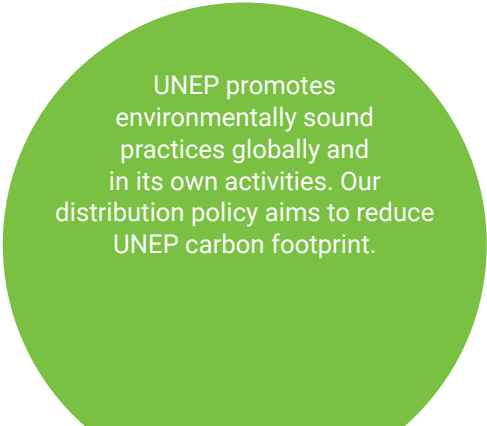




Air Pollution and Development in Africa: Impacts on Health, the Economy and Human Capital





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Conflict of Interest Statements

No potential conflict of interest was reported by any of the authors.

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For the last twenty years, Africa's growth has been accelerating. Before the coronavirus outbreak, the continent was on track to more than triple its population this century while making enormous gains in health. Life expectancy has been increasing and infant mortality declining, and deaths from communicable diseases, including malaria and AIDS, are on the decline.

However, even without the ongoing pandemic, the continent is facing challenges. Ambient air pollution is lower than in many other parts of the world but is already contributing to an increasing number of deaths, including from pneumonia, heart disease, stroke, diabetes, chronic lung disease, and lung cancer. The burning of fossil fuels – coal, oil and gas – to drive economic growth lies behind the increasing morbidity.

But there is another way.

This is the main message of the study, "Air Pollution and Development in Africa: Impacts on Health, the Economy and Human Capital" which assesses the impacts of ambient air pollution on health and the economy in African countries, now and in the future. Using data from the World Health Organization and the Institute for Health Metrics and Evaluation, this report will help leaders of African countries understand the full health and economic implications of various pathways to economic growth and development.

First, the report looked at the contribution of air pollution to disease and death. As families across Africa move away from traditional biomass fuels such as wood and charcoal to liquefied petroleum gas and non-polluting renewables such as wind and solar, household air pollution is declining. But at the same time, industrialization and economic growth mean ambient pollution is increasing. In 2019, it was responsible for an estimated 383, 419 deaths across Africa.

The report also finds that ambient pollution caused by fossil fuels has clear economic downsides. In Ethiopia, Ghana and Rwanda, disease and death caused by ambient air pollution result in substantial annually recurring losses in economic production of between 0.08 and 0.3 per cent of gross domestic product.

Looking to the future economic impacts of ambient air pollution, the authors then examine the projected impact on children's IQ. Air pollution exposure in children is associated with IQ loss and this is not only of great social importance, but also of economic relevance because, high intelligence – as measured by IQ – underpins a country's human capital and is a key predictor of economic prospects. Widespread IQ loss can have significant implications on the prospects for development in the countries of the region. The study finds that widespread exposure to ambient air pollution in children across Africa is associated with losses of intelligence totalling 1.96 billion IQ points per year.

Because many African countries are still in relatively early stages of development it is not too late to change course. They are not yet trapped in the fossil fuel-based infrastructures that have powered economic growth in other parts of the world, leading to widespread disease and catastrophic environmental damage. Renewable energy is cheaper than ever, and costs are plummeting all the time, while the African continent, and in particular sub-Saharan Africa, has abundant sun and wind, the natural resources to make renewables work on a large scale. Within the past decade, global investment in wind and solar has grown from 4% of all energy investment in 2010 to 18% today and is still rising.

In many countries, it is now cheaper to generate electricity from renewables than from fossil fuels. With wise and far-sighted investments in renewable energy and clean technologies, the countries of Africa can limit air pollution, avoid mistakes made elsewhere, build human capital, and accelerate development. It is my hope that this report will inspire policymakers across the continent to continue moving in this direction as they start looking to build back better after the coronavirus pandemic. This would benefit Africa's future development, and its people.

Susan Gardner,
Director, Ecosystems Division, UNEP

Executive Summary

The overarching goal of this report was to quantify air pollution's impacts on health, human capital, and the economy across Africa, with particular focus on Ethiopia, Ghana and Rwanda. The study's specific objectives were to:

- Examine the current levels of and trends in Household Air Pollution (HAP) and Ambient (outdoor) Air Pollution (AAP) in select African nations.
- Examine the burden of disease attributable to HAP and AAP.
- Quantify the impacts of air pollution on the economy and human capital with focus on the intersection between air pollution and economic development.
- Quantify the impacts of air pollution on children's intelligence (measured by IQ).
- Offer science-based recommendations for the prevention and control of air pollution.

Methods

We used 2019 GBD morbidity and mortality data. We examined data for the entire African continent but focused especially on three rapidly developing countries – Ethiopia, Ghana and Rwanda. We estimated economic output lost to air-pollution-related disease by country. We quantified PM_{2.5} pollution's contribution to IQ loss in children.

Findings

Africa is undergoing both environmental and epidemiological transition. Household air pollution (HAP) remains the predominant form of air pollution, but it is declining overall. Air pollution in Africa is comprised of Household Air Pollution (HAP) and Ambient Air pollution (AAP). The relative contribution of each type varies from country to country. HAP is declining across the continent as families move away from using solid fuels such as wood, straw, and animal dung, towards using cleaner fuels such as Liquefied Petroleum Gas (LPG). By contrast, levels of Ambient Air Pollution (AAP) are beginning to

increase. These increases occur as countries develop economically, industrialize, and become linked to global supply chains. People move into cities for employment opportunities, increasing the numbers of gasoline- and diesel-powered cars, trucks and buses on the roads. Sources of AAP include electricity generation in coal- and oil-fired power plants, industrial emissions, transportation related emissions, and crop burning.

Air pollution was responsible for 1.1 million deaths across Africa in 2019. HAP accounted for 697,000 deaths and AAP for 394,000. AAP-related deaths increased from 361,000 in 2015 to 383,000 in 2019 with greatest increases in the most highly developed countries. Two-thirds of AAP-related mortality is due to non-communicable diseases. Economic output lost to air-pollution-related disease was \$3.0 billion (in 2019 International dollars) in Ethiopia (1.16% of GDP), \$1.6 billion in Ghana (0.95% of GDP), and \$349 million in Rwanda (1.19% of GDP). Exposure to air pollution during pregnancy and early childhood can cause brain damage defects in children that reduces their cognitive function (as measured by IQ). Cognitive function – often measured by IQ – is a key predictor of earning potential, health and longevity, and in this way underpins human capital and national progress. PM_{2.5} pollution was responsible for 1.96 billion lost IQ points in African children.

Discussion

Air pollution in Africa has major negative impacts on health, human capital and the economy. These impacts are growing in magnitude as countries develop. Rising levels of AAP are of particular concern. Increases in AAP and in AAP-related disease are evident today in Ghana, the most economically advanced of the countries we examined, and are beginning to appear in Ethiopia and Rwanda. They are the consequence of urbanization, industrialization and rapid economic growth. While the increases are still relatively modest, they represent a clear departure from

the pattern of the past two decades. Based on experience from other countries, these increases are likely the leading edge of a looming problem. If AAP is not urgently addressed, it could increase exponentially in African countries and in a worst-case scenario approach the levels seen currently in Asia.

The health and economic consequences of rapid escalation of AAP could undermine efforts across Africa to advance economic development, build human capital, and attain the Sustainable Development Goals (SDGs). In the absence of deliberate intervention, AAP will worsen, widespread disease and death, diminish economic productivity, impair human capital formation, and

undercut development. Fortunately, many African countries are well positioned to avoid damaging levels of AAP, prevent disease, and pursue smart pathways to development. Because they are in relatively early stages of industrialization and thus not entirely reliant upon a fossil-fuel driven economic base, African nations have a unique opportunity to avoid the pollution that has accompanied economic development in other countries that powered their growth by massive combustion of coal, oil and gas. African countries have a unique opportunity to pursue smart, non-polluting pathways to economic growth. Air pollution in Africa can be prevented. Prevention will require leadership, foresight, and courage.

Africa is a vast continent undergoing massive and rapid change. Africa's population, currently the world's youngest – with a median age of 19.7 years - is projected to more than triple in this century from 1.3 billion to 4.3 billion.¹ Africa is urbanizing and is projected to have 13 megacities by 2100. African countries are advancing economically, industrializing, and building infrastructure² (**Box 1**).

Africa is in transition. The continent is simultaneously undergoing a transition in environmental risks from traditional to modern sources of pollution and a massive epidemiologic transition from communicable to non-communicable diseases (National Research Council, 2020).⁶

Reflecting the epidemiologic transition, life expectancy across Africa has nearly doubled from 36.5 years in 1950 to 64.1 years today.⁷ Infant mortality has fallen by approximately 70% from 187 deaths per 1,000 live births in 1950 to 51 per 1,000 in 2019.⁷ Deaths from communicable diseases decreased from 5.2 million (UI: 4.9 million - 5.6 million) in 1990 to 4.5 million (UI: 4.0 million - 5.3 million) in 2019, despite the continuing toll of AIDS, malaria and tuberculosis. In the same time period, deaths from noncommunicable diseases (NCDs) increased in number from 2.1 million (UI: 1.9 million - 2.4 million) to 3.8 million (UI: 3.4 million – 4.2 million) (**Figure 1**).⁸⁻¹⁰

BOX 1: Economic Development in Three African Countries

The three Sub-Saharan countries that are the focus of this analysis have pursued differing pathways to economic development:

- **Ethiopia.** From 1958 through to 1973, Ethiopia sought to boost its economy by focusing on producing consumer goods for the domestic market, attracting foreign investors and expanding the manufacturing sector.³ In the mid-1980s after the revolution, Ethiopia attempted to shift economic priorities away from agriculture and towards import substitution and labor-intensive industries.³ In 2002, Ethiopia created the Industrial Development Strategy (IDS), which focused on eradication of poverty and sustainable development. The IDS placed emphasis on enhancing exports and linkages to international markets to foster internal economic growth.
- **Ghana.** In 1965, eight years after gaining independence, Ghana began to implement a broad, long-term strategy to move the country from low-income to middle-income status by the year 2020.⁴ The country was able to halt and reverse the downward trajectory of its economy and repair broken infrastructure by reshaping its industrial structure, decreasing reliance on imports, and focusing on import substitution. Additional priorities included poverty reduction, protecting the vulnerable, and achieving financial growth. Through these actions, Ghana has grown its GDP at an average annual rate of 11.2% and has moved from low-income to lower-middle-income status.
- **Rwanda.** President Paul Kagame and his government have created a program called VISION 2020. This 20-year plan is focused on transforming Rwanda from a primarily agrarian economy into a middle-income, technology-led, data-based economy.⁵ VISION 2020 established goals for reducing poverty, overcoming division, and improving healthcare. To facilitate economic growth, Rwanda has focused on developing human resources, the private sector, and infrastructure. Additionally, the country is moving toward producing high-value, market-oriented agriculture and is focusing on regional and international integration.

