked the air quality on which they received information (figure 19). The text messages and the live information on indoor air pollution supplied by the monitors were not ignored and effectively increased the awareness of households about air quality. In addition, households with an indoor air pollution monitor disproportionately increased their knowledge of the health impacts of air pollution. The households receiving daily text messages could expand their knowledge of actions to protect health. This outcome was amplified among the households that also received the indoor air pollution monitors.

Figure 19

Indoor air pollution monitors and messages on outdoor air pollution raise household awareness



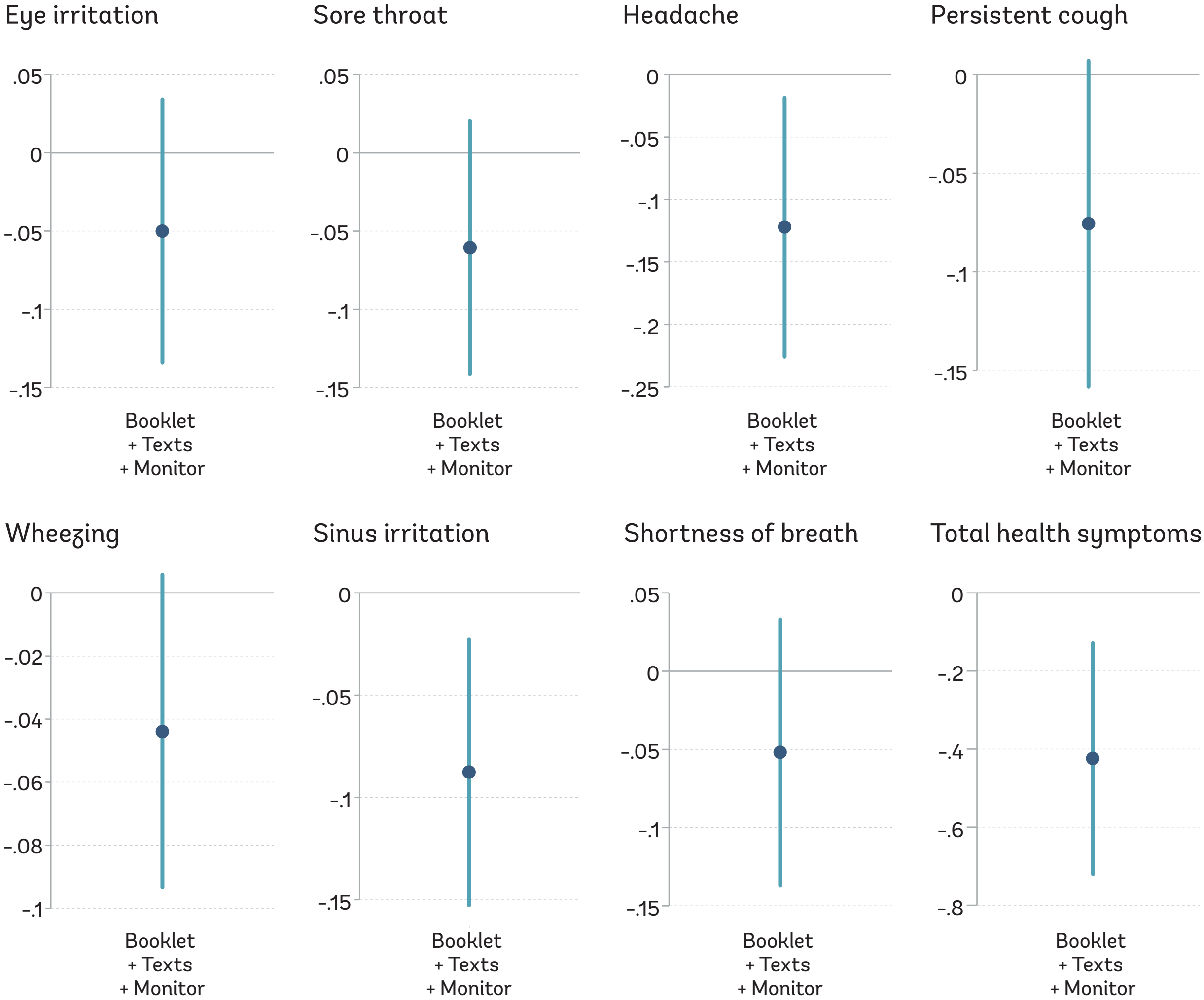
Source: World Bank calculations based on data of a two-round survey.
Note: Booklet refers to the first intervention. + Texts refers to the second intervention. + Monitor refers to the third intervention.

