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Supplementary appendix

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Supplementary Materials: Progress on Pollution

The 2017 Lancet Commission on Pollution and Health generated more than 1500 articles about the health effects of pollution in the popular press and was referenced extensively in the scientific literature.[1] We examine the extent to which this increased popular and scientific awareness of pollution and its health effects has translated into progress against pollution over the past four years.

We find that in some countries, such as China, growing scientific awareness of pollution's dangers has generated substantial growth in national expenditures for pollution control and led to significant progress in prevention of pollution-related disease. Overall, this review shows mixed rather than robust advances.

Progress on ambient air pollution

Ambient air pollution has multiple sources. These include point sources such as power plants and industrial complexes, as well as more diffuse sources including traffic-related air pollution, agricultural and other open-burning practices, and dust, both natural and anthropogenic; natural dust, mainly crustal dust, has been reported to contribute up to one-third of the $PM_{2.5}$ load in some cities.[2,3] Household sources, the primary cause of Household Air Pollution (HAP) also contribute to ambient air pollution.

The world's highest ambient $PM_{2.5}$ levels – on a population-weighted average – are seen in India, closely followed by Nepal. Other areas of great concern are Bangladesh and Pakistan, which both also have very high $PM_{2.5}$ pollution levels. China, which until the last decade also had very high levels of ambient air pollution has recently made significant progress.[4]

India. Air pollution was responsible for 1·67 million deaths in India in 2019 - 17·8 percent of all deaths in the country, the largest number of air-pollution-related deaths of any country in the world.[5] The majority of these deaths – 0·98 million - were caused by ambient $PM_{2.5}$ pollution. Another 0·61 million were due to household air pollution.

Air pollution is most severe in the Indo-Gangetic Plain (northern India), where topography and meteorology concentrate pollution from energy, mobility, industry, agriculture, and other activities. It is home to hundreds of millions of people. This area also contains New Delhi and many of the most polluted cities.[5] Burning of biomass in households was the single largest cause of air pollution deaths in India, followed by coal combustion and crop burning. Population-weighted mean exposure to ambient air pollution peaked nationally in India at 95mg/m3 in 2014, was reduced to 82mg/m3 by 2017, but more recently has been rising slowly again.[5]

India has developed a range of instruments for tackling air pollution, including a National Clean Air Program, and in 2019 launched a Commission for Air Quality Management in the National Capital Region.[6] State Pollution Control Boards have regulatory powers to impose and enforce emissions standards on pollution sources. However, India does not have a strong centralized administrative system to drive its air pollution control efforts and consequently improvements in overall air quality have been limited and uneven.[7] Public interest litigation and actions by the Supreme Court have been instrumental in pushing action on critical pollution issues. A number of cities in India are making progress, particularly in establishing air quality monitoring systems and local level planning.[8] In recent years, these cities have seen some substantial improvements in air quality, but across more than 90 percent of the country ambient air pollution levels remain well above the WHO guideline for $PM_{2.5}$ pollution of 10 µg/m3.[9]

China. China has had air pollution control measures in place since the 1970s, and Beijing City has been controlling individual large point sources of pollution such as power plants since that time, but progress against pollution was initially slow. However, beginning approximately a decade ago, Beijing and Shanghai, inspired by planning for the 2008 Olympics and the 2010 World Expo, took the lead in addressing air pollution.

In 2013, severe episodes of pollution in major cities caused wide public concern, and the Chinese government responded by launching a "battle for blue skies". A key breakthrough was the recognition that about one-third of the pollution in major cities was from regional sources outside the cities' jurisdiction. Accordingly, a cross-jurisdictional Regional Coordination Group was established in 2013 and then in 2018, the State Council, at the central level, elevated the administrative status of the group to include national ministries. At the same time, the central government established and implemented a Five-Year National Air Quality Action Plan (2013-2018). Funding for this plan totaled about RMB1.65 trillion (US$244 billion in 2017 dollars). Under this plan, effective interventions against pollution were undertaken in the major urban airsheds of Beijing-Tianjin-Hebei, the Pearl River Delta, and the Yangtze River Delta. This was followed by a Three-Year Plan (2018-2020), which continues to be updated, with increasing focus on those cities and regions that have not made sufficient progress. The health benefits of this investment are estimated to have been 1.5 times the cost.[10]