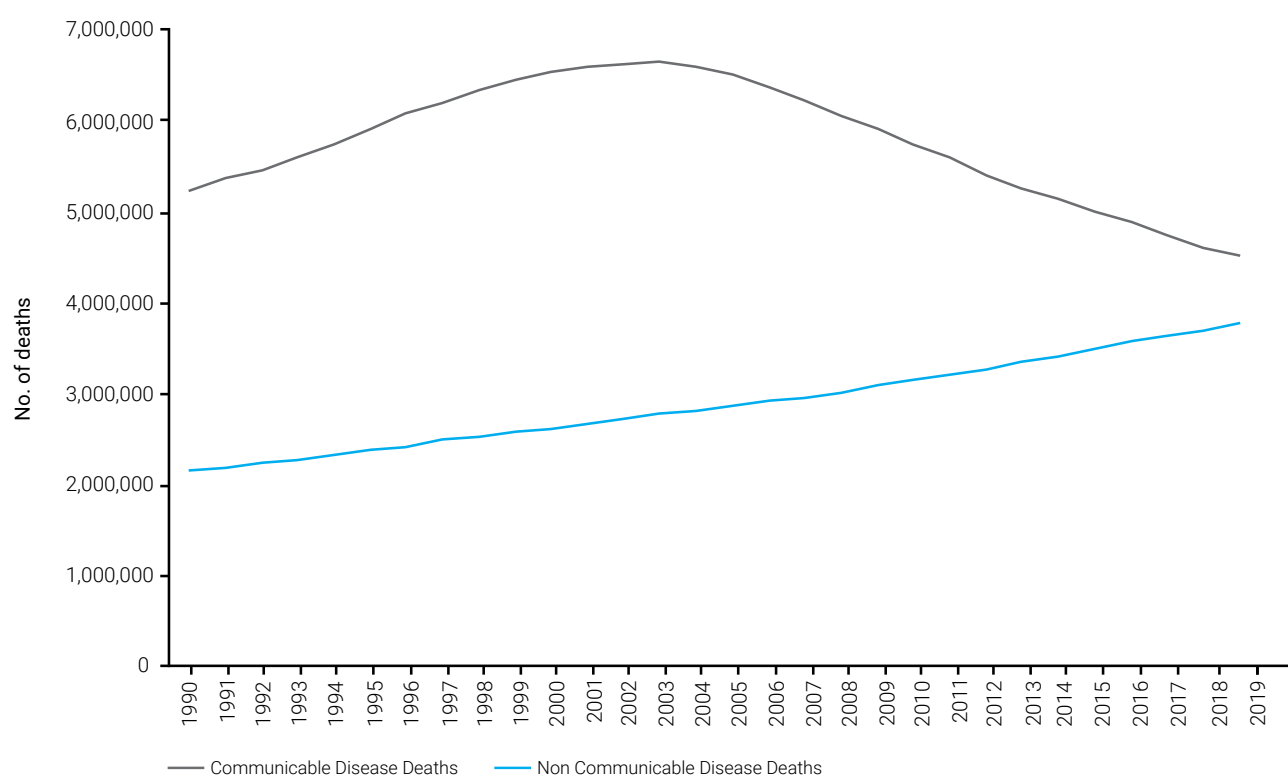


Figure 1. Deaths Attributable to Communicable and Non-Communicable Disease, Africa, 1990-2017

There is a major need to understand how the environmental risk transition is shaping the epidemiological transition in Africa and specifically to understand how changing patterns of pollution are driving the rise of noncommunicable disease and affecting economic development.¹¹⁻¹⁶

The goals of this study are: (1) to quantify the impacts of air pollution – both HAP and AAP – on health, human capital, and the economy in a rapidly changing Africa; and (2) to identify opportunities for control of air pollution and prevention of pollution-related disease. We examine data for the entire continent, but focus especially on three rapidly emerging sub-Saharan countries, Rwanda, Ghana and Ethiopia.

Estimation of Morbidity and Mortality due to Air Pollution

We relied on data from the World Health Organization's (WHO) Global Health Observatory for information on concentrations and trends in HAP and AAP.^{17,18} We utilised the 2019 Global Burden of Disease (GBD) study for information on morbidity and mortality attributable to HAP and AAP.^{7,9}

Estimation of Losses in Economic Output Due to Air-Pollution-Related Morbidity and Mortality

Air pollution has been associated with output losses in agriculture, the service sector and manufacturing industries¹⁹⁻²¹. To estimate income/output losses attributable to air-pollution-related morbidity in Africa in 2019, we estimated labor income (as measured by output) per worker based on labor's contribution to GDP, and then adjusted by the probability that a person (of a given age) was working. We calculated labor income per worker in each country by multiplying 2019 GDP²² by labor income's share of GDP^{23,24} and dividing by the number of persons employed.²² Because not all persons are employed, labor income per worker was adjusted by the fraction of persons in each age group who are working.²³

Air pollution also reduces non-market production (e.g., household production), and these losses are not captured by traditional, GDP-focused analysis. Satellite account data for the United States estimate the value of home production to equal 25% of GDP.²⁵ A comparable estimate for Ghana is 35%.²⁶ We applied this 35% figure to all three countries to reflect the contribution of non-market output. Details are presented in the Supplementary Appendix.

Our estimate of expected output loss per person, by age, was multiplied by the number of Years Lost Due to Disability (YLDs) attributable to air pollution in 2019 for persons of each age.²⁷ This quantity, summed across all ages, provides an

estimate of the total loss in economic output/income due to air pollution-related disease.

To quantify air pollution's impact on human capital, we estimated the loss in present discounted value of an individual's labor income, as measured by output, resulting from pollution-related mortality. We first calculated output per worker, and then adjusted output per worker to reflect the probability that an individual is working at each age and that he survives to each future age. The probability that a person is working at each age is measured by the ratio of working to total population, by age, for each country.²³ Survival probabilities were estimated using country-specific life tables.²⁸ The present value of lost labor output depends on the rate at which output grows and on the rate at which it is discounted to the present. We use the assumptions underlying the Lancet Commission Report, viz., that the discount rate exceeds the rate of growth in output per worker by (a) 1.5, (b) 3.0 percentage points. Details are presented in the Supplementary Appendix.

Estimation of IQ Loss due to Air Pollution

Air pollution exposure during sensitive periods of brain development in pregnancy and early childhood can cause brain injury in children, which reduces cognitive function as measured here by IQ score and this impedes formation of human capital.²⁹⁻³¹

To develop an exposure-response function quantifying the relationship between air pollution exposure in early life and IQ loss, we conducted a systematic search of the world's literature. We utilized the systematic review and evidence integration strategy developed by the US National Institute of Environmental Health Sciences Office of Health Assessment and Translation and enumerated in the PRISMA statement.³² Through this analysis, we developed a coefficient quantifying the relationship between PM_{2.5} concentration and IQ loss. Details are presented in the Supplementary Appendix.

Findings

Air Pollution in Africa

HAP is the dominant form of air pollution across most of Africa, but it is declining – albeit slowly and unevenly. HAP is declining across the continent as families move away from using solid fuels such as wood, straw, and animal dung, towards using cleaner fuels such as Liquefied Petroleum Gas (LPG). AAP, by contrast, is beginning to increase.¹⁷ These increases occur as countries develop economically, industrialize, and become linked to global supply chains. People move into cities for employment opportunities, increasing the numbers of gasoline- and diesel-powered cars, trucks and buses on the roads. Sources of AAP include electricity generation, industrial emissions, vehicular exhaust, wind-blown dust, and crop burning.^{33,34} Many African countries have annual mean PM_{2.5} pollution concentrations exceeding WHO's 10 µg/m³ guideline.¹⁷ The average annual PM_{2.5} concentration in Sub-Saharan Africa in 2019 was 45 µg/m³. Ghana, Ethiopia and Rwanda all experienced mean PM_{2.5} levels well above WHO's guideline.

Disease and Death Attributable to Air Pollution in Africa

In 2019, an estimated 1.1 million deaths (95% UI 932,000 – 1.26 million) attributable to air pollution occurred across Africa.⁷ These included an estimated 697,000 deaths (95% UI 526,000 – 879,000) due to HAP, 383,000 deaths (95% UI 289,000 – 491,000) attributable to ambient PM_{2.5} pollution and 11,300 deaths (95% UI 4,800 – 18,300) from ambient ozone pollution (**Table 1**).⁷

Air pollution is now the second largest cause of death in Africa. It is responsible for more deaths than tobacco, alcohol, road accidents, and drug abuse.⁹ Only AIDS causes more deaths. Deaths attributable to air pollution result from lower respiratory infections (336,460 deaths, UI: 251,827 – 430,493), ischemic heart disease (223,930 deaths, UI: 185,558 – 268,252), neonatal disorders (186,541 deaths, UI: 152,569 – 229,402), chronic obstructive pulmonary disease (70,479 deaths, UI: 53,765 – 87,251) and stroke (193,936 deaths, UI: 165,936 – 227,196).

Patterns of air-pollution-related disease and death vary across Africa. Highest rates are seen in countries of lowest Social Development Index.⁷ While HAP-related deaths are declining⁷, AAP-

Table 1. Deaths Attributable to Air Pollution, Africa and Globally, 2017

Type of Pollution	Africa (95% UI)	Global (95% UI)	% of all global deaths in Africa
All air pollution	1.1 M (932,000 - 1.26 M)	6.7 M (5.9 M - 7.5 M)	16.3%
Ambient PM _{2.5} Pollution	383,419 (288,615 - 491,042)	4,140,971 (3,454,414 - 4,800,290)	9.3%
Household Air Pollution	697,000 (526,000 – 879,000)	2.3 M (1.6 M - 3.1 M)	30%
Ambient Ozone Pollution	11,230 (4,800 - 18,300)	365,000 (175,000 - 564,000)	3.1%

Source: IHME⁷

related deaths have begun to increase - from 26 deaths per 100,000 (UI: 17 – 40) in 1990 to 29 per 100,000 (UI: 22 - 37) in 2019.⁷ **(Figure 2)** An upward trend in AAP-related mortality is now clearly evident in Ghana, the most economically advanced of the three countries we examined in detail, and is beginning to appear in Ethiopia and Rwanda **(Box 2)**.

Differences in air-pollution-related disease and death are seen by gender, with 43% of AAP-related and 47% of HAP-related deaths occurring in women.⁷

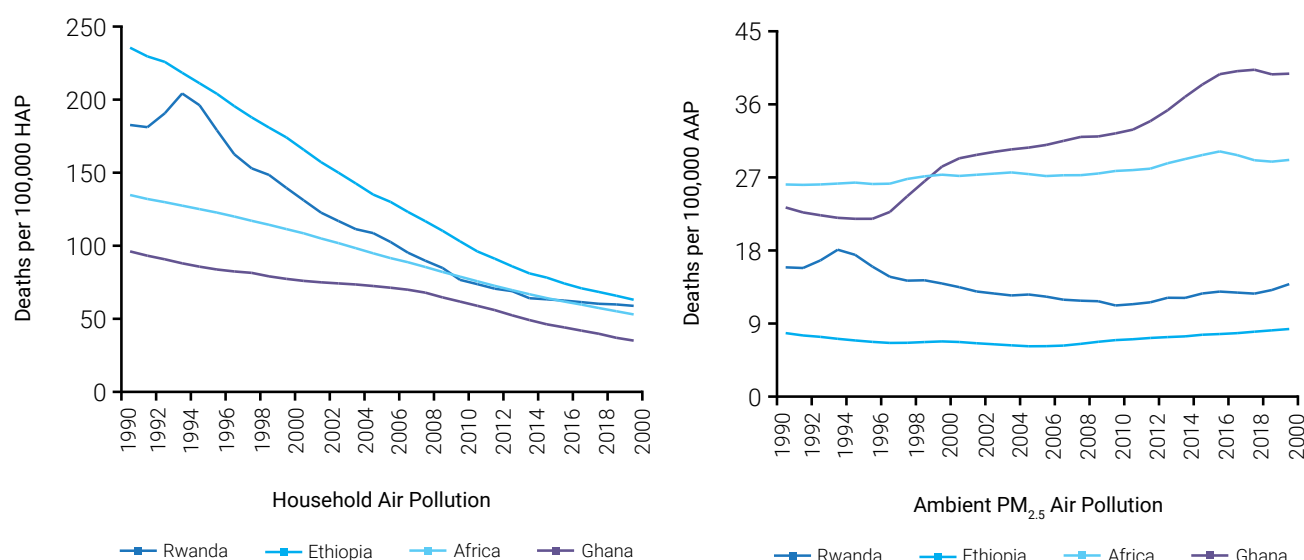


Figure 2. Deaths Attributable to Household Air Pollution (HAP) and Ambient PM_{2.5} Air Pollution (AAP), Ethiopia, Ghana and Rwanda, 1990-2019

BOX 2. The Intersection between Economic Development and Air Pollution- Ethiopia, Ghana and Rwanda

In the three countries that are the focus of this analysis, HAP exposures are greatest in Ethiopia and Rwanda where an estimated 98% of households burn solid fuels for cooking and heating³⁵. Thus, the HAP-associated increase in PM_{2.5} concentrations above background was estimated to be 205 µg/m³ in Ethiopia and 153 µg/m³ in Rwanda in 2017. In Ghana, by contrast, only 84% of households burned solid fuels, and the HAP-associated increment in PM_{2.5} exposure concentration above background was estimated to be 91.4 µg/m³.