The increased information and knowledge resulting from the second and third interventions translated into behavioral change and the adoption of protective actions among households. Households receiving the text messages reported that they avoided opening windows or going out and also increased the ventilation in the dwelling when outdoor pollution levels were high (figure 19). The effect of the interventions was even stronger among the households receiving both text messages and indoor air pollution monitors, suggesting that the more well targeted the information, the better.

The third intervention—providing the booklet, daily text messages about indoor and outdoor pollution, and indoor pollution monitors—significantly reduced adverse health outcomes. The first and second interventions did not have a substantial impact on self-reported health outcomes. However, figure 20 shows that receiving information on indoor air pollution through the third intervention greatly reduced adverse health consequences. Indeed, households in the third intervention group reported declines in all adverse health symptoms. The largest and most significant declines were observed in the case of headaches and sinus irritations. The sum of all reported symptoms also decreased substantially through the third intervention (figure 20, final panel). This effect is partly driven by a reduction in indoor smoking among households receiving the indoor air pollution monitors. Among the households receiving indoor monitors, 30 percent reported

Figure 20

Information on indoor and outdoor air pollution the consequences of exposure reduces adverse health outcomes



Source: World Bank calculations based on data of a two-round survey.
Note: Booklet + Texts + Monitor refers to the households targeted in the third intervention.

that they reduced the time they spent smoking cigarettes in the home because of the information they received from the monitors. Households in the third intervention group also reported the largest changes in awareness of the adverse effects of air pollution and in indoor and outdoor adaptive behaviors, such as opening windows while cooking. These behavioral changes are also likely to have driven part of the observed improvements in health.

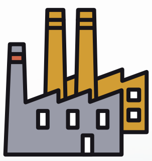
Overall, increasing access to information on air pollution, the associated risks, and protective actions allows households to self-protect and is likely to be progressive. The less well-off and less well educated in Tbilisi are disproportionately affected by greater indoor air pollution (see section 8). Poor and less well educated households also have less capacity to adapt because they are less likely to adopt mitigating behaviors or possess protective equipment. The impact of the three RCT interventions does not vary substantially by socioeconomic status, but significantly improves air pollution awareness, protective behavior, and health. Improving household information about air pollution through text messages or indoor air pollution monitors could yield substantial benefits in economic development and shared prosperity. More generally, targeted information campaigns or incentives for adopting information and protective devices, such as monitors or air purifiers, could be effective and progressive.

CHAPTER 10

Policy recommendations

Progress has been made, but challenges remain in reducing air pollution levels and impacts in Tbilisi. The government adopted, in 2020, the Improved Ambient Air Quality Monitoring Law, which represents a major step forward in tackling air pollution in the country. However, the launch of zonal air quality management plans has been delayed, and institutional capacity must be enhanced to support the success 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 (MEPA 2021). In the meantime, passenger transport activity is expected to rise by almost 60 percent, and freight activity by 240 percent relative to 2015 (World Bank 2023). Increasing the regulation of car imports and accelerating technical inspection reform could reduce outdoor air pollution in Tbilisi. Incentivizing the use of electric vehicles could also reduce traffic-related emissions, while preparing Georgia for the green transition. There are excise taxes on oil products and cars, but the incentives need to be stronger to promote vehicles that emit less pollution. The share of such vehicles is now negligible. The authorities in Tbilisi are expanding public transportation services, but there is scope for still greater expansion.



