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Air Pollution and Poverty

PM2.5 Exposure in 211 Countries and Territories

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Abstract

Air pollution is one of the leading causes of death worldwide, especially affecting poorer people who tend to be more exposed and vulnerable. This study contributes (i) updated global exposure estimates for the World Health Organizations's 2021 revised fine particulate matter (PM2.5) thresholds, and (ii) estimates of the number of poor people exposed to unsafe PM2.5 concentrations. It shows that 7.28 billion people, or 94 percent of the world population, are directly exposed to unsafe average annual PM2.5 concentrations. Low- and middle-income countries account for 80 percent of people exposed to unsafe PM2.5 levels. Moreover, 716 million poor people (living on less than $1.90 per day) live in areas with unsafe air pollution. Around half of them are located in just three countries: India, Nigeria, and the Democratic Republic of Congo. Air pollution levels are particularly high in lower-middle-income countries, where economies tend to rely more heavily on polluting industries and technologies. The findings are based on high-resolution air pollution and population maps with global coverage, as well as subnational poverty estimates based on harmonized household surveys.

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Air Pollution and Poverty:
PM2.5 Exposure in 211 Countries and Territories

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1. Introduction

Air pollution has wide-ranging and profound impacts on human health and well-being. Poor air quality has been shown to be responsible for over 4 million death each year from outdoor pollutants, another 2.3 million from indoor air pollution, a wide range of cardiovascular, respiratory, and neurological diseases, as well as reductions in cognitive abilities (WHO, 2018). Studies show that the vast majority of the world's population face unsafe air pollution levels. Yet, our understanding of what exact air pollution levels should be considered *unsafe* is still evolving. Based on the latest medical evidence the WHO updated its air quality guidelines in 2021, significantly increasing the stringency of its 2005 guidelines.

A growing evidence base also highlights that the exposure to and impact of air pollution are not equally distributed. As health and productivity suffer, evidence from the US has shown that air pollution reinforces socio-economic inequalities. Especially poor and marginalized groups are often exposed to higher pollution levels. In addition, these groups also tend to be more vulnerable to the impacts of pollution, since low-paying jobs are more likely to require physical and outdoor labor, meaning that people are faced with heightened exposure. Pollution sources, such as industrial plants or transport corridors, are disproportionately placed in low-income neighborhoods. And as they increase air pollution further, this drives down housing prices, which in turn reinforces their status as low-income neighborhoods. Constraints in terms of the accessibility, availability and quality of health care provision further increase air pollution related mortality among low-income groups.

In short, socio-economic marginalization makes people more exposed and vulnerable to air pollution. Yet, apart from substantial evidence for the US, little evidence exists documenting the global scale of poor people's exposure to harmful air pollution. A better understanding of the interplay between air pollution and poverty could be crucial for several reasons. Studies from high-income countries on the mortality and morbidity associated with air pollution may not be directly transferable to low-income countries and communities, where the nature of occupations and health care differ substantially. The health and productivity implications of unsafe air pollution will also impact the socio-economic development prospects of low- and middle-income countries. This is especially pertinent in low-income countries, which – as this study shows – still tend to have relatively low pollution levels compared to more industrialized middle-income countries. In these countries, it will be important to ensure that development progress does not come hand in hand with intensifying air pollution and the associated adverse effects.

Against this context, this study explores the global prevalence of unsafe outdoor air pollution, and how it interacts with poverty. It uses global high-resolution data on ambient air pollution (outdoor concentrations of PM2.5), population distribution, and poverty to provide aggregate exposure estimates (see Section 3.1 on data sources). It also shows that pollution levels are most hazardous in middle-income countries, where economies tend to rely more heavily on polluting industries and technologies. This study does not cover indoor air pollution, which is another pervasive risk to health and well-being, especially in developing countries.

Overall, this study contributes to the literature in two ways. It offers the first global population PM2.5 exposure estimates based on the WHO's recent guidelines, revised in September 2021, with detailed national and subnational estimates. It also offers the first global estimates of PM2.5 exposure and its interaction with national and subnational poverty levels.

The rest of this study is organized as follows. Section 2 reviews the existing evidence on air pollution, health impacts and development outcomes. Section 3 summarizes the data sets and analytical methods used in this study. Section 4 presents results, and section 5 concludes.

2. Existing evidence

Air pollution is pervasive, caused by a wide range of economic activities.
Air pollution refers to the heightened concentration of a range of different pollutants, most notably particulate matter (PM), ozone (O3), nitrogen dioxide (NO2), carbon monoxide (CO), and sulfur dioxide (SO2). While also occurring naturally, hazardous concentration levels of these pollutants are predominantly the result of human activities, including transport, fossil fuel combustion, and agriculture. This also means that their occurrence has high spatial correlation. For instance, major urban centers typically have increased concentrations of all of the above-mentioned pollutants. Using remotely sensed carbon dioxide (CO2) measurements from over 1,200 cities in 138 countries, Dasgupta et al (2021) show that emission levels correlate strongly with population size and economic development levels, though the presence of public transport systems (subways) can reduce local emissions.

The vast majority of the world's population faces air pollution levels that are considered unsafe by the WHO. For PM2.5, one of the most pervasive pollutants, the WHO's 2005 guidelines recommend for average annual concentrations not to exceed 10 $\mu g/m^3$ (WHO, 2005). Southerland et al (2022) study PM2.5 concentration trends over two decades for over 10,000 urban centers, and show that 86% (2.5 billion inhabitants) of urban inhabitants lived in urban areas that exceeded the WHO's 2005 guideline threshold of 10 $\mu g/m^3$ for PM2.5. The WHO's (2021) Global Air Quality Guidelines further revise the 2005 guideline threshold down to 5 $\mu g/m^3$, meaning that an even higher percentage of the world's population is exposed to unsafe concentrations.

Exposure to unsafe levels of particle concentration has a wide range of health impacts.
The WHO's revised threshold reflects a growing body of evidence on the wide-ranging global burden of disease associated with air pollution. There is strong evidence on the causal relationship between air pollution – especially PM, O3, NO2, SO2 – and all-cause mortality, as summarized by the WHO (2021). Heightened air pollution exposure has been shown to increase the risk of chronic obstructive pulmonary disease, ischemic heart disease, lung cancer, stroke, as well as chronic and acute respiratory diseases such as asthma (Cohen et al., 2017; WHO, 2018). Besides cardiovascular and respiratory diseases, growing evidence exists on the role of PM2.5 exposure in increasing the risk of type II diabetes and neurological diseases such as Alzheimer's (Peters et al., 2019; GBD 2019 Risk Factors Collaborators, 2020). Evidence also suggests that air pollution exposure increases neonatal mortality due to low birth weight and short gestation (GBD 2019 Risk Factors Collaborators, 2020; Patel, et al. 2021). Cumulative exposure to air pollution can also result in a range of health issues that lower long-term quality of life (O'Neill, et al. 2003).

Estimates of the number of people affected by air pollution related diseases are staggering. The WHO (2018) estimated that ambient (i.e. outdoor) air pollution caused 4.2 million premature deaths in 2016. Of these deaths, 58 percent were due to ischemic heart disease and stroke, 18 percent were due to chronic obstructive pulmonary disease and acute lower respiratory infections, and 6 percent due to lung cancer. Such ambient air pollution is driven mainly by fossil fuel combustion, transport and industry. In addition, the WHO highlights the serious health risks due to indoor air pollution faced by about 2.6 billion people who rely on coal and biomass for cooking and heating their homes. In 2016, the WHO attributed about 3.8 million premature deaths to such indoor air pollution. The 2019 Global Burden of Disease study (GBD) estimates that 4.5 million premature deaths were due to ambient air pollution and another 2.3 million premature deaths due to indoor air pollution. PM2.5 is identified as the pollutant responsible for the vast majority of air pollution deaths.

Focusing specifically on PM2.5 exposure in urban areas, Southerland et al (2022) show that average pollution levels have decreased in most regions between 2000 and 2019. Nevertheless, PM2.5 attributable deaths have increased in the same period in all regions except Europe, and North and Latin

America – mostly driven by changes in population sizes, shifting age structures, and pre-existing disease prevalence. They estimate that 1.8 million premature deaths in urban areas can be attributed to PM2.5 exposure in 2019. These numbers suggest that meaningful reductions in air pollution deaths can only be achieved through rapid pollution reduction and improved access to affordable high-quality health care.

Besides mortality and morbidity effects, air pollution also reduces cognitive ability and productivity of affected populations. Empirical evidence from brain-training experiments shows that PM2.5 exposure impairs cognitive abilities of adults, while these effects are largest for those in prime working age and those with low ability (La Nauze and Severini, 2021). There is even evidence that short-term exposure to air pollution negatively affects the performance of highly skilled workers – professional baseball umpires have been documented to make more incorrect calls when exposed to high levels of carbon monoxide (Archsmith et al 2018). Such evidence on the relationship between air quality and brain health explains how air pollution can negatively impact productivity and exacerbate inequalities (Peeples 2020).

Poor people tend to be more exposed and more vulnerable to air pollution.
While global estimates of air pollution deaths differ somewhat from study to study, the evidence is in strong agreement that air pollution is one of the leading causes of deaths (Lelieveld et al. 2020). Several factors are compounding so that this burden is disproportionately borne by low- and middle-income countries. Especially in the developing countries of South and East Asia, large populations are located in densely populated urban areas. Less stringent air quality regulations, the prevalence of older polluting machinery and vehicles, subsidized fossil fuels, congested urban transport systems, rapidly developing industrial sectors, and cut-and-burn practices in agriculture are all contributing to heightened concentration levels. In addition, high proportions of physical and outdoor labor mean that more people are faced with heightened exposure. Constraints in terms of the accessibility, availability and quality of health care provision further increase air pollution related mortality in developing countries (Lelieveld, et al. 2020). Evidence on air pollution in India suggests that a one GW increase in coal-fired capacity corresponds to a 14 percent increase in infant mortality rates in districts near versus far from the plant site (Barrows et al 2019). This effect is 2-3 times larger than estimates from the developed world.

The burden of air pollution not only falls disproportionately on poorer countries; within countries poorer and more marginalized communities also tend to be exposed to higher pollution levels (Jbaily et al. 2022; Bell et al 2013). This inequality in exposure is well documented in the United States, where data on socio-economic characteristics is available with high spatial disaggregation (Fann et al, 2018; Bell et al, 2013; Colmer et al, 2020; Kioumourtzoglou et al 2016; Bell & Ebisu, 2012; Mikati et al. 2018).

Patel et al. (2021) show that in the US, industrial planning policies have disproportionately placed polluting industries in areas with large Black, Hispanic and Asian populations. As a result, these minority groups face systematically higher pollution levels. Tessum et al. (2021) show that the disproportionate exposure to high PM2.5 exposure by racial-ethnic minorities in the US is not limited to industrial emitters. The study documents that the disproportionate pollution exposure is consistent across all major emission categories, across states, urban and rural areas, income levels, and exposure levels. Studying the period from 2004 to 2016, Jbaily et al (2022) show that in addition to ethnic minorities, low-income populations also face systematically higher PM2.5 pollution levels – and these exposure disparities have been increasing over time. Air quality is also documented to influence real estate prices, so that lower-income households tend to locate into cheaper, more polluted neighborhoods (Chay & Greenstone, 2005).

Outside the US, evidence on the inequality in air pollution exposure is more limited – often due to a lack of socio-economic data with high spatial disaggregation. Hajat et al. (2015) offer a systematic review of the literature on socio-economic disparities and air pollution exposure, compiling country- and city-level evidence from all regions. They confirm the strong evidence of unequal exposure in the US, but find mixed evidence for European countries. Only a limited number of studies exists for Asian and African countries, though they tend to confirm the presence of inequality in exposure found in the US.

In short, there is convincing evidence from the US and other case studies that poor people are disproportionately exposed and vulnerable to air pollution. Yet, there is limited evidence documenting how many poor people globally face unsafe air quality, and how their pollution burden is distributed across and within developing countries. In this context, we contribute (i) the first updated global exposure estimate for the WHO's 2021 revised air pollution guidelines, and (ii) the first estimates of the number of poor people exposed to unsafe PM2.5 concentrations.

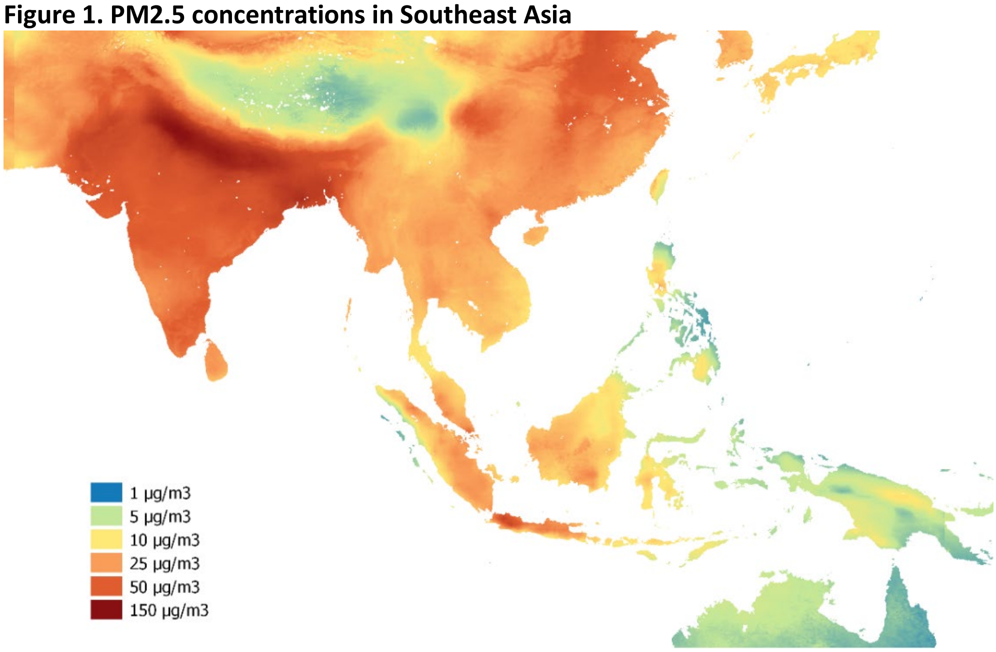
3. Data and methods

3.1. Data sets used in this study

This section details the data sets used in this study to calculate global population exposure to high concentrations of air pollution.