AAP exposures show the opposite pattern. Mean population-weighted ambient PM_{2.5} concentrations in Ethiopia and Rwanda in 2017 were 34 µg/m³ and 32 µg/m³, respectively. By contrast, in more economically advanced Ghana, the population-weighted ambient PM_{2.5} concentration was 41 µg/m³.

Patterns of morbidity and mortality reflect these gradients. Thus, in Ethiopia and Rwanda, the number of deaths and the fraction of DALY's attributable to HAP is 3 to 4 times greater than the number associated with AAP. In Ghana, the ratio is approximately 2:1.

The predominance of HAP exposures in all three countries reflects their relatively early stage of economic development.

Loss of Economic Output Due to Air-Pollution-Related Morbidity

Estimates of income losses due to air-pollution-related morbidity for each country are presented in **Table 2**. All estimates are in 2019 International dollars. HAP accounts for over 80% of morbidity damages in Ethiopia and Rwanda, but for only half of damages in Ghana, reflecting relative stages of economic development.

The loss in output due to air-pollution-related disease was estimated at approximately \$318 million (2019 International dollars) in Ethiopia, \$249 million in Ghana, and \$41 million in Rwanda in 2019. Expressed as a % of GDP these losses amount to 0.12% of GDP in Ethiopia, 0.15% in Ghana, and 0.14% in Rwanda.

Loss of Human Capital Due to Air-Pollution-Related Mortality

Economic losses due to air pollution-related deaths reflect the number of deaths in the country, the age distribution of these deaths, income (output) per worker, the rate at which labor income is assumed to grow, and the rate at which it is discounted. The present value of future income lost due to air-pollution-related death depends also on the probability of survival to future ages and on labor force participation rates at each age.

Table 3 presents human capital losses due to air-pollution-related deaths in 2019 in both 2019 International dollars (Panel A) and as a percent of GDP (Panel B). The estimated loss in output due to air pollution-related premature death was approximately \$2.71 billion (2019 International dollars) in Ethiopia, \$1.38 billion in Ghana, and \$308 million in Rwanda in 2019. Expressed as a % of GDP these losses are 1.04% of GDP in Ethiopia, 0.80% in Ghana, and 1.05% in Rwanda.

Table 2. Lost Economic Output due to YLDs Attributable to Air Pollution, Ethiopia, Ghana and Rwanda, 2019 (95% CI in parentheses)

Country	Air Pollution	Ambient PM Pollution	Household Air Pollution
1. Panel A: in million 2019 International dollars			
Ethiopia	318	29	289
	(228, 426)	(15, 52)	(200, 397)
Ghana	249	121	128
	(183, 325)	(71, 175)	(78, 190)
Rwanda	41	7	33
	(30, 53)	(3, 14)	(23, 46)
2. Panel B: in % of GDP			
Ethiopia	0.123	0.011	0.111
	(0.088, 0.164)	(0.006, 0.020)	(0.077, 0.153)
Ghana	0.145	0.07	0.075
	(0.106, 0.189)	(0.041, 0.102)	(0.046, 0.111)
Rwanda	0.142	0.027	0.116
	(0.104, 0.184)	(0.012, 0.049)	(0.078, 0.159)

Note: These calculations are based on the Supplementary Appendix, assuming that labor income's share of GDP by country is: Ethiopia (0.44), Ghana (0.48) and Rwanda (0.74). All figures reflect labor force participation rates from the International Labour Organization and assume that non-market output equals 35% of each country's GDP. All figures in Panel A are in 2019 International dollars.

Table 3. Present Value of Economic Output Lost due to Air-Pollution-Related Deaths, Ethiopia, Ghana and Rwanda, 2019 (95% CI in parentheses)

Country	Air Pollution	Ambient PM Pollution	Household Air Pollution
1. Panel A: in million 2019 International dollars			
Ethiopia	2705	286	2414
	(2,023, 3,561)	(119, 548)	(1,729, 3,247)
Ghana	1379	720	651
	(941, 1,959)	(414, 1,123)	(345, 1,045)
Rwanda	308	57	250
	(212, 429)	(23, 111)	(157, 366)
2. Panel B: in % of GDP			
Ethiopia	1.041	0.11	0.929
	(0.778, 1.370)	(0.046, 0.211)	(0.665, 1.249)
Ghana	0.802	0.419	0.379
	(0.547, 1.140)	(0.241, 0.653)	(0.201, 0.608)
Rwanda	1.051	0.194	0.853
	(0.722, 1.463)	(0.080, 0.378)	(0.538, 1.249)

Note: These calculations are based on the Supplementary Appendix, assuming that the discount rate (r) is 1.5 percentage points higher than the rate of growth in output per worker (g). All figures in Panel A are in 2019 International dollars.

The combined output losses due to air-pollution-related morbidity and mortality in these three countries are substantial: \$3.02 billion (USD) (1.16% of GDP) in Ethiopia; \$1.63 billion (0.95% of GDP) in Ghana; and \$349 million (1.19% of GDP) in Rwanda.

Air Pollution and IQ Loss in African Children

Our systematic survey of the literature seeking studies that could support development of an exposure-response function quantifying the relationship between $PM_{2.5}$ pollution concentrations and IQ loss in children identified 1,169 articles. After removing duplicates, we identified 770 studies that met our criteria. We eliminated 671 of these studies through reviewing abstracts and determining that they did not meet our criteria, and we eliminated another 77 not relevant to our investigation. At the conclusion, we identified 22 studies that quantitatively examined relationships between air pollution and IQ loss in children. None were conducted in African children.

We determined that the most appropriate study was an investigation by Wang *et al.* examining IQ loss among 1,360 children enrolled in a longitudinal cohort in Southern California.³⁰ These children were exposed to concentrations of $PM_{2.5}$ pollution ranging from 2.14 to 25.36 mg/m^3 . We selected this study because of its robust design, large sample size, the wide range of $PM_{2.5}$ concentrations examined, the careful attention paid to covariates, and the form in which the effect estimate was expressed.

Wang found that each inter-quartile increase in mean annual $PM_{2.5}$ concentration in the year preceding IQ assessment was associated with a decrease in Performance IQ (PIQ) of 3.08 points (95% CI: -6.04, -0.12). Associations of $PM_{2.5}$ pollution with Full-Scale IQ and Verbal IQ, though also negative, were not statistically significant (-2.00, 95% CI: -4.84, 0.24 and -1.42, 95% CI: -4.48, 1.64, respectively).³⁰ From these data, we calculated that the slope of the relationship between $PM_{2.5}$ concentrations and PIQ loss in this range is -0.61 PIQ points per 1 mg/m^3 increase in

PM_{2.5}. Details are presented in the Supplementary Appendix.

Using this coefficient, we developed three estimates of air-pollution-related PIQ loss among children in Ethiopia, Ghana and Rwanda. In the most conservative analysis, we assumed that the slope of -0.61 PIQ points per 1 mg/m³ increase in exposure applied only to PM_{2.5} concentrations below 25.36 mg/m³, the upper bound of the PM_{2.5} pollution concentrations evaluated in the Wang study. In this analysis, we assumed that the slope of the relationship was zero at concentrations above 25.36 mg/m³ and that no further loss of PIQ points occurred above this level.

In our second and third estimates, we assumed that PIQ loss does occur at PM_{2.5} concentrations above 25.36 mg/m³, but that the relationship is weaker than at lower levels. Thus, we assumed a slope of -0.3 points per 1 mg/m³ increase in PM_{2.5} concentration above 25.36 mg/m³ up to 50 mg/m³ in the first of these analyses, and a slope of -0.1 points per 1 mg/m³ increase above 25.36 mg/m³ up to 50 mg/m³ in the second analysis.

Based on our most conservative analysis, we estimated that the total loss of cognitive function in children across all of Africa in 2019 was 1.96 billion PIQ points (**Table 4**). In Ethiopia, air pollution was responsible for an estimated loss of 180.5 million PIQ points, in Ghana, for 43.7 million PIQ points, and in Rwanda, for 18.5 billion PIQ points. Our two follow-on analyses estimated substantially greater PIQ losses (**Table 4**).

Table 4. Performance IQ (PIQ losses) in Children, Africa, Ethiopia, Ghana and Rwanda, 2019

Country	Annual mean PM _{2.5} (mg/m ³) (WHO)	Child population (<10 years of age)	PIQ loss for slope of -0.61 for 16.09-25.36 mg/m ³ ; 0 above 25.36 mg/m ³	PIQ loss for slope of -0.61 for 16.09-25.36 mg/m ³ ; -0.1 above 25.36-50 mg/m ³	PIQ loss for slope of -0.61 for 16.09-25.36 mg/m ³ ; -0.1 above 25.36-50 mg/m ³
Ethiopia	33.80	31,948,362	180,508,244	256,609,241	205,875,242
Ghana	54.00	7,741,749	43,740,883	100,967,892	62,816,553
Rwanda	36.20	3,274,564	18,501,287	29,150,169	22,050,914
Africa Total			1,959,085,783	3,562,469,927	2,493,037,256

The main finding of this analysis is that air pollution in Africa – Household Air Pollution (HAP) plus Ambient Air Pollution (AAP) - is a major threat to health, human capital and economic development. Air pollution was responsible for an estimated 1.1 million deaths across the continent in 2019 (UI: 932,000 - 1.26 M) 16.3% of all.⁷ Air pollution is now the second largest cause of death in Africa, exceeded only by AIDS.⁷

A second key finding is that AAP and its associated diseases are beginning to increase across Africa, while HAP and its diseases are in decline.¹⁰ HAP still accounts for 60% of all air-pollution-related deaths across Africa, and polluting fuels such as charcoal and kerosene are still prevalent.⁷ But thanks to sustained interventions by governments, NGOs and UN organizations, disease and death from HAP is now declining, albeit slowly and unevenly.

Ethiopia, Ghana and Rwanda are all at critical inflection points in their economic development. Within the past 3-5 years, all have begun for the first time to see increases in AAP and in AAP-related mortality.⁷ This upward trend is most clearly evident in Ghana, the most economically advanced of the countries, and beginning to be seen in Ethiopia and Rwanda.⁷

Experience from other countries suggests that the increases in AAP appearing in Africa today could be the harbinger of a looming problem. In the absence of visionary leadership and intentional intervention, AAP could become a much larger cause of disease and premature death than at present and could pose a major threat to economic development.^{11-16,36}

Our analysis shows that air pollution already has large negative impacts on the economies of African countries and suggests that in absence of deliberate intervention these impacts could become still greater in the near-term future. These impacts involve reductions in human capital - the individual and societal capabilities

that enable countries to thrive, adapt and chart their futures. Air pollution reduces human capital through causing disease, disability and premature death that remove economically productive people from the workforce.³¹

Air pollution impedes the formation of new human capital in African countries and undermines prospects for future development by causing brain injury to young children that, in turn, diminishes cognitive function, reduces IQ, and decreases lifelong economic productivity.^{29-32,35} Air pollution exposures in early development - during pregnancy and in the first years after birth - have been shown to be most critical in terms of their impacts on cognitive function.