Due to these extensive efforts, ambient $PM_{2.5}$ pollution and household air pollution from the burning of solid fuels have decreased markedly in China.[11] The Beijing region has made noteworthy progress since the inception of the National Air Quality Action Plans, and average mean $PM_{2.5}$ levels have dropped by nearly 40 percent as against a Plan target of 25 percent.[12] While these are remarkable improvements, $PM_{2.5}$ concentrations in Beijing are still above both Chinese standards and WHO guidelines. Across the country, mean population-weighted $PM_{2.5}$ exposures were reduced to about 48ug/m^3 in 2019, down from a peak of 63ug/m^3 in 2013.[4] Despite these gains, 81 percent of China's population still lives in regions where air pollution levels exceed the WHO Interim Target 1.[13] The least-cost actions against air pollution have now mainly been taken in China. Further progress will require more finance and more innovative approaches.

Mexico. Mexico City grew very rapidly in the 1980s and 1990s, with sharp increases in population, industrialization, and motorization. This growth resulted in hazardous levels of air pollution, with daily particulate levels (measured as PM_{10}) peaking at about 300mg/m^3 on occasions. In 1990, facing a public health crisis, the Federal Government set up a cross-sectoral Working Group which developed an Integrated Program against Atmospheric Pollution 1990-94 for the wider metropolitan area, comprising Mexico City and 17 adjacent municipalities.

Mobile sources – cars, trucks, and buses - are the main contributors to air pollution in the Mexico City metropolitan area, with emissions inventories showing that over 50 percent of the primary $PM_{2.5}$ emissions consistently come from these sources.[14] Key interventions under a series of programs have therefore concentrated on addressing transportation through actions such as imposing fuel quality standards for vehicles and for other industrial engines; control technologies for vehicles; and testing requirements for cars. More recent actions have included stricter fuel and emissions standards and upgrading the informal microbus systems including the construction of a large-scale Bus Rapid Transit

(BRT) network. Controls have also been placed on industrial emissions and efforts are focusing more on cooking with fuelwood and on agricultural burning.

These coordinated efforts across the metropolitan area, including a significant public information and involvement component, have reduced particulate pollution levels from 1990s levels, especially in terms of daily peak episodes. Mexico has continued to strengthen its air quality monitoring and has recently established regulations to help address the health impacts of air pollution by standardizing air quality monitoring systems and communication of results to the public. These regulations also provide support to government agencies at various levels to compile and analyze air quality and health data and to publish results.[15] Expanded financial assistance is being prepared to support agencies in implementing these norms.

Progress in African Cities

Africa now contains three of the world's megacities, with populations estimated at over ten million, in Cairo, Egypt; Kinshasa, DR Congo; and Lagos, Nigeria. Lagos, a coastal city of 24 million people, exemplifies how air pollution is undermining the growth and health of Africa's megacities. Road transport is the main source of ambient air pollution in Lagos. Most vehicles are over 15 years old, using outdated emission control technologies and burning fuel with high sulfur levels - 200 times higher than U.S. standards for diesel. Industrial emissions from cement, chemicals, furniture, and steel industries are the second leading source of air pollution in Lagos. Generators supply half of Lagos' total energy demand and are the third source of air pollution. The incomplete combustion of gasoline and oil used to operate generators results in heavy air pollution. Artisanal refineries in the oil-rich Niger Delta also contribute to episodic air pollution in local areas.[16] Lagos has recorded $PM_{2.5}$ levels as high as 68 $\mu g/m^3$, concentrations far above the WHO air quality guideline of 10 $\mu g/m^3$, and in the same range as those recorded other polluted megacities in Africa such as Cairo (76 $\mu g/m^3$). Illness and premature deaths due to ambient air pollution were responsible for economic losses of $2.1 billion in 2018 in Lagos State, representing about 2.1 percent of the state's GDP.[17] Artisanal refineries in the oil-rich Niger Delta contribute to episodic air pollution in those areas of Nigeria.[16]

The rapid annual growth of the largest African cities continues, but is slowing, and now the fastest urban growth is taking place not in megacities but in large "secondary cities."[18] These growing urban areas are affected by a wide variety of air pollution sources: biomass burning for domestic and commercial uses; traffic (old vehicles using dirty fuel); agricultural burning and wildfires; waste burning; and small-scale industry.