Air pollution data (PM2.5): In this paper, we study the differentiated exposure to PM2.5 pollution across countries, rather than the cumulative load of all pollutants. Hence, in this study we focus on PM – one of the most common pollutants, and one that is primarily caused by fossil fuel combustion, such as car engines and coal or gas power plants. Airborne PM is commonly categorized by the diameter of particles, as this determines aerial transport and removal processes as well as their impacts within the respiratory tract (WHO, 2021); i.e. PM2.5 for particles of up to 2.5 µm in diameter, and PM10 (up to 10 µm). In this study we focus on PM2.5, which are among the most harmful pollutants as they can pass through the lungs into the bloodstream and affect other organs.

Figure 1. PM2.5 concentrations in Southeast Asia



Source: authors' visualization based on van Donkelaar et al (2021)

We use the gridded data set of ground-level fine particulate matter (PM2.5, in µm/m^3) concentrations provided by van Donkelaar et al (2021). The data set offers both annual and monthly mean concentrations for the years 1998 to 2019 with global coverage and at a resolution of 0.01 degree. The data set is constructed by combining Aerosol Optical Depth (AOD) satellite retrievals from the NASA MODIS, MISR, and SeaWIFS instruments with the GEOS-Chem chemical transport model, and subsequently calibrating to global ground-based observations using a geographically weighted regression. The resolution of 0.01 degree (equivalent to about 1.1 kilometer at the equator) is well suited to capture regional variation in concentrations, though not granular local variations.

As a global modeled data set, some uncertainty is to be expected, though sensitivity tests suggest good agreement with ground measurements (van Donkelaar et al, 2021). For more spatially nuanced analyses, for instance at the neighborhood or street level, alternative data based on local measures would be required. Moreover, it should be noted that the chemical composition of PM2.5 particles can differ by pollution source (Thurston, et al 2022). PM2.5 particles associated with the combustion of fossil fuels are more toxic due to higher acidity levels (e.g. sulfuric particulate matter from coal burning). The global PM2.5 can inform on total particle concentration, but not the spatial variation in the chemical composition (i.e. acidity) of particles.

Population density: We estimate the location of people using the WorldPop Global High Resolution Population data set (WPGP), produced by the University of Southampton, the World Bank, and other partners. It offers global coverage and is available yearly from 2000 to 2020. While WorldPop provides several data sets (including poverty, demographics, and urban change mapping), we use the population density map (WorldPop-PPP-2020). In a raster format, this data set provides the number of inhabitants per cell, with a resolution of 3 arcseconds, thus specifying the distribution of population. This information is based on administrative or census-based population data, disaggregated to grid cells based on distribution and density of built-up area, which is derived from satellite imagery (Freire et al., 2016, 2020).

The choice of population density map is important for estimating people's exposure to natural hazards. Smith et al. (2019) provide a sensitivity analysis for flood exposure assessments using different population density maps, including WorldPop (3 arcsecond). They show that high-resolution population density maps perform best in capturing local exposure distribution, particularly the High-Resolution Settlement Layer (HRSL) with 1-arcsecond, or ~30 m resolution, produced jointly by Facebook, Columbia University and the World Bank. While HRSL is only available for a limited number of countries, WorldPop is shown to perform better than alternatives with global coverage, such as LandScan data (30-arcsecond, ~900 m resolution) (Bright et al., 2015).

Subnational poverty rates: For 1,755 of the 2,227 subnational units, the World Bank's Global Subnational Poverty Atlas offers several poverty estimates, which are all derived from the latest available Living Standards Measurement Survey (LSMS) for the respective country (World Bank, 2021). Areas where no poverty estimates are available tend to be high-income countries and small island states. For the purpose of this study, the standard World Bank definitions of poverty are used to determine the number of poor people in a given subnational administrative unit. Specifically, poverty is defined by the daily expenditure thresholds of $1.90, $3.20, and $5.50.

Administrative boundaries: The definition of national administrative boundaries follows the standard World Bank global administrative map. However, national boundaries are further disaggregated into subnational units for all countries where World Bank household surveys are available with subnational representativeness. These subnational units are typically provinces or states (i.e. admin1) but can also include custom groupings of subnational regions determined by the sampling strategy of household surveys. Overall, this study covers 211 countries, which are disaggregated into 2,183 subnational units.

3.2. Methodology and step-wise computational process

To estimate the number of people who are exposed to unsafe air pollution levels, this study follows a computational process in four main steps, which are outlined in this section. For further details, refer to Rentschler and Malhab (2020), who offer a detailed description of the stepwise computational process that is replicated in this study.

Resample the PM2.5 data: The air pollution map is resampled to ensure that pixels align with the gridded population density map.

Define air pollution risk categories: While the air pollution map offers average annual PM2.5 concentration levels along a continuous scale, the values are aggregated into six risk categories as summarized in Table 1. These risk categories are defined in line with the air quality guideline (AQG) level by the WHO (2021). The WHO recommends an annual PM2.5 AQG level of up to 5 µg/m. For countries with PM2.5 concentrations above this threshold, it recommends interim targets at 10, 15, 25, and 35 µg/m^3, which correspond to a linearly increasing mortality rate (Table 1). At higher concentrations, the concentration-response function of mortality may no longer be linear. The epidemiological evidence underpinning these AQG thresholds for PM2.5 is discussed in a systematic review by Chen & Hoek (2020). Each 1 degree cell of each country is assigned one of the six risk categories. This is repeated for the world's landmass of 149 million square kilometers, which implies the processing of about 300 million data points.

Table 1. PM2.5 concentration thresholds

Risk classification		PM2.5 concentration	Mortality
Safe	**No/minor risk**	≤ 5 µg/m^3	*baseline*
Unsafe	**Low**	5 – 10 µg/m^3	4% increased mortality rate
	Moderate	10 – 15 µg/m^3	8% increased mortality rate
	High	15 – 25 µg/m^3	16% increased mortality rate
	Very high	25 - 35 µg/m^3	24% increased mortality rate
	Hazardous	over 35 µg/m^3	> 24% increased mortality rate

Assign air pollution risk categories to population headcounts at the pixel level and aggregate to the administrative unit: As the air pollution and population density maps are converted into the same spatial resolution, each population map cell can be assigned a unique air pollution risk classification – these cells can then be aggregated to the administrative unit level (e.g. province or district level). This allows the calculation of population headcounts for each risk category and for each (sub-)national administrative unit. This process yields an estimate of the number and share of people exposed to no-, low, moderate, high, very high and hazardous air pollution concentrations throughout the year. We offer these exposure headcount maps as global gridded layers with a resolution of 90 meters. In addition, we aggregate them to administrative units, including for each country and subnational unit. These estimates are further aggregated to yield regional and global estimates.

Compute the number of poor people exposed to air pollution risk: While poverty estimates are not available at the pixel level, the World Bank's Global Subnational Poverty Atlas (GSPA) of harmonized household surveys provides them at the subnational level for at least 153 countries. These poverty shares are multiplied with the population headcount that is estimated to be exposed to unsafe air pollution, in order to obtain an estimate of the number of poor people in each administrative unit exposed to air pollution risk.

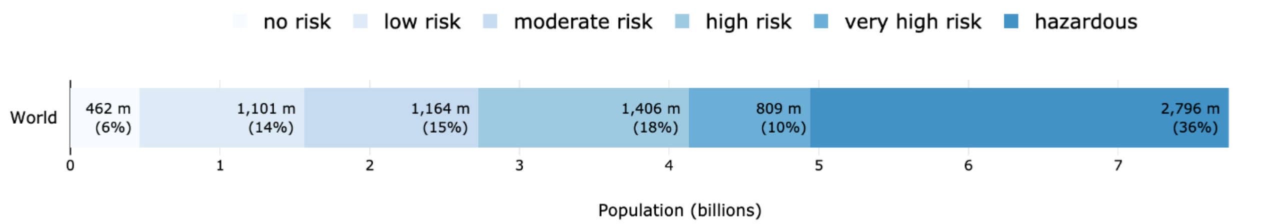
4. Results

For each of the countries analyzed, the results are available as raster files with a 1km spatial resolution and as shapefiles with data aggregated to the admin 1 (sub-national), admin 0 (national), regional, and global levels. In this section, we present visualizations of key findings as maps, using a variety of spatial scales, as well as graphs to highlight pertinent insights.

4.1. Global and regional air pollution exposure

Our estimates show that globally 7.3 billion people face air pollution levels considered unsafe by the WHO (i.e. annual average concentration over 5 µg/m^3; Figure 2); 6.2 billion people are directly exposed to at least moderate level of air pollution risk (i.e. annual average concentration over 10 µg/m^3); for 2.8 billion people pollution levels are hazardous – with PM2.5 concentrations over 35 µg/m^3 and over 24 percent increased mortality risk relative to safe areas. Only 462 million people world-wide are exposed to PM2.5 that are considered safe by the WHO (lower than 5 µg/m^3). In other words, considering a global population of 7.7 billion (World Bank, 2019), approximately 94 percent of the world's population are exposed to unsafe levels of PM2.5 concentration.

Figure 2. Global population headcounts exposed to different levels of air pollution risk



By regionally disaggregating global exposure headcounts, it becomes apparent that air pollution risks are particularly prevalent in certain regions. At 2.2 billion people, the East Asia and Pacific (EAP) region has the highest number of people exposed to unsafe PM2.5 concentrations – corresponding to about 95 percent of EAP's total population. In the South Asia region (SAR), about 1.8 billion people are exposed to unsafe levels of air pollution – i.e. about 99 percent of the SAR population. In all other regions, the number of people exposed to high levels of air pollution account for a smaller share of the overall population. In the Middle East and North Africa (MENA), Sub-Saharan Africa (SSA), and Europe and Central Asia (ECA) regions and the United States and Canada, between 95 to 92 percent of the respective regional populations are exposed to unsafe PM2.5 concentrations. In Latin America and the Caribbean, exposure as a share of population is slightly lower (84 percent). Figures 3 and 4 provide a breakdown of regional exposure estimates in absolute and relative terms.

Figure 3. Regional disaggregation of the global headcount estimates of people exposed to unsafe PM2.5 concentrations

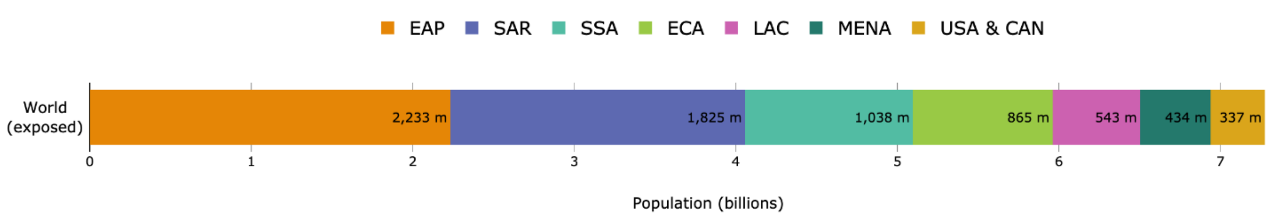
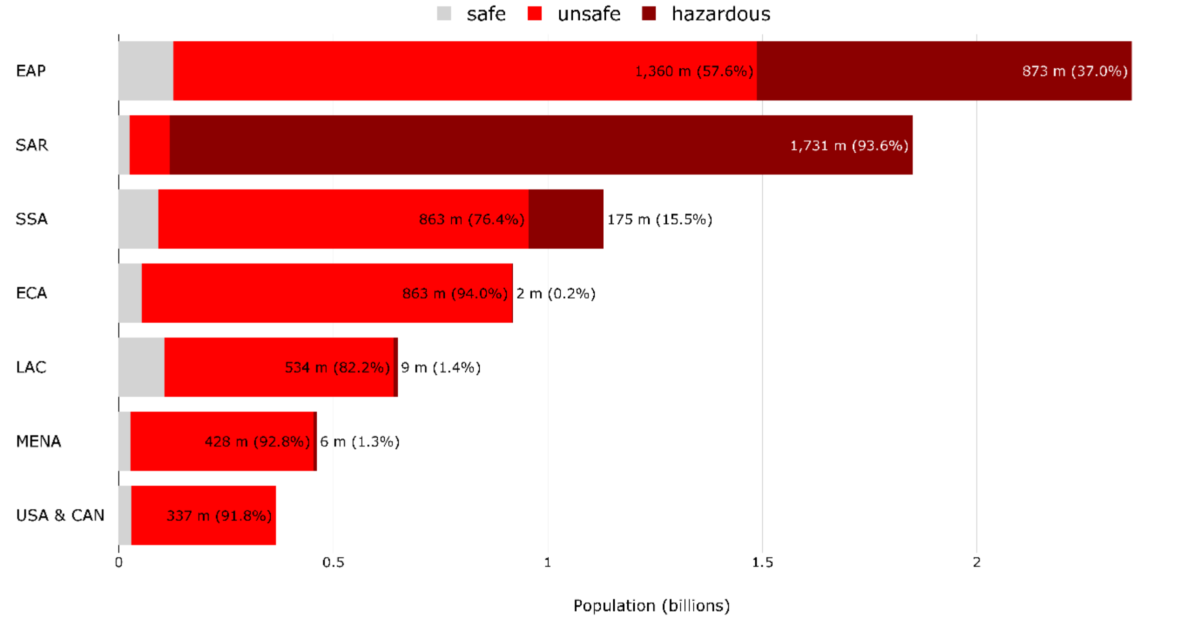


Figure 4. Number of people exposed to air pollution by region (and as share of total regional population)



4.2. Countries with the largest air pollution exposed populations

Several countries stand out with particularly large populations directly exposed to unsafe air pollution levels, thus corroborating the findings by Landigran et al (2018; Figures 5 and 6). The two most populous countries, China and India, also have the highest absolute population exposure to unsafe air pollution. About 36% of all people exposed to unsafe concentrations of PM2.5 air pollution globally reside in India or China. In India, 1.36 billion people (or 99 percent of the population) are exposed to unsafe PM2.5 concentrations (i.e. over 5µg/m^3), of which 1.33 billion (96 percent) face hazardous levels (over 35 µg/m^3). In China, 1.41 billion people (or 99 percent of the population) face unsafe PM2.5 concentrations (i.e. over 5µg/m^3), of which 0.765 billion (53 percent) face hazardous levels (over 35 µg/m^3).