We estimate in the most conservative of our three models that the total loss of cognitive function due to air pollution in children across all of Africa in 2019 was 1.96 billion Performance IQ (PIQ) points. PIQ primarily reflects “fluid” cognitive abilities, i.e., the ability to reason and solve novel problems in contrast to Verbal IQ, which reflects “crystallized” or acquired abilities.

On the positive side, African countries are uniquely well positioned to avoid AAP. Most are still in relatively early stages of development. With a few exceptions, most notably Nigeria, African countries are not yet deeply invested in fossil-fuel-based infrastructure. They therefore have a unique opportunity to advance their societies by investing in renewable energy and non-polluting technologies and minimizing reliance on oil and natural gas. With wise choices, African countries can develop sustainably and achieve prosperity, while avoiding the AAP and the AAP-related disease and death that have plagued development in countries that relied on coal, oil and gas to power their economic growth.³⁶⁻⁴¹

Limitations in the study

Our estimates of the burden of disease and death due to air pollution in Africa are conservative and undercount air pollution's full impacts because they are based solely on air pollution-disease pairs deemed by the GBD investigators to be definite or probable.⁹ It seems likely that new studies will reveal additional links between air pollution and disease thus increasing future estimates of the disease burden attributable to air pollution.

A further series of limitations reflects gaps in the air pollution data. We considered only two components of AAP - ozone and PM_{2.5} - because no information was available on other pollutants. The exposure-response functions relating air pollution levels to disease risk are derived largely from data collected in high-income countries and may be imperfectly applicable to the African context. In our estimates of disease burden attributable to PM_{2.5} pollution, we relied on the commonly used, but admittedly imperfect assumption of equitoxicity of all fine airborne particles, because there are no data available to rebut this assumption. Lastly, ground-level monitoring of air pollution across the African continent is highly incomplete, and much information on AAP levels is therefore based on satellite monitoring.

Our economic estimates undercount the total costs of air pollution because they are based on the above-noted undercounting of disease, do not capture health expenditures attributable to air-pollution-related illness, and do not capture the impacts of air pollution on agricultural yields or ecosystem services.

Our estimates of air pollution's impacts on IQ loss in African children are likely low. PM_{2.5} pollution concentrations above 25 mg/m³ almost certainly have greater negative impacts on children's IQ than lower concentrations. Yet because we had no information on the association between PM_{2.5} air pollution and IQ loss at concentrations above 25 mg/m³, we assumed in our main analysis that higher levels have no additional impact. A potential further source of underestimation of IQ loss is synergy between air pollution and social deprivation.³¹ In heavily polluted countries of low SDI, such interactions could substantially magnify air pollution's impact on IQ loss. Finally, we did not estimate the economic losses that likely result from IQ loss in African children. These losses are likely very large.³⁶

Our portrayal of the epidemiologic and environmental risk transitions in Africa is incomplete and cannot possibly cover the continent's extraordinary diversity.

Recommendations

A key finding of the 2018 Lancet Commission on Pollution and Health was that pollution can be controlled and pollution-related disease prevented.³⁰ We echo that recommendation here. Prevention is achieved by identifying and quantifying pollution sources and then deploying data-driven control strategies based on law, policy, technology and enforcement that target those sources. This Commission noted that many countries have successfully used these tools to control air pollution, and that these pollution control programs have proven highly cost-effective. The Lancet Commission on Pollution and Health concluded on the basis of this experience that pollution control is “a winnable battle”.

We offer the following recommendations for prevention and control of air pollution in Africa. These are based on recommendations made by the Lancet Commission on Pollution and Health.³⁰

1. Invest in clean renewable energy. As African countries develop, urbanize, and increase their energy needs, we strongly recommend that they pursue smart, non-polluting growth strategies that prioritize the use of wind, solar and hydropower, promote clean technologies, and minimize reliance on fossil fuels.^{32,33,34} Rapid adoption of renewable energy sources will be the single most important step to reduce AAP and AAP-related disease, disability and death across the continent.

This is an opportune moment to pursue a growth strategy based on renewables, because today for the first time in history, heat and electricity can be produced more cheaply from wind and solar energy in many parts of the world than from any fossil fuel.³⁵ This profound shift reflects technology advances that since 2010 have reduced the cost of producing electricity from solar cells by 81% and from wind by 45%. These costs are expected to decrease still more over the next five years, as ever more electricity is produced from wind and solar and further advantages of scale are realized.³⁶

Because it is now so cheap to produce energy from renewable energy, investments in fossil fuels run the risk of becoming stranded assets that fail to yield an economic return.^{37,38} The US Energy Information Administration estimates that by 2023 it will cost \$36.60 per megawatt-hour to produce electricity from wind and \$37.60 to produce solar energy, versus \$40.20 to produce energy from gas.³⁹

We recommend the following specific steps towards clean energy in Africa:

- a. Take advantage of Africa’s abundant wind and sunshine and reap the health and economic benefits of cheap, non-polluting energy produced by modern-day solar cells and wind turbines by directing national investment strategies away from oil, coal and gas toward wind, solar and other renewable sources of energy.
- b. Reduce reliance on coal. This can be accomplished through not allowing construction of new coal mines and coal-fired power plants and phasing out of existing coal-fired power plants. As the costs of producing energy from renewables continue to fall, arguments for energy production from coal, oil, and gas become increasingly untenable.
- c. Reduce reliance on oil and gas. Avoid becoming entrapped in long-term, multi-year contracts with oil and gas companies. Avoid construction of oil and gas pipelines and storage facilities.
- d. Reduce road traffic and traffic-related pollution by raising fuel taxes and parking fees, levying congestion charges, creating vehicle-free zones and cycle paths, and improving public transport. Additional measures may include enforcing mandatory inspection and maintenance for all vehicles and providing subsidies for electric vehicles.

- e. Regulate the open burning of waste by households and firms and place restrictions on agricultural burning, including burning forest to convert to agricultural land as well as crop residue burning.
- 2. Make air pollution prevention and control a top priority. African countries have a unique opportunity to incorporate air pollution prevention and control into all aspects of development planning, because many are still at a relatively early, malleable stage of development where pathways to progress are not fully fixed or heavily locked into fossil fuels. Forward planning that designs pollution out of national development and prevents its escalation is the most efficient and cost-effective way to prevent pollution and pollution-related disease. Strategies to avoid pollution can also reduce greenhouse gas emissions, prevent non-communicable disease, and accelerate progress on the SDGs.
- 3. Allocate sustainable, long-term funding for air pollution control. Funding for pollution control needs to increase substantially within countries as well as internationally and needs to be reliably sustained over multiple years.

Until recently, pollution control has been overlooked in development planning and neglected in the global health agenda. For too long, pollution has been regarded as the unavoidable price of economic progress. This outmoded view has been superseded by recent rapid reductions in the price of renewable energy. It needs to be discarded. Leaders of governments and civil society must recognize that pollution imposes a burden of disease as well as great economic costs on their societies and that in today's world, pollution is no longer inevitable.

- 4. Reduce household air pollution (HAP). Reduce household air pollution (HAP) through the promotion of cooking options such as LPG, biogas, electric induction stoves and, where possible, renewables. An example may be seen in India where government-subsidized programmes including Unnat Chulha Abhiyan programme, launched in 2014 provides modified biomass cook stoves to low-income households, and the Pradhan Mantri Ujjwala Yojana programme, launched in 2016 provides

liquefied petroleum gas (LPG) to 80 million low-income households.^{40,41}

A further benefit of reducing HAP is that it will reduce ambient air pollution. HAP from cookstoves is a major source of AAP in low-income and middle-income countries. Efforts to control AAP will be undermined if HAP is not also addressed.⁴²

- 5. Conduct source apportionment studies to identify and quantify the worst sources of air pollution. Source apportionment studies allow countries to determine which pollution sources cause the most harm and focus control efforts on these sources. Some interventions are effective in the short term and will deliver 'quick victories'. Others may be better suited for the mid-term or the long-term.
- 6. Track air pollution through the establishment of robust air pollution monitoring systems. Pollution monitoring is the bedrock of tracking progress toward pollution control. Monitoring is critical to evaluating the success of air pollution interventions and guiding enforcement. Real-time, consistent, on-line publication of air pollution monitoring data is a highly effective tool for public education.
- 7. Advance air pollution control through public education campaigns. Education of the public in African countries will be key to building broad support for air pollution control programs.
- 8. Champion air pollution control through the establishment of multi-sectoral partnerships. A further key to successful air pollution control is collaboration not only across health and environmental organizations, but also the formation of effective partnerships with the finance, energy, agriculture, development, and transport sectors.
- 9. Promote research and build research capacity on air pollution, human health and the economy in African research institutions. Support for research will build long-term scientific and technical capacity within countries and strengthen national economies. Creation of an African research infrastructure is an investment in the future.

In conclusion, courageous and visionary leaders who recognize air pollution's grave dangers, engage civil society and the public, and take bold,

evidence-based action to stop pollution at source will be key to the prevention of air pollution in Africa. Pollution prevention strategies that hold great promise are transition to non-polluting

renewable energy sources such as solar, wind, and hydropower; reducing reliance on fossil fuels; enhancing public transport; and incorporating pollution prevention into all forward planning.



Smog in Cairo, Egypt.
B Wolff, 2005.

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I. Measurement of Losses in Economic Output due to Air Pollution in Africa

A. Output Losses Associated with Air Pollution Mortality

We begin by estimating the present discounted value of the loss in GDP attributable to mortality associated with $PM_{2.5}$ in 2019. The loss in GDP in country i in 2019 if a worker dies is equal to labor's share of GDP (α) multiplied by GDP (Y_i), divided by the number of persons who are employed (L_i). We assume that workers of all ages in a country produce the same output per worker. Because not all persons of age j are working, the expected value of GDP per worker for a person of age j ($W_{ij,2019}$) is equal to $(\alpha Y_i / L_i)$ times the ratio of the number of workers of age j , L_{ij} , to the population of age j , N_{ij} .

$$W_{ij,2019} = (\alpha Y_i / L_i) * (L_{ij} / N_{ij}) \quad (1)$$

In our calculations below we assume that labor's share of GDP (α) is constant over time. We also assume that the ratio of L_{ij}/N_{ij} remains constant over time.

To calculate the loss in market and non-market output in 2019 we modify equation (1) to allow for household production. The Bureau of Economic Analysis in the US estimates household production to equal 25% of GDP. The comparable estimate for Ghana is 35% and 30% for India. We therefore calculate $W'_{ij,2019}$

$$W'_{ij,2019} = (\alpha Y_i / L_i) * (L_{ij} / N_{ij}) + \lambda_j (\alpha Y_i / L_i) * [1 - (L_{ij} / N_{ij})] \quad (1')$$

where λ_j represents the fraction of output attributable to non-market production for a person of age j .