Reliable data on air quality across Africa, however, is limited. In the WHO urban air quality database, 41 cities in twelve Sub-Saharan countries reported their data.[19] Currently only 7 of 54 African countries have reliable real time air quality monitoring, although steadily improving satellite imaging and analysis is helping to fill the voids.[20,21] South Africa and Senegal have established continuous air quality monitoring systems and other countries, including Ghana and Nigeria, have carried out monitoring programs at intervals, though funding for maintenance and quality control is sporadic.

More detailed epidemiological and technical studies and analysis are needed in African cities to assess and quantify the health impacts of air pollution. While innovative approaches such as examining historical records of visibility at airports near urban areas (Addis Ababa, Nairobi and Kampala) have demonstrated declines in air quality over recent decades, more consistent data are needed to support interventions.[20,21] A practical and effective approach in a city might comprise an integrated network made up of a reference grade ground monitoring station that can improve the accuracy of satellite measurements and linked to lower-cost air monitors to detect hotpots and identify temporal variations.[22] Kampala and Nairobi are examples of cities that are moving in this direction.

Despite challenges such as traffic congestion, some African cities are working to reduce ambient air pollution. Several African countries are working to upgrade transport fuel quality where dirty diesel is still predominant. West African countries have recently pledged to introduce cleaner fuels and vehicle standards across the region.[23, 24] Some counties have made considerable progress, although implementation of clean fuel regulations has been patchy, with Nigeria, the biggest country in the region, not yet fully controlling high sulfur fuel imports.[25] There is also growing attention to the problem of used vehicle exports from Europe, the USA, and Japan to countries with few or no regulatory controls on CO^2 and $PM_{2.5}$ emissions. While some countries, such as Morocco, Tunisia, and Côte d'Ivoire have strong regulatory controls and prohibit import of vehicles older than 5 years, many others, particularly in Western and sub-Saharan Africa, have little or no controls on vehicle emissions or age, resulting in higher levels of climate-driving emissions as well as road safety issues.[26]

Another positive sign for air quality in Africa is the consistent decline in levels of nitrogen dioxide (NO_2), a harmful[27] air pollutant, across the northern region of Sub-Saharan Africa. This decline is a marker for reduced agricultural burning. Satellite observations show that NO_2 concentrations during the biomass burning season in the northern fire region declined by 4·5 percent between 2005 and 2017, potentially benefitting hundreds of millions of people.[28]

Other Metropolitan Areas. Progress against air pollution has been variable in cities and countries across the world depending on a range of local geographical, political, and financial factors. In South America, some cities such as Santiago de Chile and Bogota, Colombia have made major improvements in air quality. In Santiago, the Chilean government has acknowledged the severity of the air pollution problem and is collecting real-time information, monitoring air pollution levels, and implementing interventions.

In Asia, Bangkok has been able to reduce notoriously poor air quality through a range of interventions, driven by high-level political commitment.[29] Progress against air pollution in many low-income and middle-income countries, including many highly populated secondary cities in China and India, has been mixed and is limited by low levels of human and financial resources.

Lessons Learned

A World Bank summary report reviewing ambient air pollution control efforts in major cities around the world reached a simple and clear conclusion about measures to address air pollution:

"There is no silver bullet, and air pollution will only be tackled through sustained political commitment. Information, incentives and institutions are the three prongs of an effective air pollution management strategy for any country."[14]

Monitoring of air pollution levels is fundamental to pollution control. Adequate and reliable air quality data are essential for effective decision making and for tracking progress resulting from interventions. In Europe and North America, nearly all urban areas have some reference grade ambient air quality monitoring stations and larger cities have a dozen or more. This represents about one monitor per 100-600,000 residents. By contrast, across Sub-Saharan Africa, there is just one ground-level monitor per

15.9 million people.[30,31] This low coverage is inadequate for calibration of air quality data based on remote sensing approaches and for the support of local initiatives to control pollution.