Figure 5. Absolute population exposure to high concentrations of air pollution at the country level (millions)

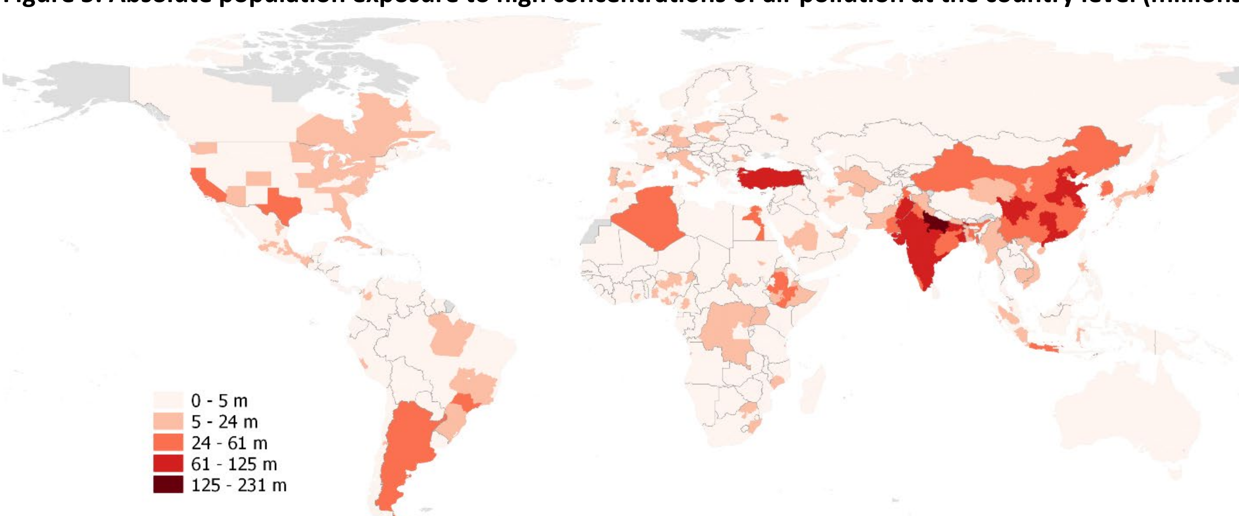
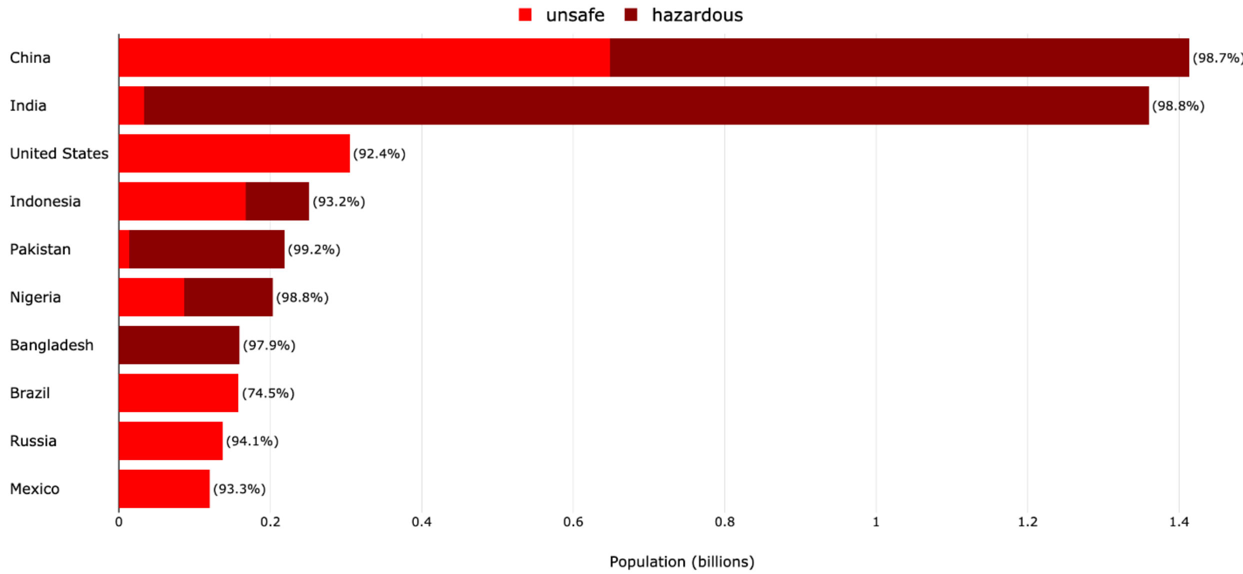


Figure 6. Countries with highest population exposure to unsafe PM2.5 levels

a) Top 10 countries: Number of people exposed to unsafe concentrations of air pollution (and as share of total national population)



b) Top 10 countries: Share of population exposed to hazardous concentrations of air pollution

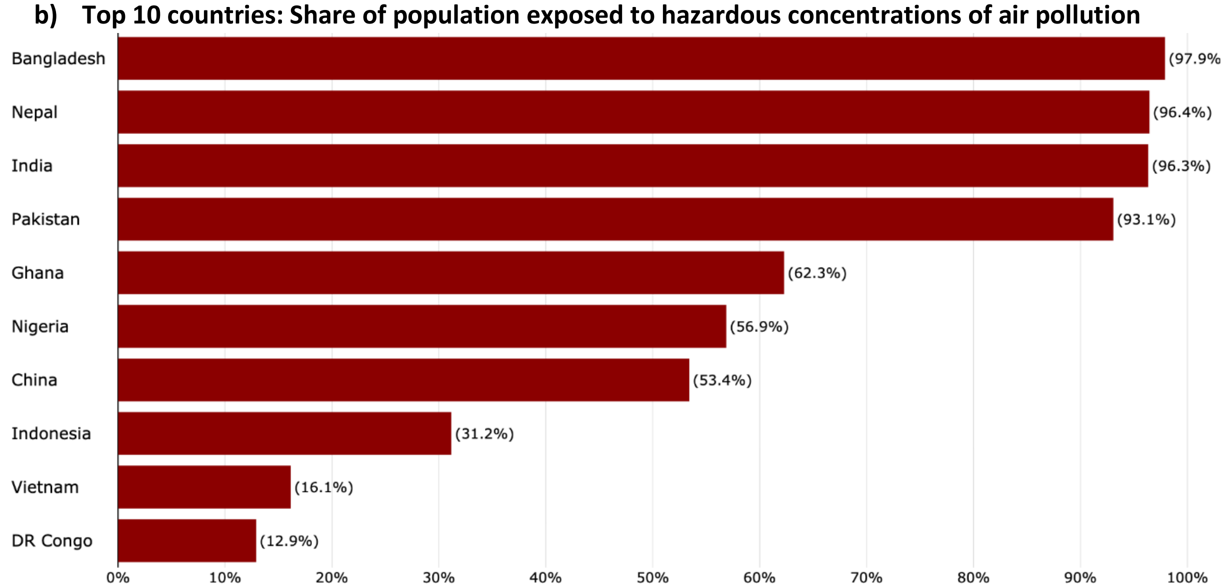
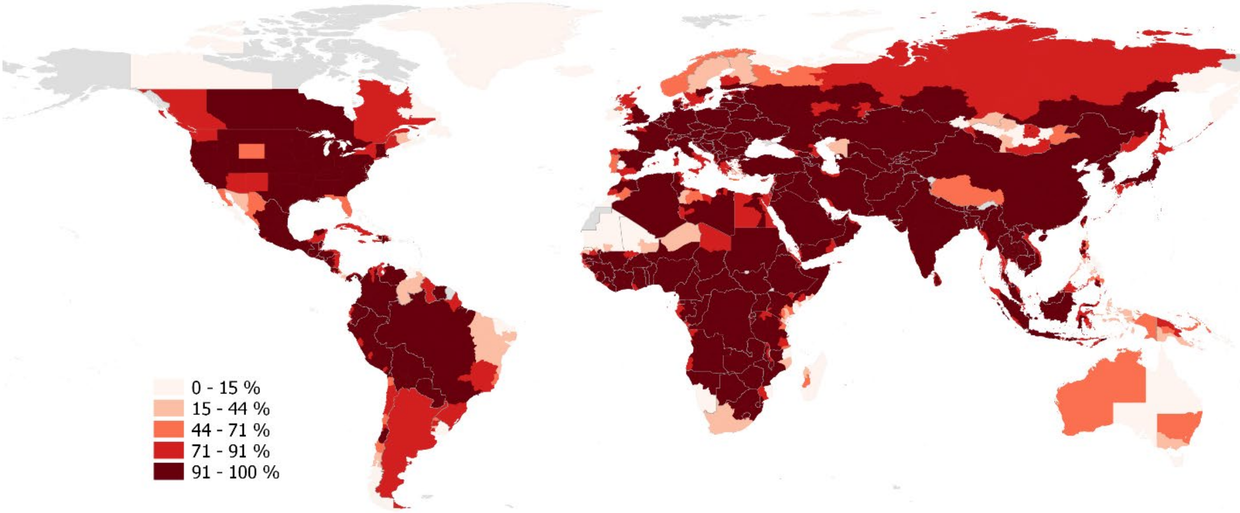


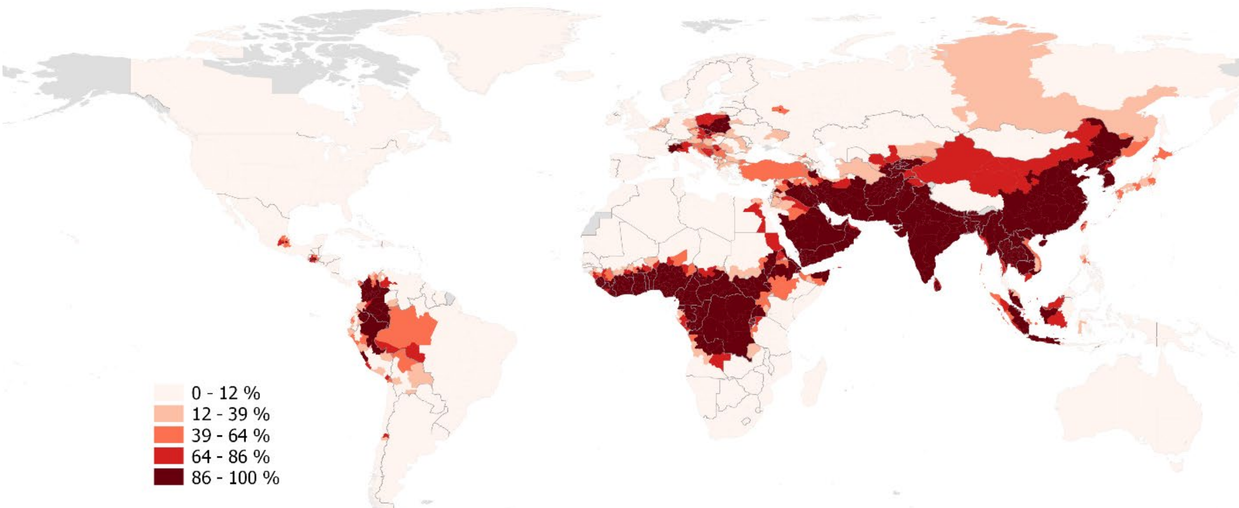
Figure 7 presents relative exposure estimates for all countries. It demonstrates that in large parts of the world and across all regions, the vast majority of the population are exposed to unsafe PM2.5 levels (i.e. over 5µg/m^3; Figure 7a). Unlike for example flood hazards, which are highly localized, air pollution tends to cover and move across large areas – for instance blanketing entire cities or regions. As a consequence, if large proportions of a population live in densely populated areas, they tend to be collectively exposed to unsafe pollution levels. Considering a higher pollution threshold of 15 µg/m^3 shows that populations in developing countries face heightened pollution (Figure 7b) – high exposure levels range from Central America, Western and Middle Africa, Eastern Europe, Middle East, as well as Central, South, and East Asia. The regions where large parts of the population even face hazardous PM2.5 concentrations (over 35 µg/m^3) are Eastern China, the Indian subcontinent, and parts of Western Africa (Figure 7c).

