Air pollution and development in Africa: impacts on health, the economy, and human capital

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Summary

Background Africa is undergoing both an environmental and an epidemiological transition. Household air pollution is the predominant form of air pollution, but it is declining, whereas ambient air pollution is increasing. We aimed to quantify how air pollution is affecting health, human capital, and the economy across Africa, with a particular focus on Ethiopia, Ghana, and Rwanda.

Methods Data on household and ambient air pollution were from WHO Global Health Observatory, and data on morbidity and mortality were from the 2019 Global Burden of Disease Study. We estimated economic output lost due to air pollution-related disease by country, with use of labour income per worker, adjusted by the probability that a person (of a given age) was working. Losses were expressed in 2019 international dollars and as a proportion of gross domestic product (GDP). We also quantified the contribution of particulate matter $(PM)_{2\cdot5}$ pollution to intelligence quotient (IQ) loss in children younger than 10 years, with use of an exposure–response coefficient based on previously published data.

Findings Air pollution was responsible for 1·1 million deaths across Africa in 2019. Household air pollution accounted for 697 000 deaths and ambient air pollution for 394 000. Ambient air pollution-related deaths increased from 361 000 in 2015, to 383 000 in 2019, with the greatest increases in the most highly developed countries. The majority of deaths due to ambient air pollution are caused by non-communicable diseases. The loss in economic output in 2019 due to air pollution-related morbidity and mortality was \$3·02 billion in Ethiopia (1·16% of GDP), \$1·63 billion in Ghana (0·95% of GDP), and \$349 million in Rwanda (1·19% of GDP). $PM_{2\cdot5}$ pollution was estimated to be responsible for 1·96 billion lost IQ points in African children in 2019.

Interpretation Ambient air pollution is increasing across Africa. In the absence of deliberate intervention, it will increase morbidity and mortality, diminish economic productivity, impair human capital formation, and undercut development. Because most African countries are still early in development, they have opportunities to transition rapidly to wind and solar energy, avoiding a reliance on fossil fuel-based economies and minimising pollution.

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Introduction

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] The continent is urbanising and is projected to have 13 megacities by 2100. African countries are advancing economically, industrialising, and building infrastructure (panel 1).[2] The continent is undergoing a transition in environmental risks from traditional to modern sources of pollution. Household air pollution is still the predominant form of air pollution, but it is declining, whereas ambient air pollution is increasing. At the same time, Africa is passing through a massive epidemiological transition from communicable to non-communicable diseases.[6]

Reflecting the epidemiological transition, life expectancy across Africa has almost doubled, from 36·5 years in 1950 to 64·1 years today.[7] Infant mortality has fallen by approximately 70%, from 187 deaths per 1000 livebirths in 1950 to 51 per 1000 in 2019.[7] Deaths from communicable diseases decreased from 5·2 million (95% uncertainty interval [UI] 4·9 million–5·6 million) in 1990 to 4·5 million (4·0 million–5·3 million) in 2019, despite the continuing burden of AIDS, malaria, and tuberculosis. In the same time period, deaths from non-communicable diseases increased in number from 2·1 million (1·9 million–2·4 million) to 3·8 million (3·4 million–4·2 million; figure 1).[8–10]

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 non-communicable disease and affecting economic development.[11–16]

The goals of this study are: to quantify the impacts of air pollution (both household air pollution and ambient air pollution) on health, human capital, and the economy in a rapidly changing Africa; and to identify opportunities for control of air pollution and prevention

Research in context

Evidence before this study

Africa is undergoing massive transition. The continent's population is on track to more than triple in this century, from 1·3 billion in 2020 to 4·3 billion by 2100. Cities are expanding exponentially, economies are growing, and life expectancy has almost doubled. At the same time, ambient air pollution is increasing as a consequence of increased fossil fuel combustion, and ambient air pollution-related mortality has risen from 26·13 per 100 000 population in 1990, to 29·15 per 100 000 in 2019. Although this increase is modest, it is historically unprecedented. The greatest increases are in the most highly developed African countries. To our knowledge, the impact of ambient air pollution on the economies and human capital of African countries has not previously been assessed. This information gap blinds development planning because it impedes full consideration of the threats and opportunities of various development pathways.