Effective interventions need to be developed in the context of a broad air quality planning process which involves all the relevant local jurisdictions and all the sectors within and beyond government that are in a position to influence outcomes. Basic information needs to be developed through source apportionment studies and information of pollution sources needs to be complemented by computer modelling that includes local conditions of meteorology and geography. Urban air pollution sources do not respect administrative boundaries, especially considering rural and agricultural air pollution sources, such as crop burning. An "airshed" approach is essential.[32]

Household Air Pollution (HAP)

The combustion of biomass fuels for household cooking and heating exposes more than 40 percent of the world's population to household air pollution.[33] Efforts in recent decades to reduce household air pollution by upgrading crude cooking stoves have resulted in more people having access to cleaner fuels, and the proportion of the global population with access to clean fuels and technologies inched up from 56 to 63 percent between 2010 and 2018. However, because of population increases these gains have produced only small net reductions in the numbers of people exposed to high levels of household pollution.[34] The number of people without access to clean fuels thus remains at about 3 billion.[33]

China. China has shown significant progress against household air pollution, with total deaths dropping from about 790,000 in 1990 to 271,000 in 2017 – a fall of two-thirds.[35] Much of this improvement appears to be due to reduced household solid fuel use resulting from rapid urbanization and rising incomes.[36] Rural areas have also undergone residential energy transitions, reducing both residential emissions and overall air pollution.[37]

India. Risk management for air quality in India has been challenging because of the ubiquity and magnitude of exposures attributable to ambient and household sources, that often straddle rural-urban boundaries.[38] To address this complexity, India has rolled out one of the world's most ambitious upscaling of clean cooking fuels through the Pradhan Mantri Ujjwala Yojana (PMUY) program, that over the past 5 years has provided nearly 80 million households access to liquefied petroleum gas (LPG).[39] Increased access and use of LPG is expected to accelerate the reduction of health burden attributable to household air pollution. Multiple recent studies report large contributions (ranging from 22-52 percent) from solid cooking fuel use to ambient $PM_{2.5}$.[40] The PMUY thus affords an unprecedented opportunity to achieve co-benefits for both ambient and household air pollution. As drivers of sustained LPG use are recognized and addressed, an ongoing rural exposure surveillance mechanism (similar to what is available for ambient air quality in cities) could allow the PMUY program to become a major catalyst for air quality actions in the country, while also creating seamless, clean breathing spaces for rural and urban populations.

Africa. Use of biomass for household fuel is a major issue across much of Africa, especially in rural areas where it accounts for about 90 percent of roundwood production, of which 16 percent is converted to charcoal. The African Union encourages the preparation of national strategies to address both household air pollution and deforestation, urging member states to focus on improved biomass production and consumption and on substitution of biomass energy by LPG and electricity.[41] Across Africa, however, and especially in rural areas, progress has been minimal. In Ethiopia, for example, with a population of over 100 million people, only 5 percent have access to clean fuel, despite increasing efforts by the government to enhance access.[42]

The main reasons for the limited success in reducing household air pollution include the costs of the new systems, inability to make or afford repairs to the new systems, lack of reliable access to cleaner fuels, and the continued use of "fuel stacking" where households will use more than one type of fuel or cooking technology, both to provide choice and as insurance against problems with any one system.[43] There is increasing understanding of the importance of community and sub-national factors as opposed to household characteristics as determinants of fuel-switching. A decade-long study of fuel-switching concluded that household characteristics such as size, wealth and education were strongly associated with fuel-switching in India, but community level factors were more relevant in eight other countries examined.[44]

A new approach aimed at accelerating progress toward access for households to modern cooking energy has been drafted by development partners, led by the Energy Sector Management Assistance Program (ESMAP) at the World Bank. This effort is under a Clean Cooking Fund launched in 2019 with initial support from several European governments and a funding target of $500 million with an ambition to leverage this to achieve $2 billion in investments in a transformed clean cooking market. The first investment under the Clean Cooking Fund is a $10 million contribution to a clean cooking project in Rwanda.

The Modern Energy Cooking Services (MECS) program is a five-year initiative (funded by the UK) which considers both technical and behavioral aspects. The MECS program estimates that to achieve universal access to improved cooking by 2030 (although not yet at the level of full access for everybody) would cost approximately $100 billion over the next decade.[45] For Sub-Saharan African, where much of the expenditure would be needed, it is estimated that governments would have to provide about 60 percent and households the balance.