Figure 7. Unsafe PM2.5 exposure as share of population

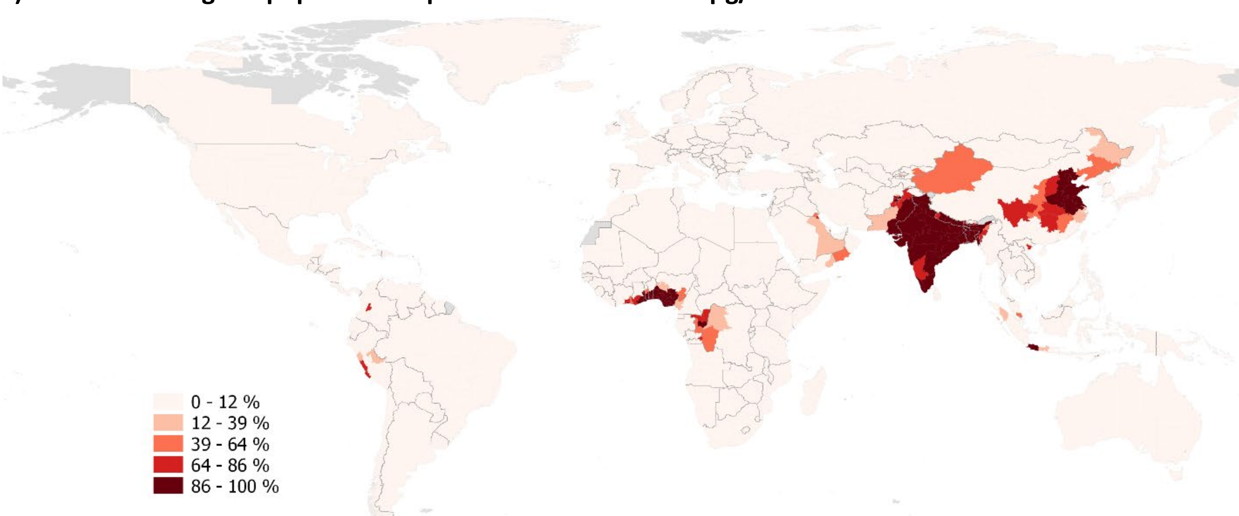
a) Percentage of population exposed to PM2.5 over 5 μg/m³



b) Percentage of population exposed to PM2.5 over 15 μg/m³



c) Percentage of population exposed to PM2.5 over 35 μg/m³

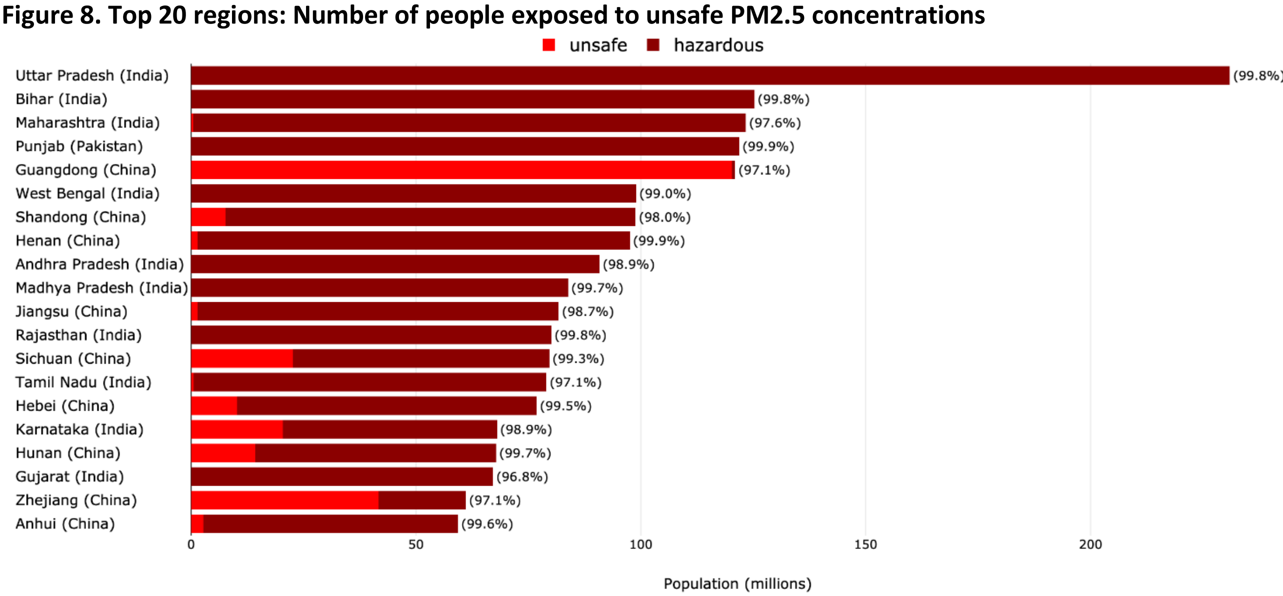


4.3. Air pollution exposure at the subnational level

Country-level estimates provided in the previous section can highlight countries in which air pollution risks are particularly prevalent. However, in most cases air pollution risks are not uniformly distributed across a country but concentrated in densely populated and urbanized areas. In this section we present PM2.5 exposure estimates disaggregated to subnational regions. World Bank household surveys are sampled to be statistically representative at different subnational levels – in this study we adopt these statistically representative subnational units which enable us to compare air pollution exposure estimates with socio-economic characteristics, such as income levels and poverty (Sections 4.4 &4.5).

Unsafe air is almost universal among the 20 subnational regions with the largest number of people exposed to PM2.5 concentration over 5 μg/m^3 (Figure 8). In these 20 subnational regions, 98.9 percent are exposed to unsafe PM2.5 concentrations (over 5 μg/m^3), and 86.3 percent are exposed to hazardous levels (over 35 μg/m^3). The most populous regions in China and India dominate the global ranking (Figure 8); of the top 20, ten are in India, nine in China, and one in Pakistan. These subnational regions have in common that they are home to large populations, are densely populated, and host to substantial industrial, agricultural and transport sector activities. For instance, the province of Punjab, Pakistan, with a population of 110 million people, contributes 57 percent of Pakistan's GDP and hosts large urban centers such as Lahore. In our estimates we also identify 774 subnational areas in which over 99 percent of the population face PM2.5 concentrations over 5 μg/m^3. In 33 subnational areas over 99 percent of the population face concentrations over 35 μg/m^3.

Figure 8. Top 20 regions: Number of people exposed to unsafe PM2.5 concentrations



4.4. Poverty and air pollution

Considering the income levels of pollution exposed populations is crucial, as it is well documented that – given the same pollution levels – poor people tend to be more vulnerable to serious health impacts. Poorer people tend to be more exposed to air pollution because they are more likely to depend on jobs that require outdoor physical labor. When affected by pollution related diseases, they also tend to have more limited access to adequate and affordable health care, thus increasing mortality rates. In addition, poorer countries tend to have less developed health care systems. In short, considering the interplay between pollution exposure and poverty can shed light on the vulnerability of affected populations.

Poverty and air pollution exposure.

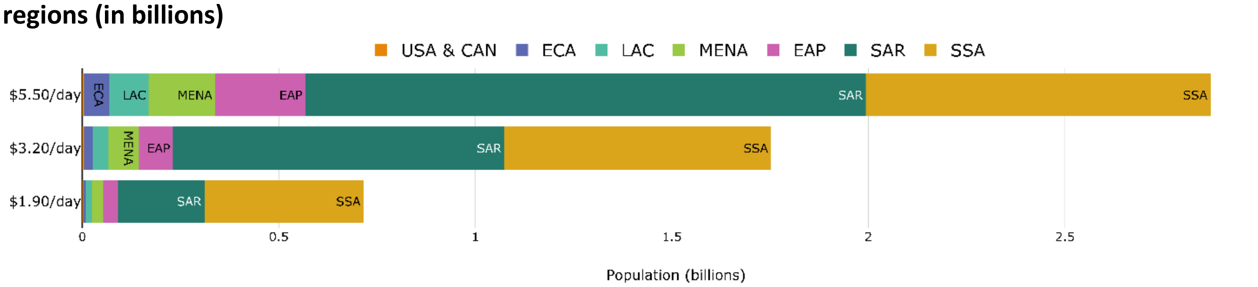
By combining air pollution exposure estimates with survey-based sub-national data on poverty, we further estimate air pollution exposure among the world's poor (Table 2). Our estimates show that 716 million people living in extreme poverty (living on less than $1.90 per day) are directly exposed to unsafe PM2.5 concentrations; of these, 405 million (or 57 percent) are in Sub-Saharan Africa (figure 9). Further, 275 million people living in extreme poverty are exposed to hazardous PM2.5 concentrations (over 35 µg/m^3). Approximately one in ten people exposed to unsafe levels of air pollution live in extreme poverty.

When poverty is defined using less extreme (i.e. higher) income thresholds, the number of air pollution-exposed poor people increases significantly. Around 1.8 billion are estimated to live in unsafe air pollution areas while living on less than $3.20 a day. The number increases to 2.9 billion when considering incomes below $5.50 a day. Increasing the poverty threshold from $1.90 to $5.50 doubles the number of poor people exposed to unsafe PM2.5 levels in Sub-Saharan Africa from 405 million to 877 million.[1] In South Asia (SAR) the number of the poor and pollution-exposed increases more than six-fold from 220 million to 1,426 million; in East Asia (EAP) the increase is six-fold from 38 million to 229 million. Overall, four of every ten people exposed to unsafe PM2.5 levels globally are living on less than $5.50 a day.

Table 2. PM2.5 exposure headcounts at different poverty thresholds

	Poverty threshold (consumption in US $ per day)		
	$1.90	**$3.20**	**$5.50**
Number of poor (millions)	768	1,853	3,034
Share of global population that is poor	9.9%	23.9%	39.2%
Number of poor that are exposed to *unsafe* PM2.5 levels (millions; over 5µg/m^3)	716	1,752	2,870
Share of population that is poor and exposed to *unsafe* PM2.5 levels (over 5µg/m^3)	9.3%	22.7%	37.1%
Number of poor that are exposed to *hazardous* PM2.5 levels (millions; over 35µg/m^3)	275	938	1,573
Share of population that is poor and exposed to *hazardous* PM2.5 levels (over 35µg/m^3)	3.5%	12.1%	20.3%

Figure 9. Number of poor people with unsafe air pollution exposure, at different poverty thresholds and by regions (in billions)



[1] In SSA, 39.3 percent of the region's total population lives in extreme poverty ($1.90), and 91.82 percent of the region's total population faces unsafe PM2.5 levels (over 5µg/m3).

Country-level poverty exposure.

Of the 716 million people living in extreme poverty and exposure to unsafe concentrations of air pollution, almost half (48.6%) are located in just three countries. With over 202 million, India has the highest number of extremely poor people exposed to unsafe PM2.5 levels of any country in the world; corresponding to 14.7 percent of India's overall population. The top 10 countries in terms of number of poor people exposed at $1.90 (figure 10) account for 67.8 percent of all poor people exposed to unsafe PM2.5 concentrations globally. Seven of the top ten countries are located in Sub-Saharan Africa. In the 10 countries with the highest share of the population being poor and exposed to high concentrations of air pollution, about 50 to 85 percent of the population is estimated to be exposed – most of which are in Sub-Saharan Africa (9 out of 10) (figure 11). Figure 12 further highlights that extreme poverty and exposure to unsafe PM2.5 concentrations coincide most acutely in Sub-Saharan Africa; though when considering higher poverty thresholds, exposure also becomes apparent in regions of the Middle East, South and East Asia, as well as Latin America.

Figure 10. Top 10 countries - number of poor people (at $1.90/day) exposed to unsafe PM2.5 levels

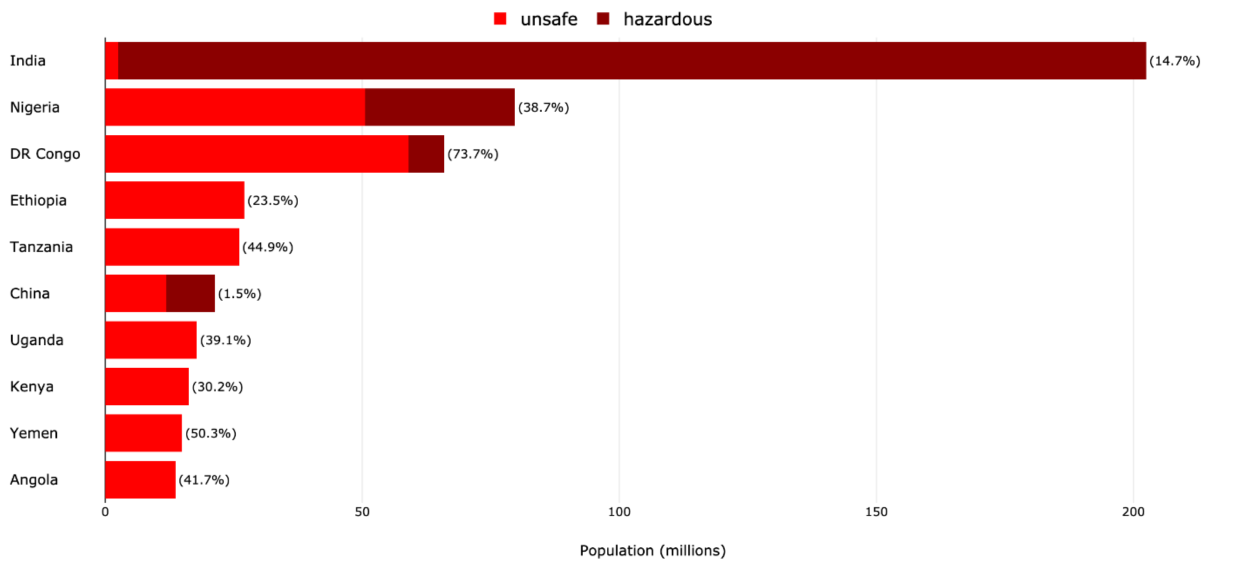


Figure 11. Top 10 countries – percentage of poor people (at $1.90/day) exposed to hazardous PM2.5 levels