Regulating industrial emissions is important in tackling air pollution in Tbilisi and supporting the green transition. The authorities submitted a new Industrial Emissions Law to Parliament in January 2023 to prevent waste generation and spillage from industrial activities into the environment. While the law is expected to support the adoption of more efficient and cleaner technology, it is not specifically aimed at reducing emissions. Enforcement of regulations on filtration and monitoring systems in industry might be effective in curbing industrial emissions. Carbon pricing also has potential for enhancing air quality by lowering emissions, especially from traffic. This could yield substantial benefits in health, productivity, and economic outcomes.

Providing targeted information about air pollution levels raises the awareness of households on air quality and the associated impacts, is conducive to behavioral change, and improves health outcomes, particularly in the case of live indoor air pollution information. Households receiving information on air pollution levels disproportionately engage in relevant protective actions, such as avoiding going out if outdoor air pollution levels are high. The more information supplied, the greater the behavioral change. Behavior change leads to substantial reductions in adverse health effects. Among households provided with indoor air pollution monitors, 35 percent reduced the frequency of smoking indoors. Targeted information campaigns or incentives for adopting devices, such as monitors, would likely reduce the exposure of the population to air pollution and improve health outcomes.

Additional programs to provide more information on the levels of indoor and outdoor air pollution and protective actions would allow households to self-protect and would likely be progressive. Poor and less well educated households have less capacity to adapt because they are less likely to adopt preventive behaviors or own protective equipment. The analysis confirms that pollution greatly affects health. Enhancing household awareness of air pollution and supporting the most vulnerable in acquiring protective and information devices is likely to yield substantial benefits in economic development and shared prosperity.

The project in Georgia can represent a roadmap for similar projects in other countries. Appropriate data are likely to be available elsewhere. Thus, data on ambient pollution and the relative wealth index are available for nearly every low- and middle-income country. Other data may have to be collected in situ, but may also already be available through governmental agencies, such as hospitalization or morbidity data. Monitor data could also be collected if there is a willing partner to collaborate in installing monitoring devices.

Appendix A. Natural experiments: data and methods

The relative wealth index

The relative wealth index described in section 2 is an indicator developed through a collaboration between the Center for Effective Global Action at the University of California, Berkeley, and Facebook's Data for Good (Chi et al. 2022). The index predicts the relative standard of living within a country based on nontraditional data sources, including satellite imagery and deidentified Facebook connectivity data. It is validated using ground-truth measurements from the Demographic and Health Surveys.[10] Data are available for more than 100 low- and middle-income countries, including Georgia, at a 2.4 kilometer resolution. The datasets are publicly accessible. They have been used, for example, by World Bank projects in Nigeria and Togo. The rank correlation between the relative wealth index score and World Bank poverty measures is significant, at approximately 0.4 [t-stat >2.96].

Weather

The ERA5 is used for data on wind direction, wind speed, temperature, and precipitation.[11] Variables are mainly introduced as bins in regressions to account for the potential nonlinearity of weather effects.

Traffic

Traffic data on Tbilisi's roads are derived from Mapbox.[12] Data are presented as the daily speed and delay time on all Tbilisi roads. Each road segment is matched to its district, and traffic intensity is quantified by the number of days with traffic jams in each district within a month. A traffic jam in a district is defined as an observed traffic speed lower than 5 km/h on one of the district's roads at any point during a day.

Industrial emissions

Data reflect an inventory of industrial emissions by type and year provided by the Environment and Climate Change Department of the Ministry of Environmental Protection and Agriculture. The data cover emissions in tons per year in 2016-2021 at industrial sites in Tbilisi.

Health

Daily data on hospitalizations are used for given ICD-10 codes associated with air pollution provided by the National Center for Disease Control and Public Health.[13] The data are available for March 2014–August 31, 2022, and include variables for organization code, name, and addresses. Hospitals were geolocated using Google Maps.

10 See Data, DHS Program (Demographic and Health Surveys), ICF International, Rockville, MD, http://www.dhsprogram.com/Data/.
11 See ERA5 (ECMWF Reanalysis v5), Copernicus Climate Change Service, European Centre for Medium-Range Weather Forecasts, Reading, UK, https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5#:~:text=ERA5%20is%20produced%20by%20the,to%20a%20height%20of%2080km.
12 See Traffic Data, Mapbox, San Francisco, https://www.mapbox.com/traffic-data.
13 For the ICD-10, see ICD-10 (International Statistical Classification of Diseases and Related Health Problems, 10th Revision, version 2019), World Health Organization, Geneva, https://icd.who.int/browse10/2019/en.