Added value of this study

In this study, we examine the increases in ambient air pollution and ambient air pollution-related disease in Africa. We estimate annual productivity losses resulting from ambient air pollution-related disease and premature death. The study includes data for all of Africa, with a focus on three rapidly developing sub-Saharan countries in different areas of the continent: Ethiopia, Ghana, and Rwanda. We consider impacts on both the market and non-market (informal) economies. We estimate that economic output lost to air-pollution-related disease was \$3·0 billion (in 2019 international dollars) in Ethiopia (1·16% of gross domestic product [GDP]), \$1·6 billion (0·95% of GDP) in Ghana, and \$349 million (1·19% of GDP) in Rwanda. Particulate matter $(PM)_{2·5}$ pollution was responsible for 1·96 billion lost intelligence quotient points in African children.

Implications of all the available evidence

Many African countries are in relatively early stages of development. They therefore have opportunities to pursue non-polluting pathways to growth and to avoid becoming entrapped in fossil fuel-based economies. With wise and far-sighted investments in renewable energy and clean technologies, the countries of Africa can avoid ambient air pollution, build human capital, and accelerate development.

of pollution-related disease. We examine data for the entire continent, but we focus especially on three rapidly emerging sub-Saharan countries: Rwanda, Ghana, and Ethiopia.

See Online for appendix

Methods

Estimation of air pollution, morbidity, and mortality

Data on concentrations and trends in household air pollution and ambient air pollution were obtained from the WHO Global Health Observatory.[17,18] Information on morbidity and mortality attributable to household air pollution and ambient air pollution was obtained from the 2019 Global Burden of Disease Study (GBD).[7,9]

Estimation of losses in economic output

Air pollution has been associated with output losses in agriculture, the service sector, and manufacturing industries.[19–21] To estimate income or output losses attributable to air pollution-related morbidity in Africa in 2019, we estimated labour income (as measured by output) per worker, based on the contribution of labour to gross domestic product (GDP), and then adjusted by the probability that a person (of a given age) was working. We calculated labour income per worker in each country by multiplying 2019 GDP[22] by labour income's share of GDP[23,24] and dividing by the number of people employed.[22] Because not all people are employed, labour income per worker was adjusted by the fraction of people in each age group who were working.[23]

Air pollution also reduces non-market production (eg, household production), and these losses are not captured by traditional, GDP-focused analyses. Satellite account data for the USA estimate the value of home production to be 25% of GDP.[25] A comparable estimate for Ghana is 35%.[26] We applied the value of 35% to Ghana, Ethiopia, and Rwanda to reflect the contribution of non-market output. Details are presented in the appendix (pp 1–5).

Our estimate of expected output loss per person, by age, was multiplied by the number of years lost due to disability attributable to air pollution in 2019 for people of each age.[27] This quantity, summed across all ages, provided an estimate of the total loss in economic output or income due to air pollution-related disease. All costs are presented in 2019 international dollars.

To quantify the impact of air pollution on human capital, we estimated the loss in present discounted value of an individual's labour 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 they survive to each future age. The probability that a person is working at each age is measured by the ratio of working people in the total population, by age, for each country.[23] Survival probabilities were estimated using country-specific life tables.[28] The present value of lost labour 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 on pollution and health: the discount rate exceeds the rate of growth in output per worker by either 1·5 percentage points or 3·0 percentage points.[29] Details are presented in the appendix (pp 1–5).