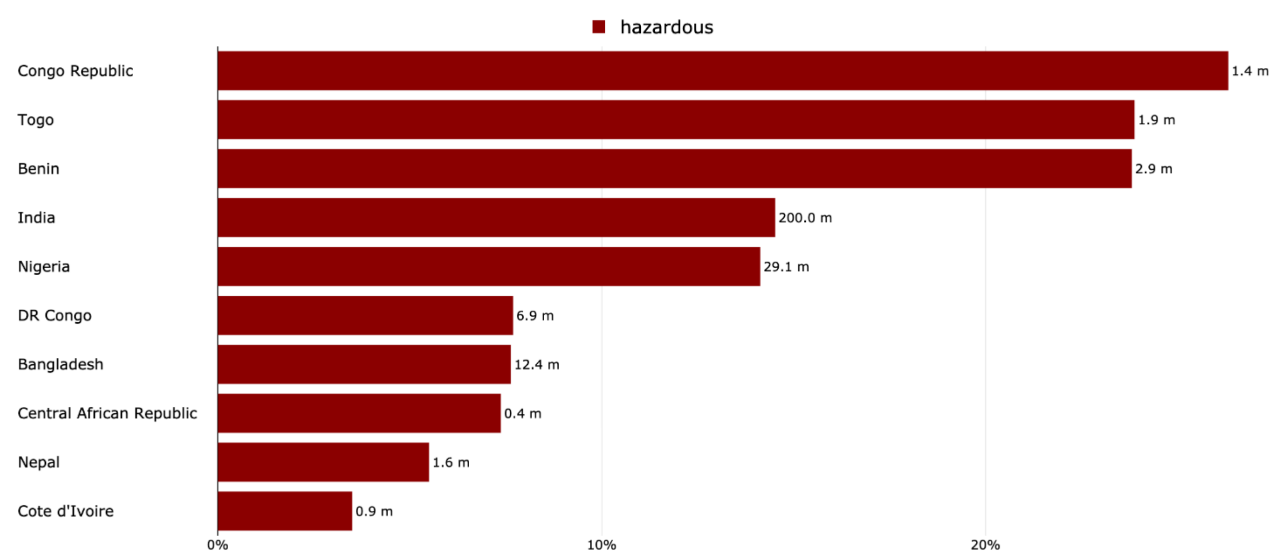
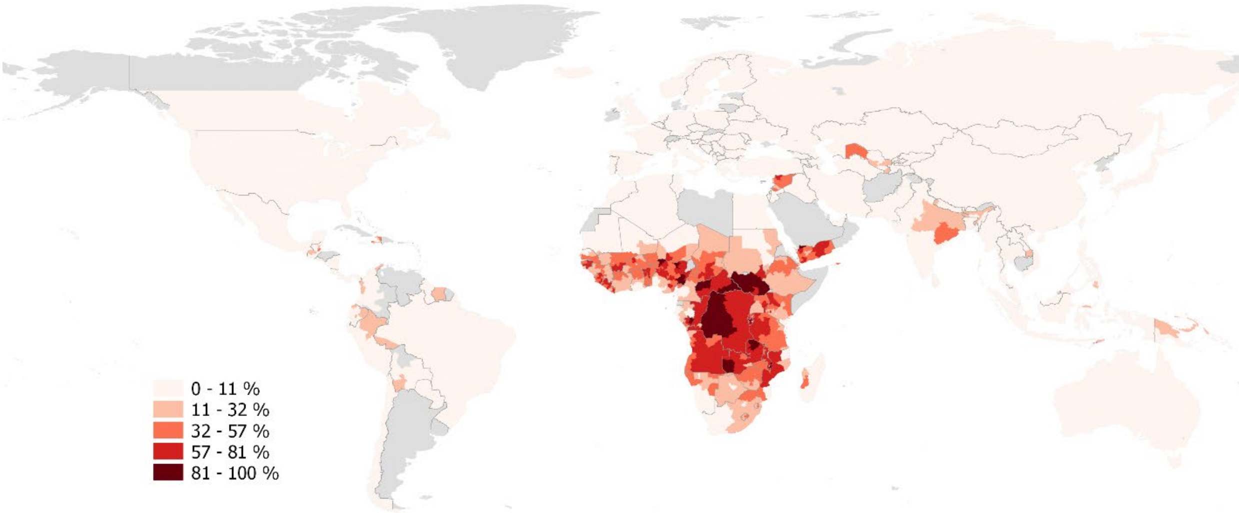
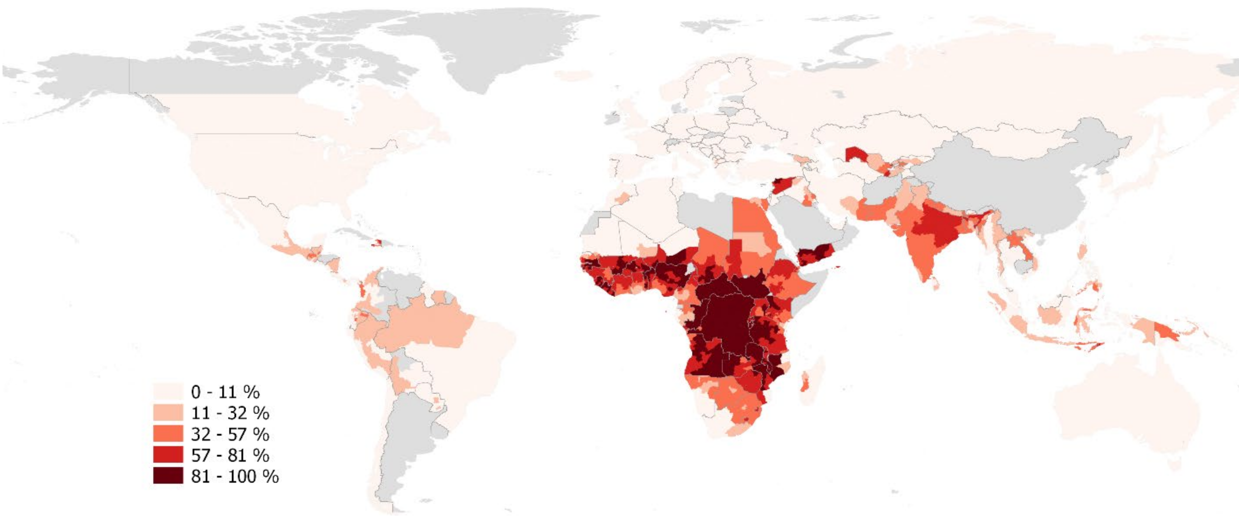


Figure 12. Regional distribution of air pollution and poverty

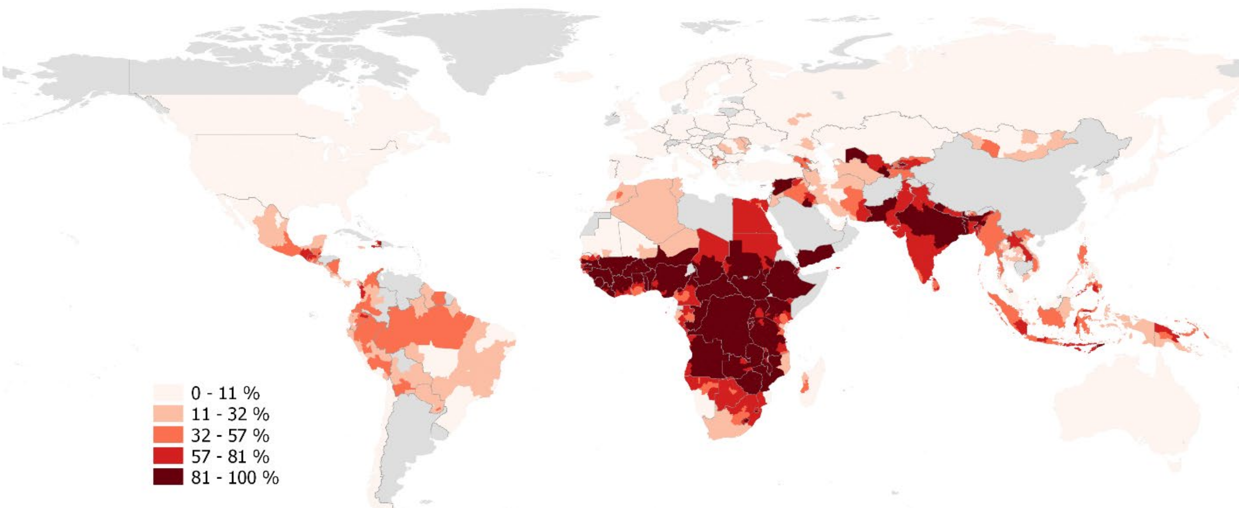
a) Share of population exposed to unsafe PM2.5 levels and living in poverty at $1.90/day



b) Share of population exposed to unsafe PM2.5 levels and living in poverty at $3.20/day



c) Share of population exposed to unsafe PM2.5 levels and living in poverty at $5.50/day

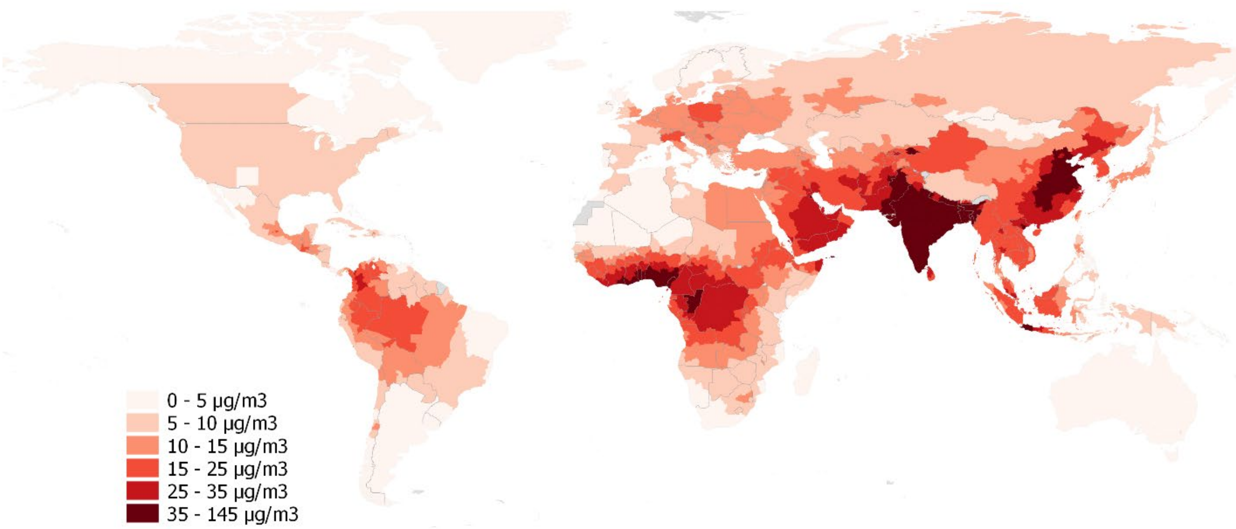


4.5. Relationship between income and air pollution concentrations

The estimates above on the geographic distribution of PM2.5 exposure suggest that pollution levels differ according to the economic development and industrialization stages of countries. The notion of the Environmental Kuznets curve would suggest that air pollution levels would be highest in middle-income countries, where polluting activities like manufacturing dominate the economy while productive capital (e.g. technology) and regulations tend not to prioritize environmental quality. In low-income countries air pollution concentrations would be relatively low, as economic activities (e.g. agriculture) tend to rely less on fossil fuels and the consumption of polluting goods (e.g. high electricity use or private car ownership) is limited to small population groups. In high-income countries pollution would be low, as economic activity tends to be focused on less polluting sectors (e.g. services), polluting activities tend to be off-shored, while clean technologies are widely available and mandated by regulation.

This also means that the pollution intensity along the economic development path is not set in stone. Whether today's low-income countries indeed follow a Kuznets type curve – i.e. intensifying pollution as a byproduct of development – depends on the availability and affordability of clean technologies, as well as the incentive structure for their adoption. For instance, the provision of subsidies for fossil fuel consumption undermines the uptake of clean technologies. This entrenches high pollution levels in low- and middle-income countries, where such subsidies are particularly common (Parry et al., 2021).

Figure 13. Mean concentrations of PM2.5



A Kuznets type relationship in air pollution exposure?

The estimates from this study show that the vast majority of people breathing unsafe air are located in middle-income countries (Figure 14). The results show that of the 7.3 billion people exposed to unsafe concentrations of PM2.5 (over 5 µg/m^3), 3.4 billion (47.3 percent) live in low- or lower-middle-income countries. In the middle-income countries 2.8 billion people are exposed to hazardous PM2.5 levels (over 35 µg/m^3), compared to just 40.5 million in low- and high-income countries combined.

In relative terms – i.e. as a share of the overall population – PM2.5 exposure is also highest in middle-income countries (Figure 15). About 64.5 percent of people in LMICs are exposed to PM2.5 levels over 35 µg/m^3, compared to just 4.4 percent in LICs and 0.9 percent in HICs. The pattern holds regardless of which concentration threshold is considered – exposure to over 5 µg/m^3, the safe threshold recommended by the WHO, or 10 μg/m³, or 35 μg/m³ (Figure 15). The regional distribution of PM2.5 concentrations (Figure 3) illustrates that these high ambient air pollution levels in MICs can be explained to a large extent by the rapid economic growth and industrialization of South and East Asia.