Real estate values

Raw data were shared by LIVO, a major real estate agency in Georgia.[14] The data were processed into a spreadsheet by the Private Sector Development Center of the ISET Policy Institute.[15] They contain the entire universe of real estate listings for sale, rent, or exchange in Georgia from January 2019 to June 2021 (30 months).

Natural experiments

Temperature inversion (existence and strength) and four wind directions interacted with municipality ID are used to instrument air pollution. The first-stage regression is specified as follows (see section 3):

$$PM_{it} = Inversion_{it} + InversionStrength_{it} + I(WindDirection_{it} = d) \times I(Municipality_i = m) + Weather_{it} + \tau_t + \gamma_i + \varepsilon_{it} \quad (A.1)$$

where PM_{it} represents monthly $PM_{2.5}$ pollution in district i in month t, sourced from van Donkelaar et al. (2021). On the right-hand side, the variables are as follows:

- $Inversion_{it}$ is the occurrence indicator for temperature inversion in district i in month t.
- $InversionStrength_{it}$ represents the strength of the inversion obtained from ERA5 data.
- $I(WindDirection_{it} = d) \times I(Municipality_i = m)$: Municipality-specific wind direction indicators are included as supplementary variables. Specifically, the wind direction in district i in month t is categorized into four groups—northeast, northwest, southwest, and southeast—and encoded as dummies, denoted as $(WindDirection_{it} = d)$. These four dummies are then interacted with municipality fixed effects to account for varying pollution levels in each municipality, denoted as $I(Municipality_i = m)$. This accounts for the fact that pollution from a same direction may differ because of the industrial structure of neighboring areas.
- $Weather_{it}$: Wind speed, precipitation, and temperature are included 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, the standard errors are clustered 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, ordinary least squares and instrumental variable regressions are used to study the impact of air pollution on health and real estate values. Specifications are similar. The specification for real estate is as follows:

$$ln(P_{it}) = \widehat{PM_{it}} + Characteristics_{it} + \tau_t + \gamma_i + \varepsilon_{it} \quad (A.2)$$

where $\widehat{PM_{it}}$ is the district-month level $PM_{2.5}$ concentration instrumented using wind directions and inversions. In the ordinary least squares equivalent, the satellite measure (PM_{it}) is used directly in equation A.2. $Characteristics_{it}$ includes housing characteristics and distance to school/store/hospital. τ_t includes year-month fixed effects, and γ_i captures district fixed effects.

14 See LIVO (Real Estate Website, Georgia), https://livo.ge/. [In Georgian.]
15 See ISET-PI (International School of Economics-Policy Institute) (portal), International School of Economics, Tbilisi State University, Tbilisi, Georgia, https://www.iset-pi.ge/en?.

Appendix B. Randomized controlled trial

The project includes an RCT on the effectiveness of interventions that supply information on air pollution. The goal of this experiment is to answer the following questions:

- Do households benefit from receiving information on air pollution? The analysis assesses whether the information affects the knowledge of respondents on the impacts of air pollution, exposure to air pollution, and avoidance behaviors and on the health, economic, and cognitive outcomes.
- Which type of information is the most effective and efficient among households receiving the booklets, daily information on outdoor air 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:

- Treatment group 1 (T1): T1 households receive a booklet containing information on the health-related risks of air pollution and information on avoidance behaviors, such as reducing outdoor activities, closing windows if outdoor air pollution levels are high, or using air purifiers.
- T2: In addition to the booklet, T2 households receive information on outdoor air pollution levels by text message once per day. The information is captured by the project PurpleAir monitors that are the nearest to the households. The households receive data on the average level in the morning (8 am–10 am) before the text message is sent, at 10 am. This information is correlated with pollution levels later in the day and is therefore likely to reflect future trends in pollution levels.
- T3: In addition to the booklets and the information on outdoor air pollution, T3 households receive indoor air pollution monitors. The average level of indoor air pollution over the previous 24 hours is thereby added to the text message. In addition, the indoor air pollution monitors provide live feedback on indoor air pollution through color changes from green (good) to red (bad) depending on the level.