Estimation of intelligence quotient (IQ) loss

Air pollution exposures during sensitive periods of brain development in pregnancy and early childhood can cause brain injury in children, which reduces cognitive function as measured by IQ score and impedes formation of human capital.[30–32] To develop an exposure–response function quantifying the relationship between air pollution exposure in early life and IQ loss, we did a systematic search of the global literature. We used 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 (appendix p 13).[33] Through this analysis, we developed a coefficient quantifying the relationship between particulate matter $(PM)_{2\cdot5}$ concentration and IQ loss in children younger than 10 years. Details are presented in the appendix (pp 13–16).

Role of the funding source

UN Environment Programme scientists participated as individuals in the writing of the report. However, the funder had no role in study design, data collection, data analysis, or data interpretation.

Results

Household air pollution is the dominant form of air pollution across most of Africa, but it is declining, albeit slowly and unevenly. Ambient air pollution, by contrast, is beginning to increase.[17] Sources of ambient air pollution include electricity generation, industrial emissions, vehicular exhaust, wind-blown dust, and crop burning.[34,35] Many African countries have annual mean $PM_{2\cdot5}$ pollution concentrations exceeding the WHO guideline of 10 µg/m³.[17] The average annual $PM_{2\cdot5}$ concentration in sub-Saharan Africa in 2019 was 45 µg/m³. Ghana, Ethiopia, and Rwanda all experienced mean $PM_{2\cdot5}$ concentrations that were considerably higher than 10 µg/m³.[7]

In 2019, an estimated 1·1 million deaths (95% UI 932 000–1·3 million) attributable to air pollution occurred across Africa.[7] These included an estimated 697 000 deaths (526 000–879 000) due to household air pollution, 383 000 deaths (289 000–491 000) attributable to ambient $PM_{2\cdot5}$ pollution, and 11 300 deaths (4800–18 300) due to 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, 95% UI 251 827–430 493), ischaemic heart disease (223 930, 185 558–268 252), neonatal disorders (186 541, 152 569–229 402), chronic obstructive pulmonary disease (70 479, 53 765–87 251), and stroke (193 936, 165 936–227 196).

Patterns of air pollution-related disease and death vary across Africa. The highest rates are seen in countries with the lowest social development indices.[7] Although household air pollution-related deaths are declining,[7] ambient air pollution-related deaths have begun to increase, from 26 deaths per 100 000 population (95% UI 17–40) in 1990 to 29 per 100 000 (22–37) in 2019 (figure 2).[7] An upward trend in ambient air pollution-related mortality is evident in Ghana, the most economically

Panel 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 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 labour-intensive industries.[3] In 2002, Ethiopia created the Industrial Development Strategy, which focused on eradication of poverty and sustainable development. The strategy placed emphasis on enhancing exports and linkages to international markets to foster internal economic growth.

Ghana

In 1965, 8 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 gross domestic product 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 programme 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 health care. 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.

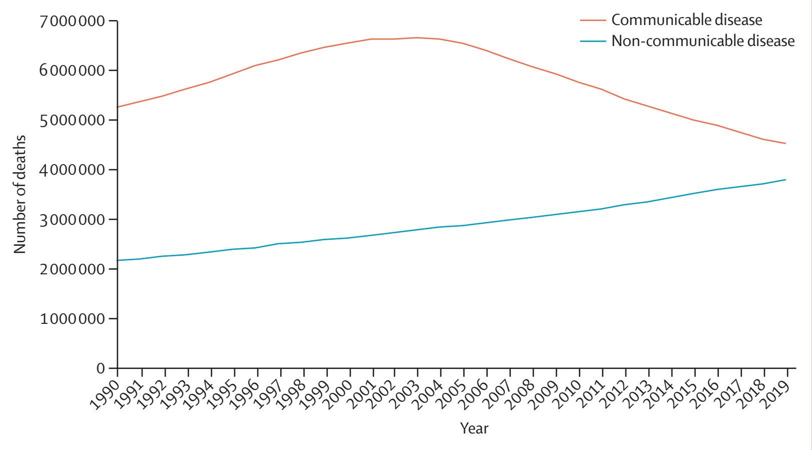

Figure 1: **Deaths attributable to communicable and non-communicable disease in Africa, 1990–2019**