Figure 14. Number of people exposed to unsafe concentrations of air pollution, disaggregated by national income level classification

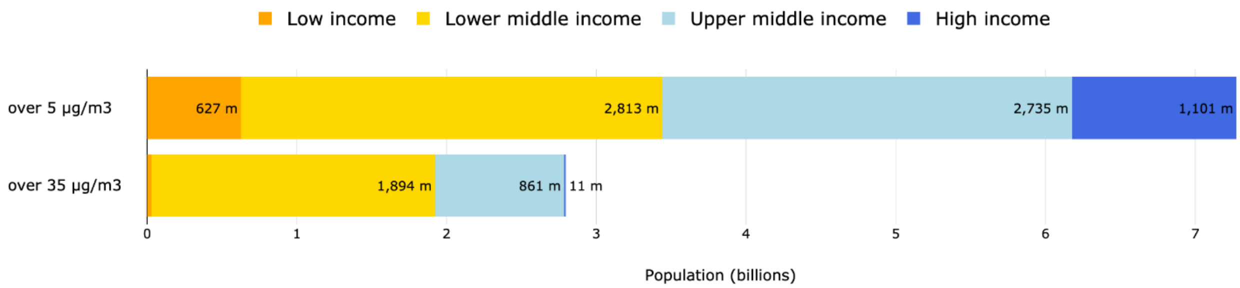
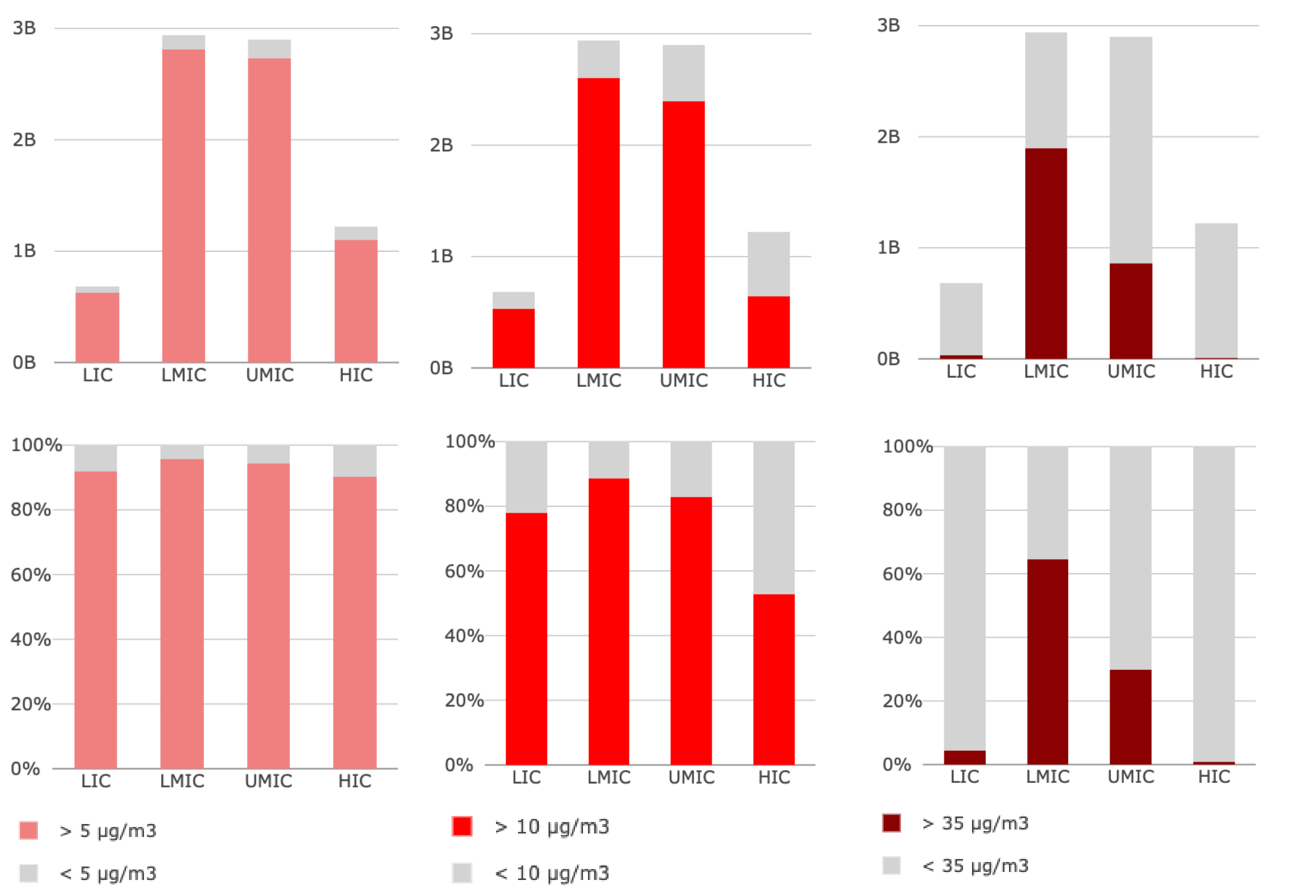


Figure 15. Global population exposure to PM2.5 concentrations. Top row: Total headcounts in billions. Bottom row: Population share exposed

a) concentration over 5 μg/m³ (4% increased mortality rate)

b) concentration over 10 μg/m³ (8% increased mortality rate)

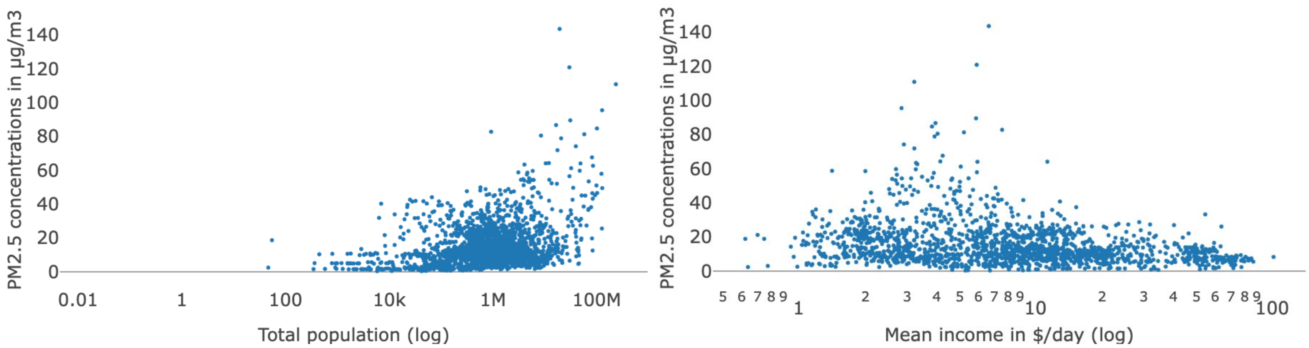
c) concentration over 35 μg/m³ (over 24% increased mortality rate)



Note: Red bars represent the population exposed to PM2.5 concentration levels over 5, 10, and 35 μg/m³ respectively. Gray bars represent the population exposed to levels below the threshold.

While this pattern is consistent with a Kuznets type relationship between pollution intensities and income levels, it is useful to consider the full range of PM2.5 concentrations (rather than a single threshold). We compute spatially averaged PM2.5 concentrations for each of the 2,183 subnational areas and compare these with population and income data. Figure 16 suggests support for two notions: areas with larger populations tend to have higher pollution levels and average pollution levels appear particularly high for areas in the middle-income category.

Figure 16. Annual average PM2.5 concentrations in 2,183 subnational regions and the relationship with population (left) and mean income (right)



We further examine this relationship statistically (Table 3) by considering both the full sample of subnational areas (models I to IV) and a subset of high-pollution areas with average concentrations over 10µg/m^3 (models V to VIII). The role of population size is consistent across all specifications. Including population as an explanatory variable for pollution levels raises explanatory power and confirms that larger populations are associated with higher pollution. This is also due to the increased polluting activities that are correlated with larger populations, such as transport, electricity generation, or industrial production. In addition, income levels have some explanatory power. For the full sample (models I to IV), higher income levels are consistently associated with lower pollution (figure 17). Negative coefficients on first and second order polynomials suggest that the relationship between income and PM2.5 is both strictly monotonically decreasing (i.e. negative first order derivative of the functional form) and concave (i.e. non-positive second order derivative).

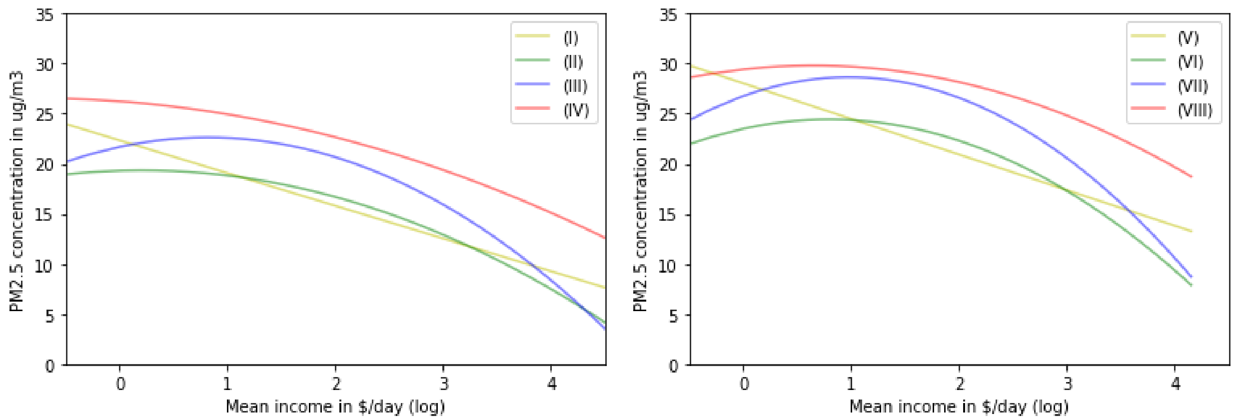
Table 3. The role of income and population in explaining mean PM2.5 concentration levels

Mean PM2.5 concentration	Full sample				Average concentration over >10µg/m3			
	(I)	(II)	(III)	(IV)	(V)	(VI)	(VII)	(VIII)
Log income	-3.2670***	0.3342	2.3043**	-0.7977	-3.5551***	2.3383	3.8596***	1.1722
	(0.281)	*(1.050)*	*(0.997)*	*(1.060)*	*(0.408)*	*(1.493)*	*(1.402)*	*(1.429)*
Log income ^2		-0.8223***	-1.4078***	-0.4958**		-1.4683***	-1.9755***	-0.9029***
		(0.231)	*(0.221)*	*(0.231)*		*(0.358)*	*(0.337)*	*(0.309)*
Log population			2.7994***	2.3827***			3.0789***	2.6146***
			(0.188)	*(0.160)*			*(0.250)*	*(0.211)*
Constant	22.3411***	19.3178***	-20.4817***	-9.6542***	28.0406***	23.5092***	-20.2021***	-10.4571***
	(0.658)	*(1.073)*	*(2.851)*	*(2.302)*	*(0.876)*	*(1.406)*	*(3.784)*	*(2.904)*
Region				YES				YES
N	1707	1707	1707	1707	1049	1049	1049	1049
adj. R2	0.073	0.079	0.185	0.420	0.067	0.081	0.196	0.440

When focusing on areas with unsafe PM2.5 levels (here with average PM2.5 concentration over 10µg/m³; models V to VIII), a Kuznets type relationship is discernable with negative coefficients for squared income terms (Figure 17). In other words, among regions with unsafe air, PM2.5 levels increase along with income up to a level of about \$9.5/day (or \$3,478/year) after which they decrease with income. However, this threshold is low, meaning that for most of the income distribution the negative relationship dominates.[2] Polynomial regression specifications can in principle be prone to over-fitting, but a non-parametric kernel regression confirms the qualitative nature of the relationship between pollution and income as summarized in Figure 17 (for kernel regression results see Annex 2).

Figure 17. Fitted lines for models (I) to (VIII)

a) Full sample **b) Average concentration over >10µg/m³**



5. Conclusion

This study offers a comprehensive account of the relationship between ambient (outdoor) air pollution exposure, economic development, and poverty in 211 countries and territories. Its global exposure estimates highlight that unsafe air quality is posing significant health risks to a vast majority of the global population. We find that 7.3 billion people, or 94 percent of the world population, live in areas that are exposed to unsafe levels of PM2.5 air pollution (PM2.5 concentration over 5 µg/m³). About 2.8 billion people, or 36 percent of the world population, are directly exposed to concentrations above 35 µg/m³ levels of air pollution, which increase mortality rates by over 24 percent.

Yet the study also shows that pollution levels are particularly high in middle-income countries. Here, a wide range of factors are contributing to heightened concentration levels, including less stringent air quality regulations, the prevalence of older polluting machinery and vehicles, subsidized fossil fuels, congested urban transport systems, rapidly developing industrial sectors, and cut-and-burn practices in agriculture. Of the 7.28 billion people exposed to unsafe PM2.5 levels, 80 percent live in low- and middle-income countries. The rapidly growing economies in South and East Asia stand out in terms of absolute exposure, driven by decades of rapid economic growth and industrialization. China (1.41 billion people) and India (1.36 billion) alone account for 36 percent of global exposure to PM2.5 concentrations above WHO guidelines.

[2] Note the switching of signs on first order polynomials between the full and restricted sample. Also note the limited increase in explanatory power (R^2) from the inclusion of squared income terms.

Moreover, this study estimates that 716 million poor people (living on under $1.90 per day) live in areas with unsafe air pollution. At least 405 million people in Sub-Saharan Africa are estimated to live in both extreme poverty (using a $1.90 a day definition) and unsafe air pollution – thus making them particularly vulnerable to prolonged adverse impacts on livelihoods and well-being. For them, the same air pollution level is likely to imply more severe health risks than for higher income households. Among low-income population groups, high proportions of physical and outdoor labor mean that they are faced with heightened exposure and intake of pollutants. Constraints in terms of the accessibility, availability and quality of health care provision further increase air pollution related mortality among poor people. For instance, a study on air pollution and infant mortality suggests that mortality risks are 2 to 3 times as large in India compared to high-income countries. Moreover, exposure to indoor air pollution – not covered in this study – also affects poor people disproportionately, as they are more dependent on the use of polluting low-cost fuels such as charcoal, kerosene, or firewood for cooking and lighting.

Air pollution is one of the leading causes of death worldwide, especially affecting poorer people who tend to be more exposed and vulnerable. The estimates provided in this study affirm the case for implementing targeted measures to reduce the pollution intensity of economic growth – for instance, supporting the uptake of less polluting technologies in industry and infrastructure, or facilitating the transition towards cleaner fuels (in particular electrification). In addition, measures are warranted to directly address the disproportionate exposure of poor people highlighted in this study. Expanding the provision of affordable and adequate health care in large urban centers in low- and middle-income countries can help reduce mortality, bringing it closer to the levels experienced in higher income countries. Mandating transparent accounting for environmental and health externalities in planning decisions can help to steer pollution sources (e.g. industrial zones or power plants) away from low-income communities. Finally, removing incentives that perpetuate the over-consumption of fossil fuels can yield a double dividend for poor people; e.g. fossil fuel subsidies are well documented to confer disproportionate monetary benefits to richer households, but the air pollution externalities associated with subsidized fossil fuel consumption are also a burden that is borne disproportionately by poorer households. Addressing these policy distortions can be pro-poor both in terms of fiscal and health benefits.

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Annex 1. Country level estimates

Empty cells reflect the lack of input data.