Figure B.1 shows the front and back covers of the booklet provided to treatment households. The booklet was translated into Georgian by the survey firm. The quick-response code magnet is shown in the center of the figure.

Figure B.1

The covers of the booklet supplied to the treatment households

The treatment groups and the respective interventions are summarized in table B.1.

Table B.1

RCT treatment groups receiving different types of information on air pollution

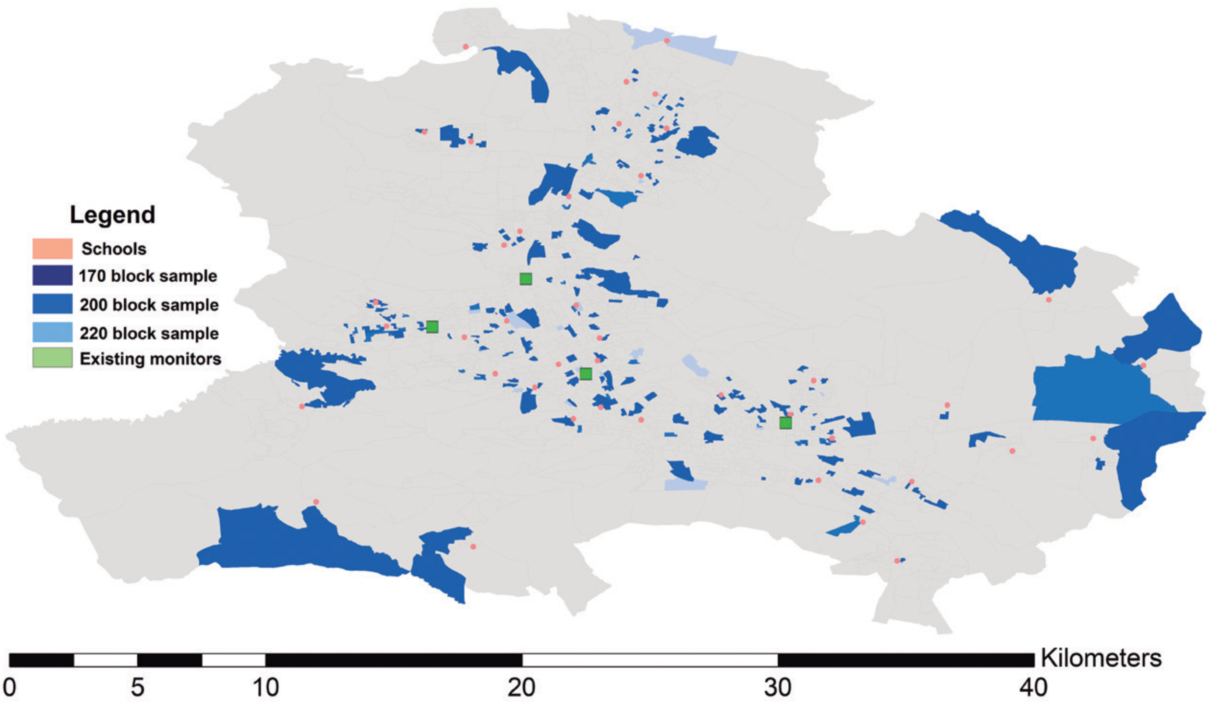
Type of Information	Control	Treatment group		
	C1	T1	T2	T3
Indoor air pollution				X
Outdoor air pollution			X	X
Booklet		X	X	X
Households, number	220	220	220	170

Sampling

The survey and RCT rely on the stratified sampling of 220 census blocks in Tbilisi. The strata are organized by income and elevation, and each contain the same number of blocks. In each selected block, three or four households were randomly selected to be assigned to the control and treatment groups and surveyed. Outdoor air pollution monitors were also installed in or near schools close to the selected blocks. Map B.1 presents the selected census blocks (light blue).