	Deaths attributable to air pollution (95% uncertainty interval)		Proportion of global deaths in Africa
	Africa	Global	
All air pollution	1·1 million (932 000–1·3 million)	6·7 million (5·9 million–7·5 million)	16·3%
Ambient $PM_{2.5}$ pollution	383 419 (288 615–491 042)	4·1 million (3·4 million–4·8 million)	9·3%
Household air pollution	697 000 (526 000–879 000)	2·3 million (1·6 million–3·1 million)	30·3%
Ambient ozone pollution	11 230 (4800–18 300)	365 000 (175 000–564 000)	3·1%

Data are from the 2019 Global Burden of Disease Study. PM=particulate matter.

Table 1: **Deaths attributable to air pollution, in Africa and globally, in 2019**

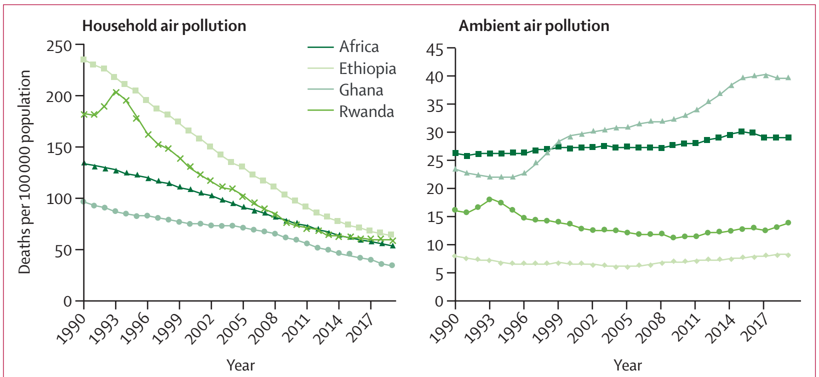

Figure 2: **Deaths attributable to household air pollution and ambient particulate matter (PM)$_{2.5}$ air pollution in Ethiopia, Ghana, Rwanda, and overall in Africa, 1990–2019**

Panel 2: The intersection between economic development and air pollution

In the three countries that are the focus of this analysis, household air pollution exposures are greatest in Ethiopia and Rwanda, where an estimated 98% of households burn solid fuels for cooking and heating.[35] Thus, the household air pollution-associated increase in particulate matter (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 burn solid fuels, and the household air pollution-associated increment in $PM_{2.5}$ exposure concentration above background was estimated to be 91·4 μg/m³.

Ambient air pollution exposures show the opposite pattern. Mean population-weighted ambient $PM_{2.5}$ concentrations in 2017 were 34 μg/m³ in Ethiopia and 32 μg/m³ in Rwanda. By contrast, in Ghana, the population-weighted ambient $PM_{2.5}$ concentration was 41 μg/m³.

Patterns of morbidity and mortality reflect these gradients. In Ethiopia and Rwanda, the number of deaths and the fraction of disability-adjusted life-years attributable to household air pollution are three to four times greater than those associated with ambient air pollution. In Ghana, the ratio is approximately 2:1. The predominance of household air pollution exposures in all three countries reflects their relatively early stage of economic development.

advanced of the three countries we examined in detail, and is beginning to emerge in Ethiopia and Rwanda (panel 2). Differences in air pollution-related disease and death are seen by gender, with 43% of ambient air pollution-related deaths and 47% of household air pollution-related deaths occurring in women.[7]

Estimates of income losses due to air pollution-related morbidity for each country are presented in table 2. Household air pollution accounts for more than 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 approximately \$318 million (in 2019 international dollars) in Ethiopia, \$249 million in Ghana, and \$41 million in Rwanda in 2019. Expressed as a proportion of GDP, these losses are 0·12% of GDP in Ethiopia, 0·15% in Ghana, and 0·14% in Rwanda (table 2).