Progress on Air Pollution and Climate Change

Climate change and air pollution are closely related, and it is now very clear that action should be taken to deal with both of these problems synergistically and that such action has high potential to produce co-benefits.[46] Practical interventions identified as addressing both problems and producing the greatest co-benefits include phasing out of fossil fuels for power production, wide-scale transition to clean renewable energy, increasing use of active transport – walking and cycling, increased use of electric vehicles, and increased use of public rather than private transportation.[29] There are also synergies between air pollution and climate change mitigation in food systems. Agricultural emissions such as methane (from animal agriculture among other sources) contribute to both warming and to health-damaging ozone formation. Other energy-intensive practices, such as the use of synthetic fertilizers, contribute to health secondary particulate matter formation when agricultural ammonia (crop burning and animal agriculture as well as fertilizer) combines with emissions from fossil fuel combustion. Agricultural emissions are a leading contributor to secondary particulate matter in the U.S., Europe, and parts of Asia.[47]

Major impediments to a transition from coal to cleaner, less polluting sources of energy are the wide availability of millions of tons of relatively cheap coal and the continuing promotion of coal burning for industrial use and power generation in low-income and middle-income by China and other coal-exporting countries.

There is potential to accelerate progress on air pollution and climate change through integrating the health co-benefits of decarbonisation into the Nationally Determined Contributions to GHG mitigation under the Paris Climate Agreement. At present, however, only a minority of countries quantify the health co-benefits of their GHG mitigation plans.[48] Actions to reduce short lived climate pollutants through fourteen measures to tackle methane and black carbon emissions can yield major benefits to health, averting 0·7 to 4·7 million annual premature deaths from ambient air pollution in 2030 and beyond and increasing annual crop yields by 30 to 135 million metric tons from ozone reductions.[49]

The contribution of renewable sources to global energy production continues to grow. Currently, wind/solar, hydropower, and nuclear together account about one third of global electricity production. The installed capacity of wind and solar combined has more than quadrupled since 2010, and is estimated to double again by 2025, at which point it will exceed global hydropower capacity. Nuclear energy's share of the global energy mix continues to slowly decline.[50]

The costs of producing electricity from wind and solar power have dropped dramatically in the past decade, and average costs of new solar photo-voltaic (PV) and wind power plants are now significantly lower than the costs of new fossil fuel plants on a long term averaged cost basis (using Levelised Cost of Electricity (LCOE)).[51,52] A basic obstacle to accelerating the switch to renewables is the long lifespan of existing coal fired plants. A large power plant can have an economic lifespan of 30-40 years if well maintained and operated, depending on fuel costs and other factors, and hundreds of millions of dollars are tied up in these plants. The longevity of new power plants emphasizes how important it is to make the best decisions now, for both climate mitigation and air quality.

Governmental investments in electric vehicles may be expected to pay for themselves many times over through reducing pollution-related disease and thus reducing health care costs and increasing economic productivity. However, enthusiasm for large-scale transition to renewables and to electric vehicles must be tempered by recognition of the potential environmental and social impacts of large wind, solar and hydro developments. Solar plants have large land areas requirements; major wind farms can impact land and coastal environments; batteries require extensive extraction of lead and rare earths; and hydropower plants have a long history of environmental and social challenges.[53−55] As for all major energy projects, careful analysis, consultation and assessment are required for good decision making.

Progress on Water, Sanitation and Hygiene (WASH)

Safe drinking water is fundamental to life and health. However, despite continued efforts over many decades and continuing improvements, inadequate Water, Sanitation and Hygiene (WASH) remains a major global risk factor for disease and premature death and has serious health and socio-economic consequences, particularly for women and girls especially in low-income and middle-income countries.[56] The importance of water and sanitation for development was recognized in the Millennium Development Goals (MDGs) and has subsequently been highlighted by the inclusion a specific Goal on WASH in the Sustainable Development Goals SDGs (SDG 6: Ensure Availability and Sustainable Management of Water and Sanitation for All).