If a person of age j dies in the current year, their contribution to GDP will be lost for all future years

of their working life. To compute the value of GDP lost in future years we assume that GDP per worker in country i grows at rate g_i . If labor's share of GDP and the fraction of population of working age (L_j/N_j) remain constant for all i and j , this implies that lost GDP at age t of a person currently of age j will equal $(\alpha Y_i / L_i) * (L_{it} / N_{it}) * (1 + g_i)^{t-j}$. This must be weighted by the probability that an individual would have survived to age t , where $\pi_{ij,t}$ is the probability that a person of age j in country i survives to age t . We therefore weight the loss in GDP in future years by the probability that an individual who dies this year would have survived to each future year of his working life. We discount the value of GDP lost in the future at the annual rate r_i .

Given the previous assumptions, the present discounted value of lost market and non-market output for a person of age j in country i who dies in 2019, PV_{ij} , is:

$$PV_{ij} = \sum_{t=j}^{84} \pi_{ij,t} \left[\left(\frac{L_{it}}{N_{it}} \right) \left(\frac{\alpha Y_i}{L_i} \right) + \lambda_j \left(1 - \frac{L_{it}}{N_{it}} \right) \left(\frac{\alpha Y_i}{L_i} \right) \right] \left(\frac{1 + g_i}{1 + r_i} \right)^{t-j} \quad (2)$$

Equation (2) is calculated for $j = 0, \dots, 84$. The value of λ_j equals 0 for children (e.g., $j = 0, \dots, 14$) and is 0.35 for larger values of j .

The total output lost due to air pollution mortality is the product of PV_{ij} and D_{ij} , the number of deaths due to air pollution in 2019 of persons of age j in country i , summed over all j . D_{ij} is computed separately for all air pollution deaths—deaths associated with ambient PM pollution, household air pollution and ground-level ozone—and separately for deaths associated with ambient PM pollution and household air pollution. Confidence intervals reflect confidence intervals in deaths due to air pollution as computed by the GBD team.⁷

B. Output Losses Associated with Air Pollution Morbidity

In each country, economic losses attributable to air pollution-related morbidity reflect the number of cases of pollution-related disease (YLDs), the age distribution of these cases, the labor force participation rate at each age and income (output) per worker. Output per worker is the product of GDP and labor income as a share of GDP, divided by the number of persons employed. Labor income as a share of GDP is difficult to estimate in developing countries—especially in countries such as Ethiopia, Ghana and Rwanda, where agriculture accounts for a large share of GDP. The Penn World Tables¹⁸ do not estimate labor income's share of GDP for Ethiopia or Ghana. For Rwanda, it is estimated to be 0.741. The International Labor Organization (2019) estimates labor income as a share of GDP to be 0.441 for Ethiopia and 0.478 for Ghana.

We compute the lost output due to morbidity associated with air pollution in 2019 by multiplying the number of YLDs associated with air pollution in 2019 by the expected loss in output per person. Results are reported by country and category of air pollution. The expected loss in output per person is given by equation (1') above. YLDs associated with air pollution, by country i and age j , YLD_{ij} , are from the GBD team (GBD 2019 Risk Factor Collaborators 2020). The output loss associated with morbidity in 2019 for persons of age j in state i , M_{ij} is given by:

$$M_{ij} = W'_{ij} \cdot 2019 \cdot YLD_{ij} \quad (3)$$

Morbidity losses, summed across all age groups, are reported by country and category of pollution: all air pollution; ambient PM pollution and household air pollution. The confidence intervals reflect confidence intervals in YLDs due to air pollution as computed by the GBD team.⁷

C. Data

To compute GDP per worker we use per capita Gross Domestic Product (Y_i)¹⁶ divided by the size of the labor force in country i (L_i)¹⁶ to compute (Y_i/L_i). Labor's share of GDP (α), obtained from the ILO (2019), is 0.44 for Ethiopia and 0.48 for



Indoor cooking with solid fuels, Ethiopia.
Photocredit: H. De Groote

Ghana. The Penn World Tables¹⁸ estimate labor income as a share of GDP to be 0.741 for Rwanda. They do not report labor income as a share of GDP for Ethiopia or Ghana.

Other parameters that vary by country include the ratio of worker to total population and survival rates. The ratio of worker to total population (L_{ij}/N_{ij}) for each country and age group comes from the ILO (2019). Because only aggregate data are reported for ages 65 and older, we determine (L_{ij}/N_{ij}) for each age over 65 by assuming that the worker-population ratio declines linearly from age 65 to age 85, becoming zero at age 85. The annual survival rate from age j to age t in each state, $\pi_{j,t}$, is computed from life tables provided by the Institute for Health Metrics and Evaluation (2021).

The present value of lost output depends on the rate of growth in output per worker (g) and the discount rate (r). As equation (2) indicates, it is the ratio of $(1+g)/(1+r)$ that determines the present discounted value of future earnings. Determining appropriate values of r and g for each country is difficult. We therefore use the assumptions underlying the Lancet Commission Report³⁰, viz., that the discount rate exceeds the rate of growth in output per worker by (a) 1.5, (b) 3.0 percentage points.

D. Results

Estimates of output losses due to morbidity are presented in **Table S.1**. Estimates are presented for particulate matter plus ozone pollution (All Air Pollution), ambient PM pollution and household air pollution. All estimates are in 2019 International dollars. Household air pollution accounts for over 80% of morbidity damages in Ethiopia and Rwanda and half of damages in Ghana. Damages as a percent of GDP are 0.12% of GDP for Ethiopia, 0.15% of GDP for Ghana and 0.14% of GDP for Rwanda.

Estimates of output losses due to premature mortality in each country are presented in **Table S.2**, based on the assumption that the discount rate exceeds the rate of growth in output per worker by 1.5%, which we treat as our base case. (Losses assuming that the discount rate exceeds the rate of growth in output per worker by 3% are presented in **Table S.3**.)

Table S.2 presents human capital losses due to air-pollution related deaths in 2019 in 2019 International dollars and as a percent of GDP. In Ethiopia and Rwanda over 80% of lost human capital is associated with household air pollution; in Ghana 47% of lost human capital is associated with household air pollution. In Ethiopia and Rwanda human capital losses are about 1 percent of GDP; in Ghana they are about 0.8% of GDP.

The combined output losses due to premature mortality and morbidity are substantial: 1.16% of GDP for Ethiopia, 0.95% of GDP for Ghana and 1.19% of GDP for Rwanda. These losses do not include other economic costs—health expenditures associated with air pollution related illness, or the monetary value of the loss in IQ points presented in the paper—and are, therefore, conservative estimates of the economic costs of air pollution.

Table S.1. Lost Output due to YLDs Associated with Air Pollution in 2019 (95% CI in parentheses)

Country	Air Pollution	Ambient PM Pollution	Household Air Pollution
1. Panel A: in million 2019 International dollars			
Ethiopia	318	29	289
	(228, 426)	(15, 52)	(200, 397)
Ghana	249	121	128
	(183, 325)	(71, 175)	(78, 190)
Rwanda	41	7	33
	(30, 53)	(3, 14)	(23, 46)
2. Panel B: in % of GDP			
Ethiopia	0.123	0.011	0.111
	(0.088, 0.164)	(0.006, 0.020)	(0.077, 0.153)
Ghana	0.145	0.07	0.075
	(0.106, 0.189)	(0.041, 0.102)	(0.046, 0.111)
Rwanda	0.142	0.027	0.116
	(0.104, 0.184)	(0.012, 0.049)	(0.078, 0.159)

Note: These calculations are based on equation (3) of this Appendix. All figures reflect labor force participation rates from the International Labor Organization and assume that non-market output equals 35% of each country's GDP. All figures in Panel A are in 2019 international dollars.

Table S.2. Present Value of Output Lost due to Air Pollution Deaths in 2019, Based on a Net Discount Rate of 1.5% (95% CI in parentheses)

Country	All Air Pollution	Ambient PM Pollution	Household Air Pollution
1. Panel A: in million 2019 International dollars			
Ethiopia	2705	286	2414
	(2,023, 3,561)	(119, 548)	(1,729, 3,247)
Ghana	1379	720	651
	(941, 1,959)	(414, 1,123)	(345, 1,045)
Rwanda	308	57	250
	(212, 429)	(23, 111)	(157, 366)
2. Panel B: in % of GDP			
Ethiopia	1.041	0.11	0.929
	(0.778, 1.370)	(0.046, 0.211)	(0.665, 1.249)
Ghana	0.802	0.419	0.379
	(0.547, 1.140)	(0.241, 0.653)	(0.201, 0.608)
Rwanda	1.051	0.194	0.853
	(0.722, 1.463)	(0.080, 0.378)	(0.538, 1.249)

Note: These calculations are based on equation (2) of this Appendix, assuming that the discount rate (r) is 1.5 percentage points higher than the rate of growth in output per worker (g). All figures in Panel A are in 2019 International dollars.

Table S.3. Present Value of Output Lost due to Air Pollution Deaths in 2019 Based on a Net Discount Rate of 3% (95% CI in parentheses)

Country	All Air Pollution	Ambient PM Pollution	Household Air Pollution
1. Panel A: in million 2019 International dollars			
Ethiopia	1832	201	1627
	(1,375, 2,401)	(86, 380)	(1,165, 2,185)
Ghana	1047	551	490
	(730, 1,460)	(322, 847)	(265, 779)
Rwanda	220	41	178
	(153, 304)	(17, 79)	(112, 259)
2. Panel B: in % of GDP			
Ethiopia	0.705	0.078	0.626
	(0.529, 0.924)	(0.033, 0.146)	(0.448, 0.840)
Ghana	0.609	0.321	0.285
	(0.425, 0.849)	(0.187, 0.493)	(0.154, 0.454)
Rwanda	0.75	0.141	0.607
	(0.521, 1.038)	(0.058, 0.272)	(0.384, 0.883)

Note: These calculations are based on equation (2) of this Appendix, assuming that the discount rate (r) is 3.0 percentage points higher than the rate of growth in output per worker (g). All figures in Panel A are in 2019 International dollars.

II. Air Pollution in Africa

Levels of ambient fine particulate ($PM_{2.5}$) air pollution vary sharply across Africa from a high of $80.1 \mu\text{g}/\text{m}^3$ air in Niger to a low of $14.90 \mu\text{g}/\text{m}^3$

in Mauritius (**Figure S.1**).⁷ Many African countries have mean annual $PM_{2.5}$ pollution levels that exceed the $10 \mu\text{g}/\text{m}^3$ threshold established in the WHO Air Quality Guidelines.