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 labour 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 labour force participation rates at each age. Table 3 presents human capital losses due to air pollution-related deaths in 2019. The estimated loss in output due to air pollution-related premature death was \$2·71 billion in Ethiopia, \$1·38 billion in Ghana, and \$308 million in Rwanda. Expressed as a proportion of GDP, these losses are 1·04% in Ethiopia, 0·80% in Ghana, and 1·05% in Rwanda.

The combined output losses due to air pollution-related morbidity and mortality in these three countries are substantial: \$3·02 billion (1·16% of GDP) in Ethiopia, \$1·63 billion (0·95% of GDP) in Ghana, and \$349 million (1·19% of GDP) in Rwanda.

Our systematic survey of 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 1169 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. Finally, we identified 22 studies that quantitatively examined relationships between air pollution and IQ loss in children. None of the studies were done in African children.

The most appropriate study was one by Wang and colleagues,[31] examining IQ loss among 1360 children enrolled in a longitudinal cohort in Southern California. These children were exposed to concentrations of $PM_{2\cdot5}$ pollution ranging from 2·14 μg/m³ to 25·36 μg/m³. We selected this study because of its robust design, large sample size, the wide range of $PM_{2\cdot5}$ concentrations examined, the careful attention paid to covariates, and the form in which the effect estimate was expressed. Wang and colleagues found that each quartile increase in mean annual $PM_{2\cdot5}$ concentration in the year preceding IQ assessment was associated with a decrease in performance IQ (PIQ) of 3·08 points (95% CI –6·04 to –0·12). Associations of $PM_{2\cdot5}$ pollution with full-scale IQ and verbal IQ, although also negative, were not statistically significant (–2·00, –4·84 to 0·24 for full-scale IQ and –1·42, –4·48 to 1·64 for verbal IQ).[31] From these data, we calculated that the slope of the relationship between $PM_{2\cdot5}$ concentrations and PIQ loss in this range is –0·61 PIQ points per 1 μg/m³ increase in $PM_{2\cdot5}$. Details are presented in the appendix (pp 13–17).

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 μg/m³ increase in exposure applied only to $PM_{2\cdot5}$ concentrations of 25·36 μg/m³ or less, the upper bound of the $PM_{2\cdot5}$ pollution concentrations evaluated by Wang and colleagues. In this analysis, we assumed that the slope of the relationship was zero at concentrations greater than 25·36 μg/m³ and that no further loss of PIQ points occurred above this concentration.

In our second and third estimates, we assumed that PIQ loss does occur at $PM_{2\cdot5}$ concentrations above 25·36 μg/m³, but that the relationship is weaker than at lower levels. Thus, we assumed a slope of –0·30 points per 1 μg/m³ increase in $PM_{2\cdot5}$ concentration above 25·36 μg/m³ up to 50 μg/m³ in the second analysis, and a slope of –0·10 points per 1 μg/m³ increase above 25·36 μg/m³ up to 50 μg/m³ in the third 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). Air pollution was responsible for an estimated loss of 180·5 million PIQ points in Ethiopia, 43·7 million PIQ points in Ghana, and 18·5 million PIQ points in Rwanda. Our second and third analyses of PIQ loss estimated substantially greater losses (table 4).

	All air pollution	Ambient $PM_{2\cdot5}$ pollution	Household air pollution
Lost economic output in 2019 international dollars, millions			
Ethiopia	318 (228–426)	29 (15–52)	289 (200–397)
Ghana	249 (183–325)	121 (71–175)	128 (78–190)
Rwanda	41 (30–53)	7 (3–14)	33 (23–46)
Lost economic output as a proportion of GDP, %			
Ethiopia	0·123% (0·088–0·164)	0·011% (0·006–0·020)	0·111% (0·077–0·153)
Ghana	0·145% (0·106–0·189)	0·070% (0·041–0·102)	0·075% (0·046–0·111)
Rwanda	0·142% (0·104–0·184)	0·027% (0·012–0·049)	0·116% (0·078–0·159)

95% CIs are shown in parentheses. These calculations are based on equations shown in the appendix (pp 1–5), assuming that labour income as a share of GDP by country is 0·44 for Ethiopia, 0·48 for Ghana, and 0·74 for Rwanda. All figures reflect labour force participation rates from the International Labour Organization and assume that non-market output equals 35% of each country's GDP. GDP=gross domestic product. PM=particulate matter.