			Safe (< 5 µg/m³)		Unsafe (> 5 µg/m³)		Hazardous (> 35 µg/m³)		Poor ($1.9) and unsafe (> 5 µg/m³)		Poor ($3.2) and unsafe (> 5 µg/m³)		Poor ($5.5) and unsafe (>5 µg/m³)		Poor ($5.5) and hazardous (> 35 µg/m³)	
	Economy/ territory	Pop. (m)	(m)	(%)	(m)	(%)	(m)	(%)	(m)	(%)	(m)	(%)	(m)	(%)	(m)	(%)
1	China	1,431.97	18.54	1.3	1,413.43	98.7	764.9	53.4	21.3	1.5						
2	India	1,377.06	17.22	1.3	1,359.85	98.8	1,326.6	96.3	202.5	14.7	716.8	52.1	1,135.1	82.4	1,109.2	80.6
3	United States	329.86	24.98	7.6	304.88	92.4	0.0	0.0	3.0	0.9	3.8	1.1	5.3	1.6	0.0	0.0
4	Indonesia	269.68	18.28	6.8	251.40	93.2	84.1	31.2	9.0	3.4	53.8	19.9	133.2	49.4	41.9	15.5
5	Pakistan	220.52	1.87	0.8	218.66	99.2	205.2	93.1	3.3	1.5	50.5	22.9	139.2	63.1	130.6	59.2
6	Nigeria	205.63	2.47	1.2	203.16	98.8	116.9	56.9	79.7	38.7	141.0	68.6	181.4	88.2	103.3	50.3
7	Bangladesh	162.83	3.42	2.1	159.41	97.9	159.4	97.9	12.4	7.6	64.4	39.5	123.6	75.9	123.6	75.9
8	Brazil	212.30	54.14	25.5	158.15	74.5	0.0	0.0	5.0	2.3	10.7	5.0	25.1	11.8	0.0	0.0
9	Russia	145.60	8.59	5.9	137.00	94.1	0.0	0.0	0.0	0.0	0.5	0.3	4.9	3.4	0.0	0.0
10	Mexico	128.79	8.68	6.7	120.11	93.3	0.0	0.0	2.1	1.6	7.9	6.1	27.5	21.4	0.0	0.0
11	Japan	123.47	7.82	6.3	115.65	93.7	0.0	0.0	0.8	0.7	1.1	0.9	1.4	1.1	0.0	0.0
12	Ethiopia	114.83	0.78	0.7	114.05	99.3	0.0	0.0	27.0	23.5	68.4	59.6	100.3	87.3	0.0	0.0
13	Egypt, Arab Rep.	102.22	4.77	4.7	97.45	95.3	0.0	0.0	3.9	3.8	29.4	28.8	72.1	70.6	0.0	0.0
14	Vietnam	96.80	3.32	3.4	93.48	96.6	15.6	16.2	1.7	1.7	5.9	6.1	20.1	20.8	2.4	2.5
15	Congo, Dem. Rep.	89.41	0.83	0.9	88.57	99.1	11.5	12.9	65.9	73.7	80.1	89.6	86.3	96.6	10.8	12.1
16	Germany	83.70	0.61	0.7	83.10	99.3	0.0	0.0	0.1	0.1	0.2	0.2	0.4	0.5	0.0	0.0
17	Iran, Islamic Rep.	83.76	1.21	1.4	82.55	98.6	0.1	0.1	0.3	0.4	2.7	3.2	12.1	14.4	0.0	0.0
18	Turkey	82.46	4.22	5.1	78.24	94.9	0.0	0.0	0.0	0.0	1.1	1.3	6.7	8.1	0.0	0.0
19	Thailand	69.68	2.18	3.1	67.51	96.9	0.0	0.0	0.0	0.0	0.3	0.5	5.0	7.2	0.0	0.0
20	Philippines	104.57	41.07	39.3	63.50	60.7	0.0	0.0	2.3	2.2	12.4	11.8	31.6	30.3	0.0	0.0
21	United Kingdom	67.23	4.26	6.3	62.97	93.7	0.0	0.0	0.1	0.2	0.2	0.3	0.3	0.5	0.0	0.0
22	France	64.64	1.74	2.7	62.90	97.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
23	Italy	60.02	4.13	6.9	55.89	93.1	0.0	0.0	0.8	1.3	1.0	1.6	1.7	2.8	0.0	0.0
24	Tanzania	57.89	4.78	8.3	53.11	91.7	0.0	0.0	26.0	44.9	40.5	70.0	48.5	83.7	0.0	0.0
25	Myanmar	53.56	0.90	1.7	52.66	98.3	0.2	0.4	0.5	0.9	6.4	11.9	26.0	48.5	0.1	0.2
26	South Africa	59.29	9.43	15.9	49.85	84.1	0.0	0.0	9.1	15.4	18.3	30.8	28.1	47.4	0.0	0.0
27	Colombia	50.78	1.43	2.8	49.35	97.2	1.0	1.9	1.9	3.7	5.1	10.1	13.1	25.8	0.3	0.6
28	Korea, Rep.	50.01	1.30	2.6	48.71	97.4	0.0	0.0	0.1	0.2	0.2	0.5	0.5	1.0	0.0	0.0
29	Kenya	53.72	6.30	11.7	47.42	88.3	0.0	0.0	16.2	30.2	30.3	56.5	40.7	75.8	0.0	0.0
30	Uganda	45.60	0.88	1.9	44.72	98.1	0.0	0.0	17.8	39.1	30.7	67.3	38.9	85.4	0.0	0.0
31	Sudan	43.72	0.24	0.6	43.48	99.4	0.0	0.0	5.6	12.7	19.4	44.4	34.3	78.4	0.0	0.0
32	Ukraine	43.61	1.02	2.3	42.59	97.7	0.0	0.0	0.0	0.0	0.2	0.4	1.5	3.5	0.0	0.0
33	Algeria	43.75	3.81	8.7	39.94	91.3	0.0	0.0	0.1	0.3	0.9	2.1	8.4	19.1	0.0	0.0
34	Iraq	40.15	0.40	1.0	39.75	99.0	0.1	0.2	0.6	1.4	5.3	13.2	19.7	49.1	0.0	0.1
35	Afghanistan	38.82	0.14	0.3	38.69	99.7	11.5	29.5								
36	Spain	45.70	7.62	16.7	38.09	83.3	0.0	0.0	0.3	0.6	0.4	0.9	0.8	1.7	0.0	0.0
37	Poland	37.81	0.26	0.7	37.55	99.3	0.0	0.0	0.1	0.3	0.2	0.5	0.4	1.1	0.0	0.0
38	Argentina	44.74	10.68	23.9	34.06	76.1	0.0	0.0								
39	Saudi Arabia	34.60	0.71	2.0	33.90	98.0	1.1	3.2								
40	Uzbekistan	33.44	0.36	1.1	33.07	98.9	1.4	4.2	4.0	12.1	14.2	42.5	26.3	78.5	1.1	3.2
41	Canada	36.84	4.46	12.1	32.39	87.9	0.0	0.0	0.1	0.2	0.2	0.4	0.2	0.6	0.0	0.0
42	Angola	32.67	2.02	6.2	30.66	93.8	0.0	0.0	13.6	41.7	20.7	63.5	26.6	81.5	0.0	0.0
43	Peru	32.82	2.40	7.3	30.42	92.7	8.5	25.9	0.8	2.5	2.6	7.9	6.8	20.9	0.6	1.7
44	Morocco	36.78	6.47	17.6	30.31	82.4	0.0	0.0	0.2	0.5	1.6	4.4	7.5	20.3	0.0	0.0
45	Ghana	30.99	1.20	3.9	29.79	96.1	19.3	62.3	3.5	11.5	8.3	26.8	15.8	51.1	8.4	27.2
46	Malaysia	31.81	2.02	6.4	29.79	93.6	2.7	8.5	0.0	0.0	0.0	0.1	0.5	1.5	0.0	0.0
47	Nepal	29.03	0.15	0.5	28.87	99.5	28.0	96.4	1.7	5.8	9.7	33.4	20.3	70.0	19.6	67.6
48	Yemen	29.68	1.03	3.5	28.65	96.5	0.0	0.2	14.9	50.3	23.3	78.5	27.0	91.1	0.0	0.2
49	Cameroon	26.38	0.30	1.1	26.09	98.9	4.0	15.2	5.8	22.0	11.1	42.1	17.4	66.0	2.4	9.1
50	Côte d'Ivoire	26.37	0.63	2.4	25.73	97.6	7.4	28.0	6.0	22.6	13.3	50.4	20.1	76.1	4.6	17.3
51	North Korea	25.40	0.80	3.2	24.59	96.8	0.4	1.6								
52	Niger	24.10	0.68	2.8	23.42	97.2	0.0	0.0	10.1	42.1	17.9	74.1	21.9	90.8	0.0	0.0
53	Mozambique	31.09	9.06	29.1	22.03	70.9	0.0	0.0	13.3	42.8	17.7	56.9	20.1	64.7	0.0	0.0
54	Venezuela	28.06	6.20	22.1	21.86	77.9	0.0	0.0								
55	Taiwan, China	23.68	1.85	7.8	21.83	92.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

56	Burkina Faso	20.86	0.09	0.4	20.77	99.6	0.0	0.0	6.9	32.9	14.2	68.3	18.4	88.3	0.0	0.0
57	Sri Lanka	21.16	1.94	9.2	19.22	90.8	0.0	0.0	0.1	0.7	1.9	8.9	7.6	36.0	0.0	0.0
58	Romania	19.21	0.05	0.3	19.16	99.7	0.0	0.0	0.4	2.3	0.9	4.9	2.0	10.2	0.0	0.0
59	Malawi	19.13	0.69	3.6	18.44	96.4	0.0	0.0	12.5	65.4	16.2	84.9	17.8	92.9	0.0	0.0
60	Zambia	18.37	0.18	1.0	18.18	99.0	0.0	0.0	10.6	57.8	13.6	74.1	15.9	86.8	0.0	0.0
61	Mali	20.23	2.19	10.8	18.04	89.2	0.0	0.0	7.7	38.2	13.3	65.8	16.7	82.5	0.0	0.0
62	Kazakhstan	18.72	0.94	5.0	17.78	95.0	0.0	0.0	0.0	0.0	0.1	0.3	1.0	5.4	0.0	0.0
63	Guatemala	17.89	0.30	1.7	17.59	98.3	0.0	0.0	1.3	7.0	3.8	21.0	7.8	43.8	0.0	0.0
64	Syria	17.30	0.30	1.7	17.01	98.3	0.0	0.0	7.5	43.6	13.0	74.9	15.7	91.0	0.0	0.0
65	Ecuador	17.58	0.59	3.4	16.99	96.6	0.0	0.0	0.5	3.0	1.5	8.8	3.9	22.4	0.0	0.0
66	Cambodia	16.62	0.25	1.5	16.37	98.5	0.0	0.0								
67	Netherlands	16.98	0.65	3.8	16.33	96.2	0.0	0.0	0.0	0.2	0.0	0.3	0.1	0.3	0.0	0.0
68	Chad	16.41	0.23	1.4	16.18	98.6	0.0	0.0	6.4	39.0	10.9	66.3	14.1	85.7	0.0	0.0
69	Chile	18.98	3.63	19.2	15.34	80.8	0.0	0.0	0.0	0.2	0.1	0.5	0.5	2.5	0.0	0.0
70	Zimbabwe	14.86	0.12	0.8	14.74	99.2	0.0	0.0	4.6	30.6	8.6	57.9	11.7	78.5	0.0	0.0
71	Guinea	12.90	0.44	3.4	12.46	96.6	0.0	0.0	2.9	22.7	7.2	55.9	10.9	84.4	0.0	0.0
72	Rwanda	12.91	0.69	5.3	12.22	94.7	0.0	0.0	6.4	49.7	9.6	74.1	11.1	86.2	0.0	0.0
73	Senegal	16.41	4.56	27.8	11.84	72.2	0.0	0.0	4.1	25.2	7.7	46.7	10.3	62.6	0.0	0.0
74	Bolivia	11.65	0.07	0.6	11.58	99.4	0.0	0.0	0.5	4.3	1.2	10.0	2.5	21.4	0.0	0.0
75	Belgium	11.56	0.17	1.5	11.39	98.5	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.3	0.0	0.0
76	Burundi	11.86	0.68	5.7	11.18	94.3	0.0	0.0	8.9	74.9	10.4	87.4	11.0	92.3	0.0	0.0
77	South Sudan	11.18	0.04	0.3	11.14	99.7	0.0	0.0	9.5	84.8	10.6	94.8	11.0	98.7	0.0	0.0
78	Benin	12.06	0.99	8.2	11.06	91.8	6.8	56.3	5.3	43.9	8.3	69.2	10.2	84.5	6.1	50.8
79	Tunisia	11.75	0.96	8.1	10.80	91.9	0.0	0.0	0.0	0.4	0.5	4.3	2.6	22.2	0.0	0.0
80	Somalia	15.81	5.04	31.8	10.78	68.2	0.0	0.0								
81	Czech Republic	10.70	0.04	0.4	10.66	99.6	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.4	0.0	0.0
82	Jordan	10.19	0.19	1.8	10.01	98.2	0.0	0.0	0.0	0.2	0.3	2.7	2.3	22.4	0.0	0.0
83	Cuba	11.25	1.27	11.3	9.98	88.7	0.0	0.0								
84	Hungary	9.64	0.09	0.9	9.56	99.1	0.0	0.0	0.1	0.5	0.1	1.1	0.3	2.7	0.0	0.0
85	Tajikistan	9.53	0.11	1.2	9.42	98.8	0.2	2.6	0.2	2.3	1.2	12.2	3.9	40.8	0.1	1.1
86	Honduras	9.86	0.45	4.6	9.41	95.4	0.0	0.0								
87	Belarus	9.44	0.14	1.5	9.30	98.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0
88	Austria	8.98	0.05	0.5	8.94	99.5	0.0	0.0	0.0	0.3	0.0	0.4	0.1	0.7	0.0	0.0
89	United Arab Emirates	9.42	0.66	7.0	8.76	93.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
90	Serbia	8.74	0.01	0.2	8.72	99.8	0.0	0.0	0.0	0.0	0.1	0.7	0.5	5.7	0.0	0.0
91	Greece	9.94	1.28	12.9	8.66	87.1	0.0	0.0	0.1	0.8	0.1	1.4	0.4	3.9	0.0	0.0
92	Haiti	11.25	2.64	23.5	8.61	76.5	0.0	0.0	2.3	20.1	4.6	40.5	6.9	61.4	0.0	0.0
93	Dominican Republic	10.78	2.40	22.3	8.38	77.7	0.0	0.0								
94	Azerbaijan	8.54	0.24	2.8	8.30	97.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
95	Sweden	9.92	1.66	16.7	8.27	83.3	0.0	0.0	0.0	0.2	0.0	0.2	0.0	0.5	0.0	0.0
96	Switzerland	8.61	0.36	4.2	8.25	95.8	0.0	0.0								
97	Togo	8.13	0.29	3.6	7.84	96.4	5.5	67.4	3.5	43.3	5.6	68.5	7.0	85.6	4.7	57.6
98	Israel	8.34	1.01	12.1	7.33	87.9	0.0	0.0	0.0	0.2	0.0	0.6	0.2	2.2	0.0	0.0
99	Australia	24.72	17.42	70.5	7.30	29.5	0.0	0.0	0.0	0.2	0.1	0.2	0.1	0.2	0.0	0.0
100	Lao PDR	7.23	0.03	0.4	7.19	99.6	0.0	0.0	0.6	7.9	2.4	33.9	5.1	70.6	0.0	0.0
101	Paraguay	7.11	0.09	1.2	7.03	98.8	0.0	0.0	0.1	1.4	0.4	5.7	1.1	15.6	0.0	0.0
102	Sierra Leone	7.86	0.90	11.4	6.97	88.6	0.0	0.0	3.3	42.2	5.6	71.6	6.6	84.1	0.0	0.0
103	Bulgaria	6.89	0.08	1.2	6.81	98.8	0.0	0.0	0.1	1.3	0.2	3.0	0.5	7.3	0.0	0.0
104	Kyrgyz Republic	6.50	0.10	1.5	6.40	98.5	0.2	3.0	0.0	0.6	0.7	10.6	3.5	53.7	0.1	1.9
105	El Salvador	6.47	0.19	2.9	6.28	97.1	0.0	0.0	0.1	1.5	0.5	7.6	1.6	25.3	0.0	0.0
106	Nicaragua	6.62	0.35	5.3	6.27	94.7	0.0	0.0	0.2	2.8	0.7	11.2	2.1	31.5	0.0	0.0
107	Turkmenistan	6.02	0.24	4.1	5.78	95.9	0.0	0.0	0.1	1.0	0.6	10.1	1.9	31.9	0.0	0.0
108	Libya	6.84	1.13	16.5	5.71	83.5	0.0	0.0								
109	Slovak Republic	5.45	0.01	0.3	5.44	99.7	0.0	0.0								
110	Portugal	9.64	4.26	44.1	5.38	55.9	0.0	0.0	0.0	0.2	0.0	0.3	0.1	0.9	0.0	0.0
111	Denmark	5.75	0.44	7.6	5.31	92.4	0.0	0.0								
112	Congo, Rep.	5.45	0.20	3.6	5.26	96.4	2.7	50.4	2.9	53.1	3.9	72.2	4.7	85.7	2.4	43.8
113	Hong Kong SAR, China	6.04	0.93	15.4	5.11	84.6	0.0	0.0								
114	Papua New Guinea	8.83	3.78	42.8	5.06	57.2	0.0	0.0	1.5	16.5	2.8	31.5	4.0	45.4	0.0	0.0
115	Singapore	5.71	0.85	14.9	4.86	85.1	4.9	85.1								
116	Central African Republic	4.79	0.06	1.2	4.73	98.8	0.7	15.6	3.4	71.7	4.1	85.8	4.5	93.7	0.7	13.6
117	Lebanon	6.33	1.66	26.2	4.67	73.8	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.3	0.0	0.0
118	West Bank and Gaza	4.92	0.33	6.7	4.59	93.3	0.0	0.0	0.0	0.8	0.2	4.1	1.0	20.0	0.0	0.0