Map B.1

Selected census blocks for surveying and installation of outdoor monitors



Sources: World Bank calculations.
Note: The selected blocks are indicated in light blue.

Appendix C. Fieldwork

The project involved the collection of survey data on the sources of air pollution, exposure, health and economic outcomes, cognition, and relevant knowledge and behaviors. During the survey rounds, 862 households were interviewed in 220 census blocks randomly drawn in four strata based on elevation and income. The stratification ensured that the selected households would be representative of the range of neighborhood incomes and elevations present in Tbilisi. The analysis included weighting by the probability of selection to ensure that the sample was representative of all of Tbilisi.

In each block, three or four households were interviewed and allocated to the various RCT treatment and control groups. Households were assigned to the control or treatment arms randomly. After assignment, the observable features of households were checked for balance across the control households and each of the treatment arms.

Two survey rounds were conducted to test for the impact of the RCT interventions by comparing the first and second round (wave) results across groups. The two waves were also used to build panel data of the households over time. The first wave was carried out in March–April 2023, and the second in May 2023. The survey was collected through face-to-face interviews using computer assisted personal interviewing. The interviews lasted approximately 20 minutes each.

Questionnaire

The first-wave questionnaire included eight sections, as follows:

- Household demographics
- Sources of air pollution
- Profile of the respondents
- Exposure to air pollution, including the measurement of air pollution indoors and outdoors at the time of the interviews
- Health outcomes
- Economics outcomes
- Cognitive test
- Knowledge of air pollution and avoidance behaviors
- Willingness to pay for protective devices

The second-wave questionnaire retained the sections that were likely to change, that is, exposure to air pollution, outcomes, the cognitive test, knowledge and avoidance behavior, and willingness to pay. Questions were also included that aimed at determining the impact of the treatments and inquiring on potential spillovers across households.

Fieldwork

The project team collaborated with the Caucasus Research Resource Center (CRRC-Georgia) on the project activities. Together, they recruited 22 enumerators, two supervisors, and one technical assistant for the installation of the indoor air monitors. The CRRC conducted two four-hour training sessions before the start of the fieldwork. During the training, interviewers tested the questionnaire and sampling instructions, became familiar with the maps, and practiced the recording of air quality using 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 familiar with maps
- Indoor monitor installment procedures
- Use of portable air monitors
- Respondent selection
- Overview of the questionnaire with special attention to problematic questions
- Conducting test interviews

The training was provided by CRRC staff. Before the actual fieldwork, all enumerators were provided with tablets, maps for every cluster, letters to the respondents explaining the aim of the project, name tags, and portable air monitors that they were to carry with them throughout the fieldwork. The technical assistant received the indoor monitors and a detailed manual on installation.

The random walk procedure

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

The measurement of air pollution

To provide information about the level of the exposure to pollution that households experienced, 50 outdoor pollution monitors were installed in public areas around Tbilisi. The monitors were carefully placed to capture pollution readings in neighborhoods that were representative of the distribution of incomes and elevations across the city. The selected neighborhoods were the same as the neighborhoods from which the household survey sample was drawn so that the sampled households are all, on average, located within 1 kilometer of an outdoor monitor. The outdoor monitors recorded the levels of $PM_{2.5}$ hourly and every day from January 2023 to June 2023.

To provide information about the level of indoor pollution to which households are exposed, 140 indoor pollution monitors were installed in selected households in the sample. These households were carefully selected to be representative of households in Tbilisi according to all relevant observable characteristics. The pollution monitors recorded the levels of $PM_{2.5}$ in the households at ten minute intervals each day from installation in early March 2023 to the removal of the monitors at the end of May 2023.