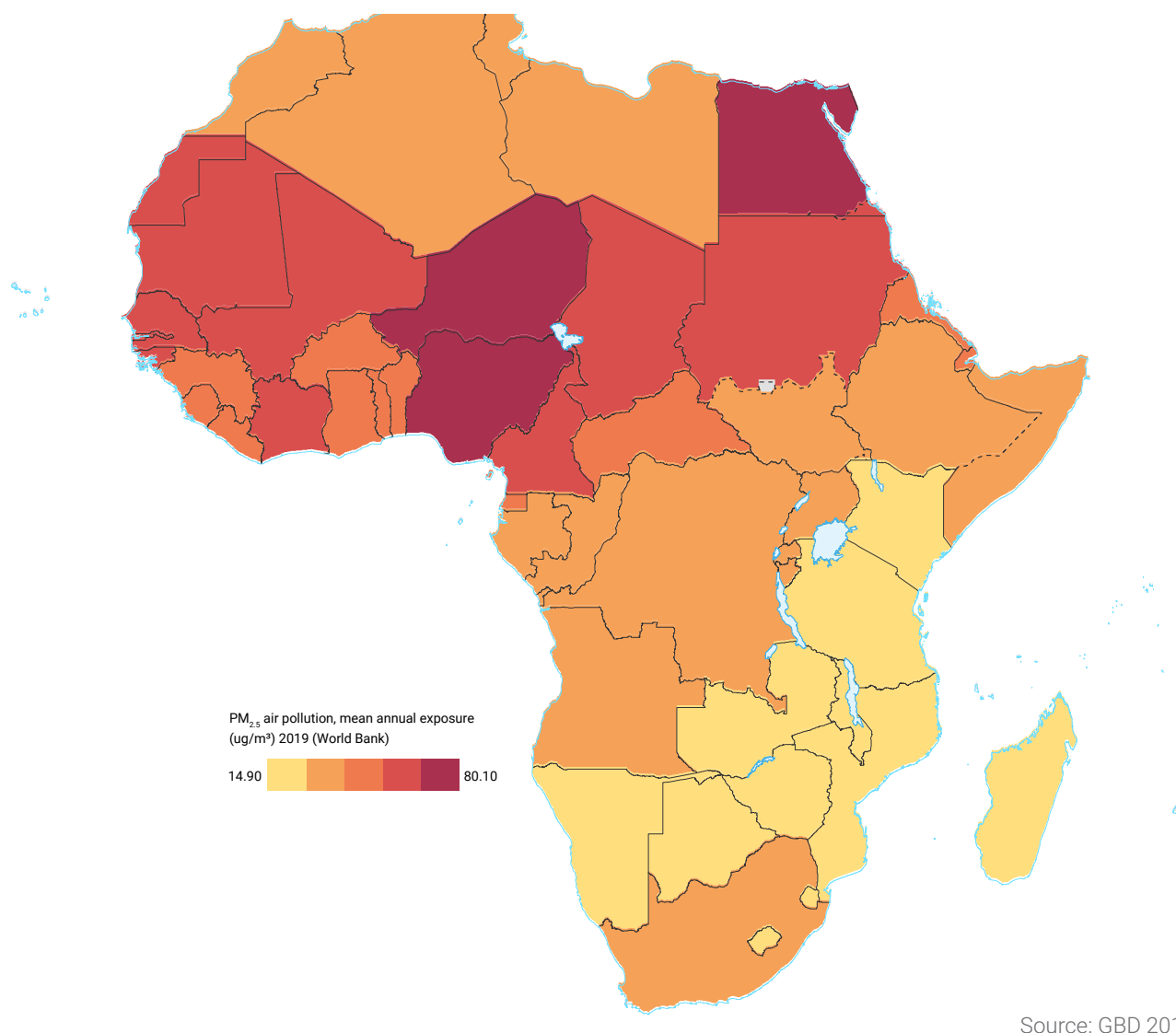


Figure S.1. Annual Mean Concentration of Airborne Particulate Pollution ($PM_{2.5}$) [$\mu\text{g}/\text{m}^3$] in Urban Areas, Africa, 2019

III. Morbidity and Mortality Attributable to Air Pollution in Africa

Air pollution is now the second largest cause of disease and premature death in Africa, exceeded only by AIDS.^{7,9,10,21} The burden of disease and death attributable to air pollution exceeds those due to high body mass index, tobacco smoke, alcohol use, transport accidents and drug use. **(Figure S.2)** Only AIDS causes more deaths in Africa each than air pollution.

Disease attributable to air pollution in Africa – measured in DALYs – results principally from lower respiratory infections (57%), ischemic heart disease (15%), chronic obstructive pulmonary disease (6%) and stroke (15%) **(Figure S.3)**.^{7,9,10,21}

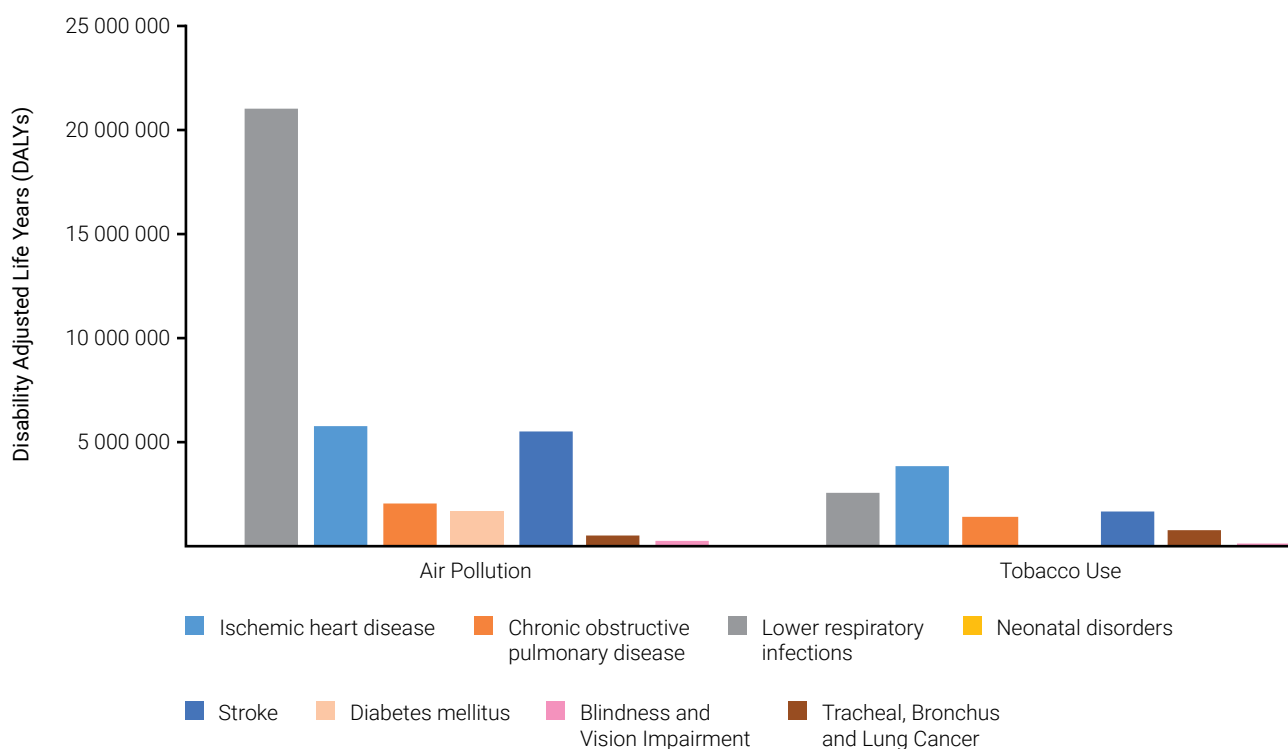
Air Pollution, Gender and Disease in Africa

Differences by gender are seen in air-pollution-related morbidity and mortality in Africa, with 57% of AAP-related and 53% of HAP-related deaths occurring in men **(Figure S.4)**.^{7,9,10,21}

IV. The Intersection of Air Pollution with Economic Development - Ethiopia, Ghana and Rwanda.

In 2019, population-weighted ambient PM_{2.5} air pollution levels in Ethiopia, Ghana and Rwanda exceeded the WHO guideline level of 10 µg/m³. In Ethiopia and in Rwanda, population-weighted ambient PM_{2.5} levels were 34 µg/m³ and 36 µg/m³, respectively.⁷ In Ghana, by contrast, which is further along the trajectory of economic development, the population-weighted ambient PM_{2.5} level was 54 µg/m³.

HAP was responsible for additional exposure and disease in all three countries, but again at varying levels.²¹ It is estimated that in 2010 98% of households in Ethiopia, and 98% of households in Rwanda, but only 84% of households in Ghana burned solid fuels for cooking.²⁹ PM_{2.5} exposures associated with HAP in these three countries were estimated to in 2017 be 205 µg/m³ in Ethiopia, 153 µg/m³ in Rwanda, but only 91.4 µg/m³ in Ghana.²⁹



Source: IHME

Figure S.2. Diseases Attributable to Air Pollution and Tobacco, Africa, 2019 (in DALYs)

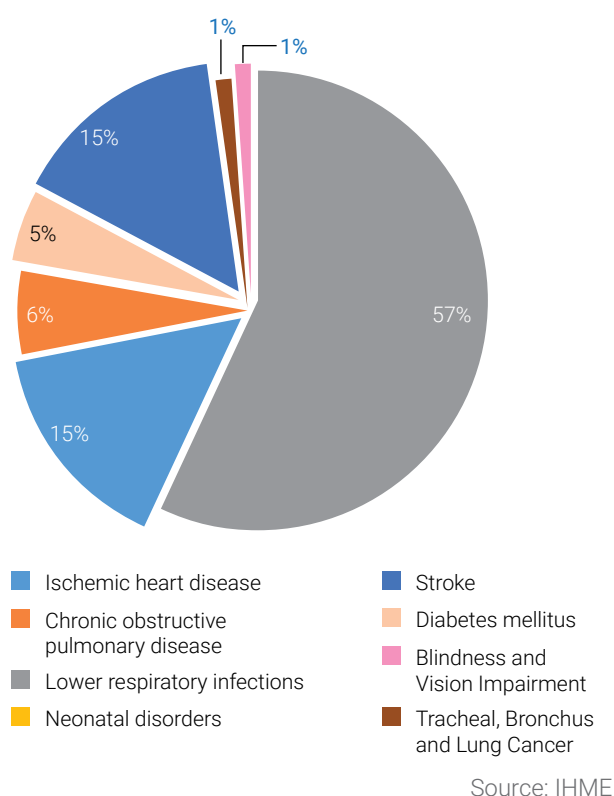


Figure S.3. Distribution (%) of DALYs Attributable to Air Pollution by Disease Cause, Africa, 2019

Air-pollution-related mortality in Ethiopia, Ghana and Rwanda reflects exposures to both HAP and AAP, but relative contributions vary ⁷ (Table S.4). Thus, in Ethiopia and Rwanda, the number of deaths attributed to HAP is 3 to 4 times the number associated with AAP. In more economically advanced Ghana, by contrast, the ratio of is only about 2:1.

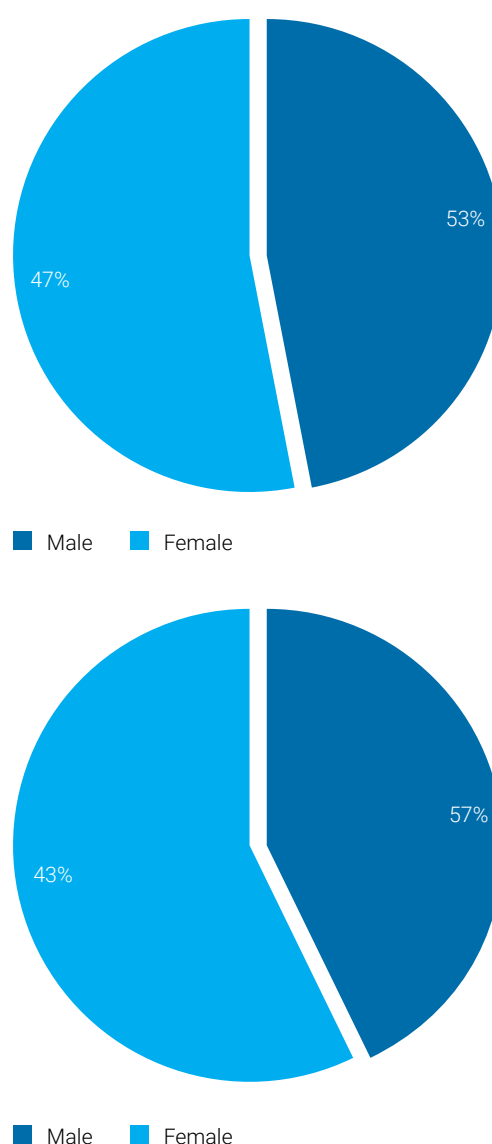


Figure S.4. Distribution of Deaths Attributable to Air Pollution by Gender, Africa, 2019