Considerable expansion of access to clean water and sanitation services has been achieved in recent decades, but a 2018 review of progress towards the achievement of the targets set under the Sustainable Development Goals concluded that it would be an enormous challenge to close existing gaps in coverage by 2030.[57] A fundamental problem is that rapidly growing populations in low-income and middle-income countries often outstrip efforts to provide clean water and sanitation, with the result that the number of people worldwide lacking adequate access to these services remains high despite valiant efforts. Thus, about 1.8 billion people gained access to at least basic water services between 2000 and 2017, and yet the population using safely managed water services increased only from 61 to 71 percent. Likewise, in the same period, 2·1 billion people gained access to at least basic sanitation services, and yet the population using safely managed sanitation services increased only from 28 to 45 percent.[58] According to UN estimates, 2·2 billion people still lack access to safe drinking water and 4·2 billion lack safely managed sanitation services.[59]

In low-income and middle-income countries where organizational and financial resources are often limited, a range of options have been used to provide safe drinking water and sanitation services and move communities up the water and sanitation ladders. These include small-scale or community-level programs. Numerous bilateral and multilateral donors, NGOs and private organizations are involved in supporting local governments in designing and implementing appropriate local systems. Additionally, some water companies in rich countries encourage their customers to join them in improving WASH in low-income and middle-income countries.

Sustainable funding for water and hygiene must come from national and local resources, although multilateral and bilateral partners have provided considerable investment support and continue to support national and local governments. The World Bank Group provided $30 billion to client countries for clean water and sanitation services over the period 2007-2016.[60] Meeting the basic water and sanitation targets of SDG6 would require capital investment of an estimated $114 billion per year through 2030.[59]

The UN High Level Panel on Water specifically considered increases in investment and finance needed to provide safe drinking water and adequate sanitation worldwide and identified several necessary changes. These include improving governance and therefore creditworthiness; leveraging private capital; more efficient use of resources; and identifying permanent revenue streams for operations and maintenance, which would also improve the attractiveness of new investment.[56,61] The scale of the challenge calls for a new approach and a clear focus to achieve the ambitious 2030 targets established under the Sustainable development Gals. The UN High Level Panel on Water specifically calls for action to catalyze change, build partnerships and increase international cooperation as the core of a comprehensive agenda to achieve the sustainable development objectives.[56]

Assessments of the disease burden from water pollution in the past have focused mainly on diarrheal disease. More recently, estimates of the burden of disease and death attributable to water pollution have been revised upward as better understanding has developed of the wider health impacts of water pollution and the broad effectiveness of interventions. Recent work has, for example, estimated the impacts of inadequate access to clean water on the burden of such diseases as ascariasis, hookworm, schistosomiasis, and trachoma.[62] Chemical pollution of drinking water is an additional large and growing global problem. The health impacts of chemically contaminated drinking water are not quantified and almost certainly undercounted.

The Lancet Commission on WASH and Health, expected to report in 2022, is undertaking a comprehensive analysis of inadequate access to water and sanitation services globally and hygiene together with an updated analysis of the burden of disease attributable to water pollution and inadequate sanitation. The Commission is also examining the evidence on the effectiveness of various interventions to improve WASH related health outcomes. The ultimate benefits of upgraded WASH are clear but it can be a challenge to link specific interventions to local health improvements.[63] It is intended that this Commission will provide an authoritative and consistent presentation of the current health burden and the potential benefits of practical interventions.

Progress on Chemicals and Metals Pollution

The Global Burden of Disease study estimates the burden of disease and premature death attributable to a small number of chemicals for which there is strong or probable evidence of health effects. The chemicals included in the GBD analysis include lead, asbestos and a series of occupational carcinogens. The 2019 Global Chemicals Outlook II likewise identifies a small number of chemicals and groups of chemicals where evidence indicates definite or probable risks of disease and death: arsenic; bisphenol A; cadmium; glyphosate; lead; microplastics; neonicotinoids; organotins; phthalates; PAHs and triclosan.[64] Beyond these few chemicals with well-characterized and quantified risks to health, there are thousands of additional chemicals in circulation worldwide. The burden of disease and death attributable to this large and growing number of manufactured chemicals is not known and almost certainly undercounted.