119	Finland	5.52	1.09	19.7	4.43	80.3	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.0
120	Costa Rica	5.08	0.67	13.3	4.40	86.7	0.0	0.0	0.1	1.2	0.1	2.8	0.5	8.9	0.0	0.0
121	Oman	5.00	0.64	12.9	4.36	87.1	0.2	4.5								
122	Liberia	5.03	0.72	14.3	4.31	85.7	0.0	0.0	2.1	41.8	3.4	68.3	4.1	81.2	0.0	0.0
123	Moldova	4.01	0.05	1.2	3.96	98.8	0.0	0.0	0.0	0.0	0.0	0.8	0.5	11.3	0.0	0.0
124	Croatia	4.00	0.27	6.9	3.73	93.1	0.0	0.0	0.0	0.5	0.0	1.0	0.1	3.0	0.0	0.0
125	Georgia	3.98	0.37	9.3	3.61	90.7	0.0	0.0	0.2	3.8	0.5	13.3	1.5	36.6	0.0	0.0
126	Eritrea	3.52	0.05	1.5	3.47	98.5	0.0	0.0								
127	Panama	4.26	0.94	22.0	3.33	78.0	0.0	0.0	0.0	0.8	0.1	2.9	0.3	7.7	0.0	0.0
128	Kosovo	3.35	0.04	1.1	3.32	98.9	0.0	0.0	0.0	0.3	0.1	2.6	0.7	20.6	0.0	0.0
129	Kuwait	4.14	0.87	21.0	3.27	79.0	2.0	47.7								
130	Bosnia-Herzegovina	3.25	0.02	0.7	3.23	99.3	0.0	0.0	0.0	0.1	0.0	0.2	0.1	2.0	0.0	0.0
131	Armenia	2.96	0.05	1.8	2.91	98.2	0.0	0.0	0.0	1.3	0.3	8.9	1.2	41.0	0.0	0.0
132	Albania	2.87	0.14	5.0	2.73	95.0	0.0	0.0	0.0	1.0	0.2	6.6	0.8	28.9	0.0	0.0
133	Norway	5.27	2.55	48.4	2.72	51.6	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.2	0.0	0.0
134	Lithuania	2.72	0.03	1.2	2.68	98.8	0.0	0.0								
135	Qatar	2.87	0.29	10.0	2.58	90.0	1.7	58.9								
136	Jamaica	2.89	0.36	12.5	2.53	87.5	0.0	0.0	0.0	1.6	0.2	8.2	0.8	26.2	0.0	0.0
137	Mongolia	3.28	0.86	26.1	2.42	73.9	0.0	0.0	0.0	0.4	0.1	3.4	0.6	18.0	0.0	0.0
138	Botswana	2.35	0.05	2.3	2.29	97.7	0.0	0.0	0.3	13.7	0.8	35.0	1.4	58.1	0.0	0.0
139	Lesotho	2.14	0.07	3.3	2.07	96.7	0.0	0.0	0.6	27.1	1.0	48.7	1.5	71.4	0.0	0.0
140	Macedonia	2.08	0.02	1.2	2.06	98.8	0.0	0.0	0.1	4.1	0.2	8.0	0.4	17.8	0.0	0.0
141	Gambia, The	2.38	0.34	14.4	2.04	85.6	0.0	0.0	0.2	8.6	0.8	32.7	1.5	62.9	0.0	0.0
142	Slovenia	2.06	0.03	1.3	2.03	98.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
143	Gabon	2.17	0.15	7.1	2.02	92.9	0.0	0.2	0.1	3.9	0.3	13.7	0.8	36.7	0.0	0.1
144	Latvia	1.86	0.07	4.0	1.79	96.0	0.0	0.0	0.0	0.7	0.0	1.3	0.1	3.0	0.0	0.0
145	Guinea-Bissau	1.85	0.11	5.9	1.74	94.1	0.0	0.0	1.1	58.8	1.4	77.5	1.6	87.2	0.0	0.0
146	Namibia	2.54	0.87	34.2	1.67	65.8	0.0	0.0	0.3	13.3	0.7	26.6	1.1	41.9	0.0	0.0
147	Madagascar	27.42	26.17	95.5	1.25	4.5	0.0	0.0	0.9	3.1	1.1	3.9	1.2	4.3	0.0	0.0
148	Equatorial Guinea	1.39	0.16	11.2	1.23	88.8	0.0	0.0								
149	Eswatini	1.16	0.01	0.7	1.15	99.3	0.0	0.0	0.3	28.2	0.6	51.3	0.8	70.8	0.0	0.0
150	Estonia	1.32	0.23	17.4	1.09	82.6	0.0	0.0								
151	Bahrain	1.43	0.38	26.6	1.05	73.4	0.7	50.0								
152	Timor-Leste	1.31	0.26	20.1	1.04	80.0	0.0	0.0	0.2	16.4	0.7	51.4	1.0	73.0	0.0	0.0
153	Cyprus	1.14	0.18	15.9	0.96	84.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
154	Ireland	4.91	4.03	81.9	0.89	18.1	0.0	0.0								
155	Djibouti	0.97	0.22	22.2	0.76	77.8	0.0	0.0	0.2	20.8	0.4	38.0	0.6	58.3	0.0	0.0
156	Bhutan	0.75	0.01	1.2	0.74	98.8	0.4	47.2	0.0	0.7	0.1	8.0	0.2	31.3	0.1	19.9
157	Mauritania	4.62	4.00	86.4	0.63	13.6	0.0	0.0	0.1	1.9	0.2	5.1	0.5	10.4	0.0	0.0
158	Luxembourg	0.62	0.01	1.5	0.61	98.5	0.0	0.0								
159	Montenegro	0.62	0.02	3.8	0.59	96.2	0.0	0.0	0.0	0.7	0.0	5.7	0.1	14.0	0.0	0.0
160	Suriname	0.58	0.02	4.0	0.56	96.0	0.0	0.0	0.1	18.6	0.2	28.7	0.3	44.5	0.0	0.0
161	Guyana	0.78	0.22	28.2	0.56	71.8	0.0	0.0	0.0	3.3	0.1	8.3	0.1	18.4	0.0	0.0
162	Belize	0.39	0.02	5.0	0.37	95.0	0.0	0.0	0.0	11.1	0.1	23.2	0.2	44.5	0.0	0.0
163	Brunei Darussalam	0.43	0.07	16.7	0.36	83.3	0.0	0.0								
164	Uruguay	3.45	3.13	90.6	0.32	9.4	0.0	0.0								
165	Malta	0.42	0.11	25.4	0.32	74.6	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.2	0.0	0.0
166	Macau, China	0.44	0.16	35.4	0.29	64.6	0.0	0.0								
167	São Tomé & Príncipe	0.21	0.09	40.6	0.12	59.4	0.0	0.0	0.0	21.1	0.1	38.8	0.1	51.3	0.0	0.0
168	Andorra	0.08	0.01	9.2	0.07	90.8	0.0	0.0								
169	New Zealand	2.63	2.57	97.6	0.06	2.4	0.0	0.0								
170	Isle of Man	0.08	0.04	49.1	0.04	50.9	0.0	0.0								
171	San Marino	0.03	0.00	1.1	0.03	98.9	0.0	0.0								
172	Liechtenstein	0.03	0.01	19.7	0.03	80.3	0.0	0.0								
173	Cayman Islands	0.06	0.06	94.2	0.00	5.8	0.0	0.0								
174	Puerto Rico	2.86	2.86	100.0	0.00	0.0	0.0	0.0								
175	Trinidad & Tobago	1.38	1.38	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
176	Mauritius	1.26	1.26	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
177	Comoros	0.82	0.82	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
178	Fiji	0.79	0.79	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
179	Solomon Islands	0.59	0.59	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
180	Cabo Verde	0.52	0.52	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
181	Bahamas	0.37	0.37	100.0	0.00	0.0	0.0	0.0								
182	Iceland	0.33	0.33	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
183	Barbados	0.28	0.28	100.0	0.00	0.0	0.0	0.0								
184	Vanuatu	0.27	0.27	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

185	French Polynesia	0.26	0.26	100.0	0.00	0.0	0.0	0.0								
186	New Caledonia	0.26	0.26	100.0	0.00	0.0	0.0	0.0								
187	Samoa	0.20	0.20	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
188	St. Lucia	0.18	0.18	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
189	Guam	0.17	0.17	100.0	0.00	0.0	0.0	0.0								
190	Curacao	0.16	0.16	100.0	0.00	0.0	0.0	0.0								
191	Micronesia, Fed. Sts.	0.11	0.11	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
192	Grenada	0.11	0.11	100.0	0.00	0.0	0.0	0.0								
193	Aruba	0.11	0.11	100.0	0.00	0.0	0.0	0.0								
194	St. Vincent & Grenadines	0.10	0.10	100.0	0.00	0.0	0.0	0.0								
195	Tonga	0.10	0.10	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
196	Antigua & Barbuda	0.09	0.09	100.0	0.00	0.0	0.0	0.0								
197	Seychelles	0.09	0.09	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
198	Dominica	0.07	0.07	100.0	0.00	0.0	0.0	0.0								
199	Northern Mariana Is.	0.06	0.06	100.0	0.00	0.0	0.0	0.0								
200	American Samoa	0.05	0.05	100.0	0.00	0.0	0.0	0.0								
201	St. Kitts and Nevis	0.05	0.05	100.0	0.00	0.0	0.0	0.0								
202	Faeroe Islands	0.05	0.05	100.0	0.00	0.0	0.0	0.0								
203	Bermuda	0.04	0.04	100.0	0.00	0.0	0.0	0.0								
204	Sint Maarten	0.04	0.04	100.0	0.00	0.0	0.0	0.0								
205	Greenland	0.04	0.04	100.0	0.00	0.0	0.0	0.0								
206	Turks & Caicos Is.	0.04	0.04	100.0	0.00	0.0	0.0	0.0								
207	Marshall Islands	0.04	0.04	100.0	0.00	0.0	0.0	0.0								
208	Saint-Martin	0.03	0.03	100.0	0.00	0.0	0.0	0.0								
209	Maldives	0.02	0.02	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
210	Palau	0.02	0.02	100.0	0.00	0.0	0.0	0.0								
211	Tuvalu	0.01	0.01	100.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Annex 2. Non-parametric kernel regression results

Figure A.1. Non-parametric kernel regression results

a) Full sample **b) Average concentration over >10μg/m³**