Table S.4. Deaths Due to Ambient and Household Air Pollution, Ethiopia, Ghana and Rwanda, 2019 (Number of deaths and % of all deaths)

Type of Pollution	Ethiopia # of deaths (% of all deaths)	Ghana # of deaths (% of all deaths)	Rwanda # of deaths (% of all deaths)
Ambient Air Pollution			
All Ages	8,957 (1.58)	12,544 (5.94)	1,758 (2.60)
Under 5	2,779 (1.34)	2,103 (4.22)	432 (2.42)
5-14 years	79 (0.41)	58 (0.95)	16 (0.77)
15-49 years	764 (0.72)	1,597 (3.10)	169 (1.18)
50-69 years	2,072 (2.08)	4,195 (8.07)	542 (3.20)
70+ years	3,263 (2.42)	4,589 (8.86)	599 (3.66)

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Household Air Pollution			
All Ages	67,827 (11.95)	11,065 (5.24)	7,468 (11.05)
Under 5	27500 (13.24)	2152 (4.32)	2070 (11.59)
5-14 years	700 (3.66)	54 (0.87)	70 (3.37)
15-49 years	4886 (4.60)	1331 (2.58)	660 (4.60)
50-69 years	12865 (12.90)	3512 (6.75)	2144 (12.66)
70+ years	21876 (16.25)	4015 (7.75)	2524 (15.40)

Source: IHME⁷

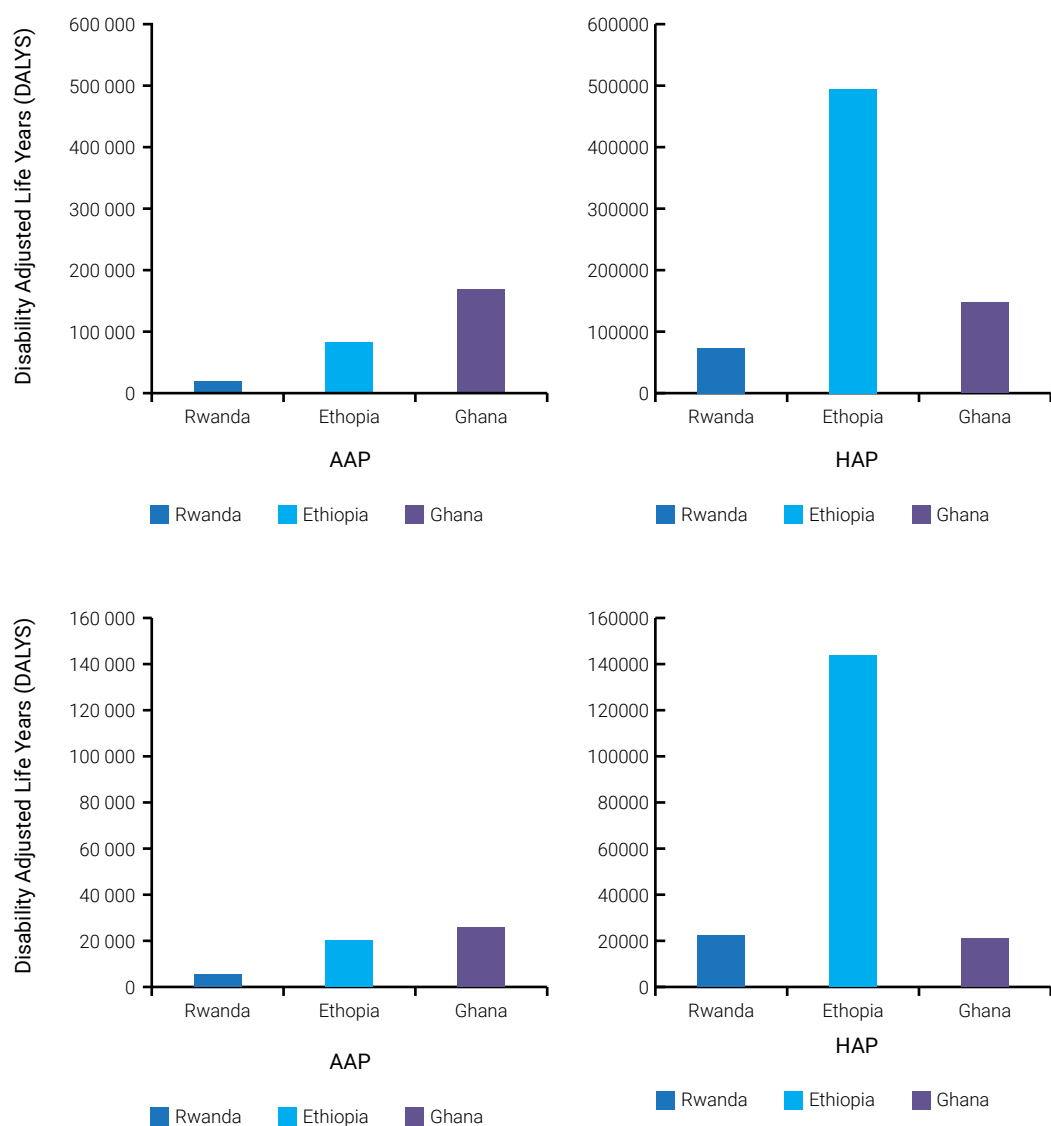
Like mortality, air-pollution-related morbidity in Ethiopia, Ghana and Rwanda, measured as Years Lost to Disability, also reflects exposure to both HAP and AAP, but again relative contributions vary (**Table S.5**). In all three of these countries, the fraction of DALYs attributable to HAP is higher than the fraction attributable to AAP. This predominance of HAP-related morbidity reflects the countries' relatively early stages of economic development.

Gradients in air-pollution-related morbidity are seen across these three countries reflecting their relative levels of economic development. Thus, the fraction of DALYs attributable to HAP is consistently highest in Ethiopia, intermediate in Rwanda, and lowest in Ghana, while the trend for AAP-related morbidity is the reverse. (**Figure S.5**).

Table S.5. Years Lost to Disability (YLDs) Due to Ambient and Household Air Pollution, Ethiopia, Ghana and Rwanda, 2019 (Number of YLDs and % of all YLDs)

Type of Pollution	Ethiopia # of YLDs (% of all YLDs)	Ghana # of YLDs (% of all YLDs)	Rwanda # of YLDs (% of all YLDs)
Ambient Air Pollution			
All Ages	16,037 (0.19)	29588 (1.07)	3840 (0.35)
Under 5	246 (0.03)	198 (0.09)	43 (0.06)
5-14 years	108 (0.01)	78 (0.02)	19 (0.01)
15-49 years	6,496 (0.14)	10337 (0.67)	1371 (0.21)
50-69 years	5,996 (0.54)	13219 (2.84)	1724 (0.91)
70+ years	3,190 (0.70)	5756 (3.54)	682 (1.22)
Household Air Pollution			
All Ages	160,370 (1.86)	32,419 (1.17)	16,920 (1.53)
Under 5	2,267 (0.27)	200 (0.10)	202 (0.30)
5-14 years	913 (0.06)	72 (0.02)	83 (0.05)
15-49 years	57,584 (1.23)	9,730 (0.63)	5,877 (0.92)
50-69 years	58,603 (5.25)	14,348 (3.09)	7,497 (3.95)
70+ years	41,002 (9.00)	8,070 (4.97)	3,261 (5.84)

Source: IHME



Source: IHME

Figure S.5. Air-Pollution-related Disease (DALYs) Caused by Cardiovascular Disease (CVD) (Panel 1) and Chronic Obstructive Pulmonary Disease (COPD) (Panel 2), Ethiopia, Ghana and Rwanda, 2019

V. Measurement of IQ Losses Due to Air Pollution in African Children

Methods

Estimation of the aggregate impact of air pollution on IQ loss in a population of children requires information on the size and age distribution of the pediatric population; information on population-weighted air pollution exposure levels; and an exposure-response function that quantifies the relationship between pollution and IQ loss.

For information on the size of the child population in each country, we relied on the 2019 Global Burden of Disease Study.⁷ To estimate annual mean population-weighted PM_{2.5} concentrations in each country, we used data from the 2019 Global Burden of Disease Study⁷

Until now, a key impediment to measuring the impact of air pollution on IQ loss in children has been lack of an exposure-response function that describes and quantifies the relationship between PM_{2.5} pollution levels and IQ. To develop such a function for African children exposed to air pollution, we conducted a systematic search of the world's literature seeking articles that quantitatively examined relationships between air pollution and IQ loss in children. The databases covered were PubMed, Scopus and Embase. Our search string included the terms: "air pollution", "fine particulate matter", "PM_{2.5}", "ozone", "nitrogen dioxide", "black carbon", "polycyclic aromatic hydrocarbon", "PAH", "second-hand smoke", "household air pollution", "cognitive function", "autism", "ADHD", "neurodevelopment", "neurotoxicity", "infant", "child", "adolescent" and "prenatal".

To screen studies for relevance, extract data, assess data quality and screen for bias, we utilized the systematic review and evidence integration process developed by the US National Institute of Environmental Health Science's Office of Health Assessment and Translation and enumerated in the PRISMA statement.²⁶ We screened search results by title and then by abstract to identify relevant articles that met the inclusion criteria.

We excluded articles if they were non-original studies, reviews, or studies that did not quantify associations between air pollution and cognitive endpoints. We excluded non-human studies and articles examining environmental exposures other than air pollution.

Results

Our systematic survey of the literature for studies that could support development of an exposure-response function quantifying the relationship between PM_{2.5} pollution levels and IQ loss in children identified 1,169 articles. **(Figure S.6)** After removing duplicates, we identified 770 studies that met our criteria. We eliminated 671 of these studies through reviewing abstracts and determining that they did not meet our criteria, and we eliminated another 77 not relevant to our investigation. At the conclusion, we identified 22 studies that examined relationships between air pollution and IQ loss in children. Of these 22 studies only one study quantitated the relationship between PM_{2.5} and PIQ points in children under 10. None were conducted in African children.

We determined that the most appropriate study for our analysis was an investigation by Wang *et al.* examining IQ loss among 1,360 children enrolled in a longitudinal cohort study in Southern California.²⁴ These children were exposed to concentrations of PM_{2.5} pollution that ranged from 2.14 to 25.36mg/m³. We selected this study because of its robust design, large sample size, the wide range of PM_{2.5} concentrations examined, the careful attention paid to covariates, and the form in which the effect estimate was expressed.

In their analysis, Wang *et al.* divided their population into four quartiles according to air pollution exposure levels: in quartile 1, PM_{2.5} exposures ranged from 2.14 to 16.08 mg/m³; in quartile 2, exposures ranged from 16.09 to 18.67mg/m³; in quartile 3, exposures ranged from 18.66 to 21.12mg/m³; and in quartile 4, exposures ranged from 21.14 to 25.36mg/m³.