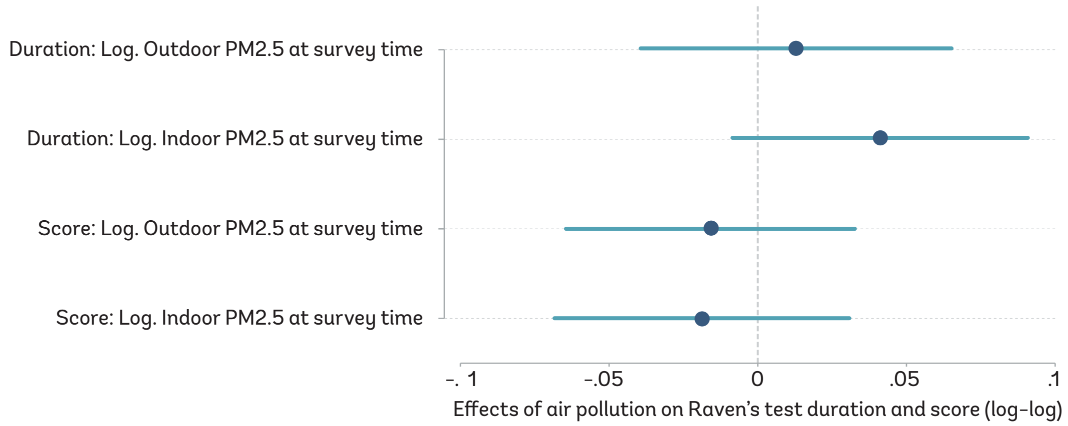
The enumerators also carried portable air pollution monitors during the interviews. For each interview, they recorded the air pollution level outside the building and inside the room where the interview was conducted.

Appendix D. Additional results

Air pollution is likely to affect productivity by hampering cognition. The survey used Raven's test to assess the cognitive performance of interviewees, which was defined by the number of correct answers and the test duration (for example, see Raven and Raven 2008). Although imprecise, the point estimates suggest that air pollution at the place and time of the survey affected cognition adversely (figures D.1 and D.2). Indeed, a 1 percent rise in indoor air pollution at the time of the survey was associated with a 4.1 percent increase in the duration of the test. The effect on cognition was more pronounced in the case of indoor air pollution than in the case of outdoor air pollution, which aligns with the higher exposure to indoor pollution during the interview process. No significant effect of cumulative exposure was found, suggesting that short-term effects may dominate. The results suggest that the main impact on cognition revolves around speed rather than accuracy. This is consistent with an association between air pollution and a reduction in cognitive capacity, causing interviewees to slow the pace of their responses to maintain accuracy.

Figure D1

Air pollution affects cognition adversely

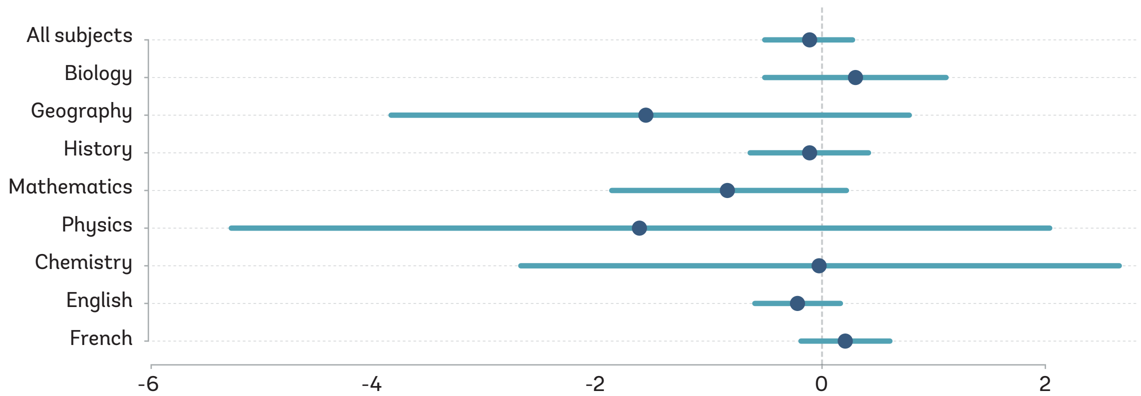


Source: World Bank calculations based on project survey data.
Note: Outdoor and indoor air pollution levels at the time of the survey are measured by the enumerators using portable monitors. The average outdoor air pollution level is measured in the neighborhoods of the survey households two weeks before the survey. The nearest project outdoor air pollution monitors are used. The data on indoor air pollution measured by indoor air pollution monitors are also used among households in the corresponding RCT groups. Among these households, the average indoor air pollution level is measured two weeks after the first survey round and one week before the second survey round. The regression is the log of the duration of Raven's test in minutes or scores gauged by the number of correct answers on the log measured air pollution levels. Household and survey round fixed effects are included, and standard errors are clustered at the block level. The estimates on outdoor air pollution are causal, while the estimates on indoor air pollution may suffer from omitted variable bias.