Table 2: **Lost economic output due to years lost due to disability attributable to air pollution in Ethiopia, Ghana, and Rwanda in 2019**

	All air pollution	Ambient $PM_{2\cdot5}$ pollution	Household air pollution
Lost economic output in 2019 international dollars, millions			
Ethiopia	2705 (2023–3561)	286 (119–548)	2414 (1729–3247)
Ghana	1379 (941–1959)	720 (414–1123)	651 (345–1045)
Rwanda	308 (212–429)	57 (23–111)	250 (157–366)
Lost economic output as a proportion of GDP, %			
Ethiopia	1·041% (0·778–1·370)	0·110% (0·046–0·211)	0·929% (0·665–1·249)
Ghana	0·802% (0·547–1·140)	0·419% (0·241–0·653)	0·379% (0·201–0·608)
Rwanda	1·051% (0·722–1·463)	0·194% (0·080–0·378)	0·853% (0·538–1·249)

95% CIs are shown in parentheses. These calculations are based on equations shown in the appendix (pp 1–5), assuming that the discount rate is 1·5 percentage points higher than the rate of growth in output per worker. PM=particulate matter. GDP=gross domestic product.

Table 3: **Lost economic output due to air-pollution-related deaths in Ethiopia, Ghana, and Rwanda in 2019**

Discussion

The main finding of this analysis is that air pollution in Africa 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, accounting for 16·3% of all deaths.[7] Air pollution is now the second largest cause of death in Africa, exceeded only by AIDS.[7]

A second key finding is that ambient air pollution and its associated diseases are beginning to increase across Africa, whereas household air pollution and its diseases are in decline.[10] Household air pollution still accounts for 60% of all air pollution-related deaths across Africa, and polluting fuels such as charcoal and kerosene are still prevalent.[7] However, thanks to sustained interventions by governments, non-governmental organisations, and UN organisations, disease and death from household air pollution are 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 the countries have begun for the first time to see increases in ambient air pollution and in ambient air pollution-related mortality.[7] This upward trend is most evident in Ghana, the most economically advanced of the countries, and is beginning to be seen in Ethiopia and Rwanda.[7]

Experience from other countries suggests that the increases in ambient air pollution appearing in Africa today could be the leading edge of a looming problem. In the absence of visionary leadership and intentional intervention, ambient air pollution could become a much larger cause of disease and premature death than at present and could pose a major threat to economic development.[11–16,29]

	Annual mean $PM_{2.5}$, µg/m³	Child population (age <10 years)	PIQ loss, points		
			Low estimate	Moderate estimate	High estimate
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	NC	NC	1 959 085 783	3 562 469 927	2 493 037 256

The low estimate of PIQ loss was calculated as a loss of 0·61 points per 1·00 µg/m³ increase in $PM_{2.5}$ from 16·09 µg/m³ to 25·36 µg/m³ and no further loss at higher concentrations. The moderate estimate of PIQ loss was calculated as a loss of 0·61 points per 1·00 µg/m³ increase in $PM_{2.5}$ from 16·09 µg/m³ to 25·36 µg/m³ and a loss of 0·10 points per 1·00 µg/m³ increase in $PM_{2.5}$ from >25·36 µg/m³ to 50·00 µg/m³. The high estimate of PIQ loss was calculated as a loss of 0·61 points per 1·00 µg/m³ increase in $PM_{2.5}$ from 16·09 µg/m³ to 25·36 µg/m³ and a loss of 0·30 points per 1·00 µg/m³ increase in $PM_{2.5}$ from >25·36 µg/m³ to 50·00 µg/m³. NC=not calculated. PM=particulate matter. PIQ=performance intelligence quotient.