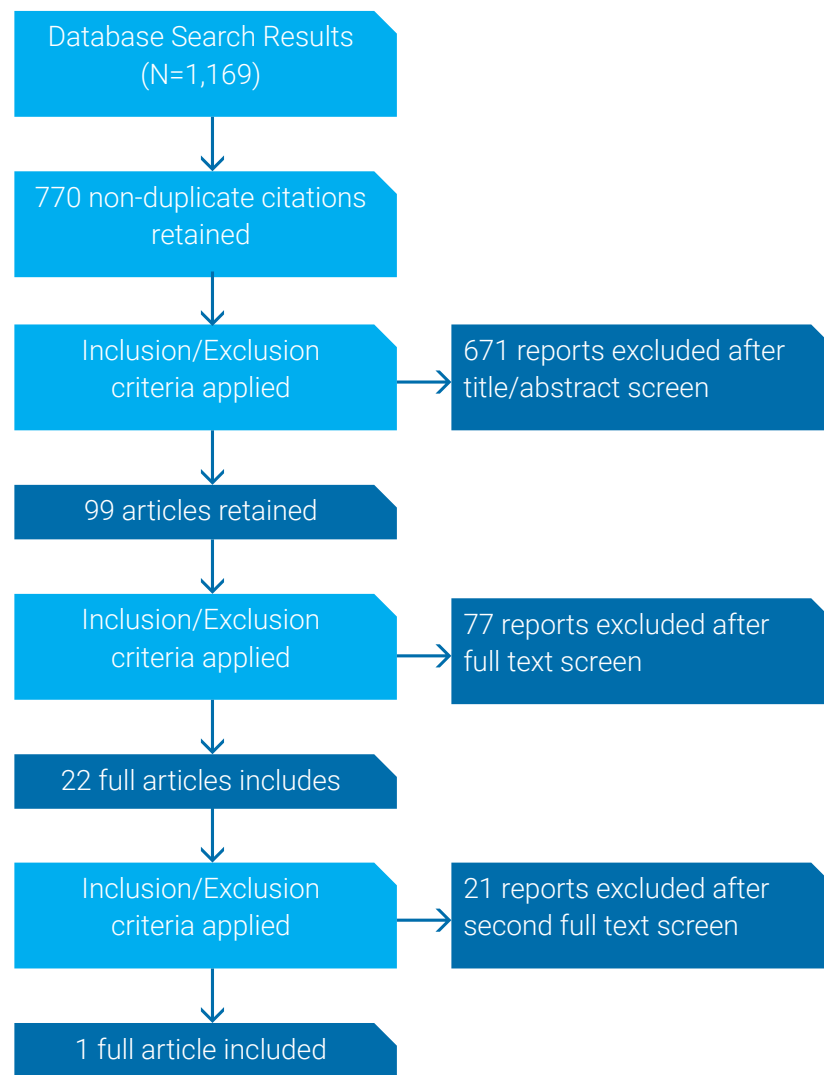


Figure S.6. Systematic Literature Search Flow Diagram

Analysis of the relationship between $PM_{2.5}$ pollution levels and IQ at ages 9-11 and 18-20 years by mixed-methods models found that each inter-quartile increase in $PM_{2.5}$ level in the year preceding IQ measurement was associated with a decrease in Performance IQ (PIQ) of 3.08 points (95% CI: -6.04, -0.12). PIQ primarily reflects “fluid” cognitive abilities, i.e., the ability to reason and solve novel problems, in contrast to Verbal IQ, which reflects primarily “crystallized” or acquired abilities. The associations of $PM_{2.5}$ with Full-Scale IQ and Verbal IQ, though also in a negative direction, were not statistically significant (-2.00, 95% CI: -4.84, 0.24 and -1.42, 95% CI: -4.48, 1.64, respectively).

Wang *et al.* made adjustments in their analysis for covariates, including socioeconomic status (SES), parental cognitive abilities, and neighborhood

characteristics. Family SES was found to be a significant effect modifier, and the adverse effect of air pollution on PIQ was greater in low SES families (-3.83 points, 95% CI: -6.98, -0.69) than in high SES families (-2.03, 95% CI: -6.12, 2.36). Sensitivity analyses that included adjustments for additional covariates, such as parental stress, maternal smoking during pregnancy, and pregnancy NO_x produced similar results.

To use the results of the Wang *et al.* study to estimate PIQ loss in African children, it was necessary to re-express the effect estimate as a slope of the relationship between $PM_{2.5}$ concentration and PIQ. In Wang *et al.*, the inter-quartile range for $PM_{2.5}$ (i.e., the 75th minus the 25th percentile of the distribution) was 5.04 mg/m³ (21.13-16.09). Dividing 5.04 by 3.08 yields a slope of -0.61 PIQ points per mg/m³

increase in $PM_{2.5}$. This coefficient is derived from a multiple regression model that included the following covariates: age, gender, ethnicity, family SES, parent's cognitive abilities, neighborhood SES, self-reported neighborhood quality, traffic density, and neighborhood greenness.

Using this coefficient, we developed three estimates of air-pollution-related loss of PIQ points among children in Ethiopia, Ghana and Rwanda. In the most conservative of these analyses, we assumed that the slope of -0.61 PIQ points per mg/m^3 applied only to $PM_{2.5}$ concentrations below 25.36 mg/m^3 , the upper bound of the $PM_{2.5}$ pollution levels evaluated in the Wang study. In this analysis, we assumed that the slope of the relationship was zero at concentrations above 25.36 mg/m^3 and that no further loss of PIQ points occurred above this level.

In our second and third estimates, we assumed that PIQ loss does occur at $PM_{2.5}$ concentrations above 25.36 mg/m^3 , but that the relationship is supralinear. Thus, we assumed a slope of -0.3 points per 1 mg/m^3 increase in $PM_{2.5}$ concentration above 25.36 mg/m^3 in the first of these analyses, and a slope of -0.1 points per 1 mg/m^3 increase in the second analysis.

In our first, most conservative analysis, we found that the total loss of cognitive function in children across all African countries in 2019 was an estimated 1,959,085,783 Performance IQ (PIQ) points. **(Table S.6)**. The results of our additional analyses show substantially greater estimated losses of PIQ.

In Ethiopia, air pollution was responsible in 2019 for an estimated loss of 180,508,244 PIQ points. In Ghana, it was responsible for a loss of 43,740,883 PIQ points. In Rwanda, it was responsible for a loss of 18,501,287 PIQ points.

Table 7. PIQ losses, by Country under Three Assumptions about the Functional Form of the Dose-Effect Relationship between $PM_{2.5}$ Air Pollution and PIQ Loss, Africa, 2016

Country	Annual mean $PM_{2.5}$ ($\mu g/m^3$) (WHO)	Child population (<10 years of age)	PIQ loss for slope of -0.61 for 16.09-25.36 $\mu g/m^3$; 0 after 25.36 $\mu g/m^3$	PIQ loss for slope of -0.61 for 16.09-25.36 $\mu g/m^3$; -0.1 for 25.36-50 $\mu g/m^3$	PIQ loss for slope of -0.61 for 16.09-25.36 $\mu g/m^3$; -0.3 for 25.36-50 $\mu g/m^3$
Mauritius	14.90	133,871	-	-	-
Seychelles	15.60	14,769	-	-	-
Comoros	17.20	155,970	106,059	106,059	106,059
Madagascar	17.90	7,604,066	8,364,472	8,364,472	8,364,472
Mozambique	20.80	9,824,027	28,194,957	28,194,957	28,194,957
Zimbabwe	20.80	4,121,621	11,829,053	11,829,053	11,829,053
Kenya	21.60	12,838,903	43,138,715	43,138,715	43,138,715
Malawi	22.30	5,263,607	19,949,070	19,949,070	19,949,070
Swaziland/Eswatini	23.3	277,951	1,222,983	1,222,983	1,222,983
Namibia	24.20	577,470	2,858,478	2,858,478	2,858,478
Botswana	24.70	475,795	2,497,921	2,497,921	2,497,921

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Country	Annual mean PM _{2.5} (µg/m³) (WHO)	Child population (<10 years of age)	PIQ loss for slope of -0.61 for 16.09-25.36 µg/m³; 0 after 25.36 µg/m³	PIQ loss for slope of -0.61 for 16.09-25.36 µg/m³; -0.1 for 25.36-50 µg/m³	PIQ loss for slope of -0.61 for 16.09-25.36 µg/m³; -0.3 for 25.36-50 µg/m³
Tanzania	24.70	17,458,133	91,655,198	91,655,198	91,655,198
Zambia	25.90	5,408,494	30,557,991	31,434,167	30,850,050
Lesotho	27.50	436,567	2,466,604	2,746,880	2,560,030
Angola	28.40	9,988,864	56,437,082	65,546,926	59,473,697
South Africa	28.70	10,211,183	57,693,182	67,924,788	61,103,717
Somalia	30.40	6,835,624	38,621,274	48,956,737	42,066,428
Tunisia	30.40	1,775,696	10,032,684	12,717,536	10,927,635
Sao Tome and Principe	31.10	48,629	274,756	358,495	302,669
Algeria	32.80	8,243,624	46,576,475	64,976,244	52,709,731
Burundi	33.30	3,868,198	21,855,321	31,069,369	24,926,670
Ethiopia	33.80	31,948,362	180,508,244	256,609,241	205,875,242
Morocco	35.10	6,225,835	35,175,970	53,554,635	41,302,192
Uganda	35.20	13,404,106	75,733,196	118,116,979	89,861,124
Democratic Republic of the Congo	35.90	26,393,298	149,122,133	232,577,740	176,940,668
Rwanda	36.20	3,274,564	18,501,287	29,150,169	22,050,914
Gabon	36.70	395,777	2,236,138	3,582,571	2,684,949
South Sudan	37.60	2,858,763	16,152,012	26,649,389	19,651,138
Libya	38.60	911,518	5,150,078	8,770,627	6,356,927
Congo, Rep.	39.30	1,374,440	7,765,585	13,513,493	9,681,554
Djibouti	43.20	298,279	1,685,274	3,281,663	2,217,404
Eritrea	44.10	1,813,613	10,246,916	20,443,049	13,645,627
Equatorial Guinea	45.30	373,288	2,109,077	4,342,086	2,853,413
Togo	46.20	2,189,680	12,371,692	26,061,571	16,934,985
Central African Republic	46.40	1,573,407	8,889,748	18,821,093	12,200,196
Benin	46.90	4,155,497	23,478,560	50,331,381	32,429,500
Liberia	50.60	1,260,472	7,121,668	16,439,077	10,227,471
Cabo Verde	51.10	106,551	602,015	2,779,280	864,557
Sierra Leone	51.10	2,335,654	13,196,445	30,461,599	18,951,496
Guinea	52.50	4,076,800	23,033,919	53,169,624	33,079,154
Burkina Faso	53.70	7,490,136	42,319,268	97,686,353	60,728,271

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Country	Annual mean PM _{2.5} (µg/m ³) (WHO)	Child population (<10 years of age)	PIQ loss for slope of -0.61 for 16.09-25.36 µg/m ³ ; 0 after 25.36 µg/m ³	PIQ loss for slope of -0.61 for 16.09-25.36 µg/m ³ ; -0.1 for 25.36-50 µg/m ³	PIQ loss for slope of -0.61 for 16.09-25.36 µg/m ³ ; -0.3 for 25.36-50 µg/m ³
Ghana	54.00	7,741,749	43,740,883	100,967,892	62,816,553
Guinea-Bissau	54.10	556,554	3,144,530	7,258,577	4,515,879
Sudan	54.70	10,776,580	60,887,680	140,548,159	87,441,173
Cote d'Ivoire	55.60	7,594,188	42,907,165	99,043,403	61,619,244
The Gambia	58.10	636,437	3,595,872	8,300,414	5,164,052
Chad	59.30	6,084,005	34,374,629	79,347,594	49,365,617
Senegal	60.20	4,194,955	23,701,493	54,710,600	34,037,862
Mali	60.60	7,451,321	42,099,966	97,180,131	60,460,021
Cameroon	64.50	8,279,472	46,779,017	107,980,874	67,179,636
Mauritania	66.80	1,085,583	6,133,546	14,158,176	8,808,423
Egypt	67.90	22,265,151	125,798,104	290,382,100	180,659,436
Nigeria	70.40	64,837,442	366,331,549	845,609,920	526,091,006
Niger	80.10	8,824,752	49,859,851	115,092,417	71,604,039
Total PIQ loss:			1,959,085,783	3,562,469,927	2,493,037,256

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