Figure D2

Scores on national unified entry examinations decline with air pollution in the previous month

% change in test score for a 1% change in PM2.5 concentration



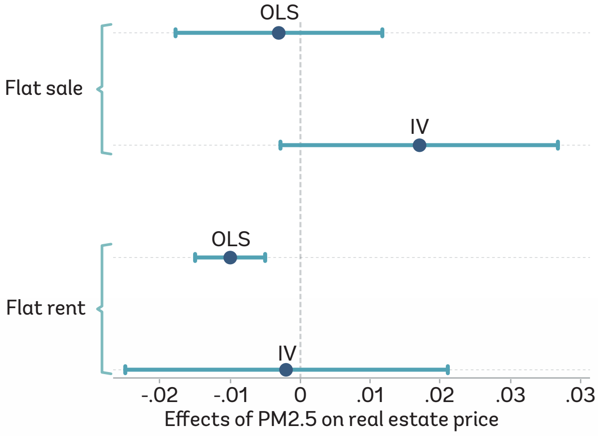
Source: World Bank calculations using student scores on the national unified entry examination.
Note: The log of the test score is regressed on the log of monthly air pollution concentration. The figure reports the estimated coefficients and 95% confidence intervals. The ordinary least squares regressions include year-month, school, and, in the first regression, subject fixed effects. The weather instruments are not sufficient to ensure relevance and apply the independent variable specification. The data and method are described in Baquié et al. (2023).

In Tbilisi, a 1 μg/m³ increase in $PM_{2.5}$ is associated with up to a 1 percent drop in rents (figure D.3). The limited number of housing real estate transactions in the LIVO dataset hinders an accurate estimation of the effect on apartment sales and private residence transactions.

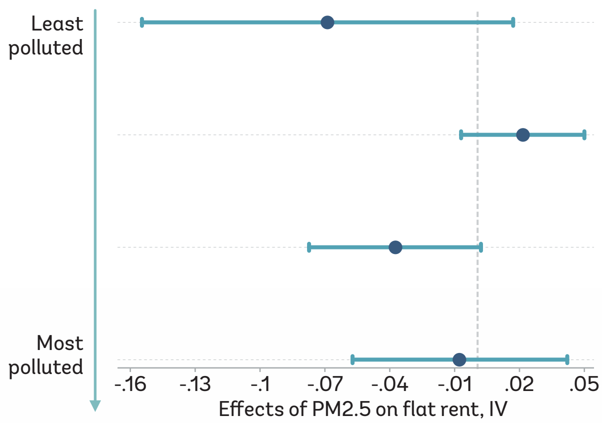
Figure D3

Air pollution significantly reduces apartment rental prices non homogeneously, Tbilisi

a. Air pollution and apartment rents



b. The marginal effect is greater in less highly polluted areas



Sources: World Bank calculations based on data of van Donkelaar et al. 2021; LIVO (Real Estate Website, Georgia), https://livo.ge/ [In Georgian]).
Note: The complete universe of sales and rental advertisements for properties in Tbilisi posted on LIVO, a major real estate website, between January 2019 and June 2021. Monthly data on real estate listings for sale, rent, or exchange in Georgia between January 2019 to June 2021 (30 months) are included in the LIVO data. The number of observations ranges from 30,000 to 60,000 depending on the month. The regressions include year-month and house/apartment fixed effects. In the independent variable specification, PM2.5 is predicted in the first stage using wind patterns and thermal inversions as instruments on weather, and year, month, and house/apartment fixed effects. The data and method are described in Baquié et al. (2023).

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