Table 4: **PIQ losses in children in Ethiopia, Ghana, Rwanda, and overall in Africa, in 2019**

Our analysis shows that air pollution already has large negative impacts on the economies of African countries and suggests that, in the absence of deliberate intervention, these impacts could become still greater in the near-term. These impacts include 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.[32]

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.[30–33,36] 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 PIQ points. PIQ primarily reflects fluid cognitive abilities—ie, the ability to reason and solve novel problems (in contrast to verbal IQ, which reflects so-called crystallised or acquired abilities).

On the positive side, African countries are well positioned to avoid ambient air pollution. 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 leapfrog heavy reliance on oil and natural gas. With wise choices, African countries can develop sustainably and achieve prosperity, while avoiding the ambient air pollution and related disease and death that have plagued development in countries that relied on coal, oil, and gas to power their economic growth.[29,37–41]

***Panel 3:* Recommendations**

We offer the following recommendations for prevention and control of air pollution in Africa. Further details are provided in the appendix (pp 18–19).

- Transition to clean, renewable sources of energy
- Make air pollution prevention and control a top priority in all countries
- Allocate sustainable, long-term funding for air pollution control
- Reduce household air pollution
- Conduct source apportionment studies to identify and quantify the most important sources of air pollution
- Track patterns and trends in air pollution by establishing robust monitoring systems
- Advance air pollution control through public education campaigns
- Champion air pollution control through the establishment of multi-sectoral partnerships
- Promote research and build research capacity on air pollution, human health, and the economy in African research institutions

Our study has several limitations. Our estimates of the burden of disease and death due to air pollution in Africa are conservative and underestimate the full impacts of air pollution because they are based solely on air pollution–disease pairs deemed by the GBD investigators to be definite or probable.[9] New studies are likely to reveal additional links between air pollution and disease, thus increasing future estimates of the disease burden attributable to air pollution.

The study is also limited by gaps in the air pollution data. We considered only two components of ambient air pollution, 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 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 ambient air pollution levels is therefore based on satellite monitoring.

Our economic estimates undercount the total costs of air pollution because they are based on the aforementioned underestimating 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 to be low. $PM_{2.5}$ pollution concentrations greater than 25 μg/m³ almost certainly have greater negative impacts on children's IQ than lower concentrations. However, because we had no information on the association between $PM_{2.5}$ air pollution and IQ loss at concentrations higher than 25 μg/m³, we assumed in our main analysis that higher levels have no additional impact. A potential further source of underestimation of IQ loss is the synergy between air pollution and social deprivation.[32] In heavily polluted countries with low social development indices, such interactions could substantially magnify the impact of air pollution on IQ loss. Finally, we did not estimate the economic losses that are likely to result from IQ loss in African children, which could be substantial.[29] Overall, our portrayal of the epidemiological and environmental risk transitions in Africa is incomplete and cannot possibly cover the continent's extraordinary diversity.

In conclusion, courageous and visionary leaders who recognise the growing danger of ambient air pollution, 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 (panel 3). Pollution prevention strategies that hold great promise are a 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.

Contributors
SF was responsible for data analysis related to the burden of disease, and contributed to data interpretation, literature review, generation of figures. SF also verified the integrity of the underlying data and had a lead role in the writing of the report. DCB was responsible for the study design and all calculations related to IQ exposure–response function. MLC was responsible for all calculations related to the economic and human capital impacts of air pollution in Africa. DCB, MLC, PK, AB, JBK, and PJL contributed to data interpretation and writing of the report. YP was responsible for calculations related to the economic and human capital impacts of air pollution in Africa and contributed to data interpretation. GT contributed to the literature review and collecting background information, generation of figures, and writing of the report. PJL verified the integrity of the underlying data.

Declaration of interests
We declare no competing interests.

Data sharing
Data supporting the findings of this study are available within the Article and appendix.

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