A key barrier to estimating the burden of disease attributable to chemicals is that for most of the thousands of manufactured chemicals now in commerce there are no reliable data on their safety or toxicity. Information is especially lacking on developmental toxicity, reproductive toxicity, the effects of long-term low-level exposures, and the health risks of chemical mixtures. Despite significant progress in the international arena since the 1990s to establish multilateral agreements regulating chemicals in waste, these advances are not enough. Indeed, a 2020 UNEP assessment of issues of concern related to the health and environmental impacts of chemicals and hazardous wastes concluded that “the global goal of sound chemicals and waste management in ways that lead to minimized adverse effects on human health and the environment has not been achieved by 2020.”[65]

Inadequate chemical safety testing is a fundamental problem and results in large data gaps in knowledge of toxic effects.[66] The EU, the USA and a few other high-income countries are supporting considerable research efforts to fill these data gaps through the development of new approaches to chemical safety testing. These ‘new approach methodologies’ overcome two major hurdles in current testing methodologies: costs and time.[67] However, these new approaches rely on high-throughput screens of non-vertebrate animal models, generate large data sets, are computationally and technologically intensive, and have high front-end costs that will make them difficult to transfer to low-income and middle-income countries. Fortunately, however, knowledge of chemical toxicity produced in high-income countries can be exported to low-income and middle-income countries to support decisions on chemical management.

In Europe, the REACH regulations adopted by the EU in 2006 (Registration, Evaluation, Authorisation and Restriction of Chemicals) have established the goal of reducing the risks posed by chemicals to health and the environment. The approach is innovative in that manufacturers or importers are responsible for demonstrating how a chemical can be safely used and must communicate risk managements measures to users and regulators before a chemical can enter markets. This is a full reversal of the previous regulatory system, which presumed chemicals to be harmless until they were proven hazardous and allowed chemicals to remain on the market until a regulator proved that they posed unacceptable risks. Further regulations have followed from REACH and the aim of a “toxic-free environment” has been adopted by the EU.

Progress in documenting the characteristics of all the main chemicals in commerce is proceeding in the EU, although slowly: only a small fraction of the 100,000 chemical compounds on the European market have been tested fully (although priority has been given to those used in the largest volumes). A shortcoming is that information collected under REACH is not completely disclosed, which can complicate access to information by affected countries and sectors and limit efforts to regulate across diverse regions. To date only 62 substances have been banned under REACH,[68] a number that while modest far exceeds the five chemicals that have been banned since 1976 in the USA under the Toxic Substances Control Act.

The European Commission has proposed a new “Chemicals Strategy for Sustainability” to move forward the EU vision of an industry that is “globally competitive in the production and use of safe and sustainable chemicals.”[69] This strategy promotes a safe and “sustainable-by-design” approach and a stronger framework to addressing pressing environmental and health concerns. It is based on the understanding that as a Union of rich Member States, the EU cannot afford a race to the bottom with the rapidly expanding chemicals industries in lower-cost countries but must instead initiate a race to the top by minimizing pollution and expanding the scope for chemicals to be re-used and recycled as part of a circular economy. Annexes to the new chemical strategy aim to build global capacity by 2024 to: (1) assess and manage chemicals in Low-income and middle-income countries, (2) ensure that industries do not produce for export chemicals banned in the EU, and (3) promote sustainable production, use, and corporate governance of chemicals.[70]

One of the most concerning aspects of chemical pollution is the failure of governments to implement long-standing commitments to basic measures that would reduce health and environmental risks. In 1992, there was a commitment made at the Rio Earth Summit to devise a Globally Harmonized System for the classification and labelling of hazardous substances, notably chemicals, that would be understandable by illiterate non-specialists and thereby provide valuable protection for the most vulnerable in society. The 2002 follow-up UN Summit in Johannesburg pledged that the GHS system should be implemented everywhere by 2008. However, UNEP’s Second Global Chemicals Outlook found that in 2018 no implementation had occurred in 120 countries including all of Africa except Zambia, all of West Asia, all of South Asia and about half of Latin America.[64] Achieving the goal of a global chemical policy should be achievable with a moderate amount of financial support for capacity building.

Other promises on chemical safety that remain off-track and behind schedule include the commitment made under the Stockholm Convention on Persistent Organic Pollutants (POPs) to remove from use by 2025 all equipment containing polychlorinated biphenyls (PCBs). These chemicals, found in electrical transformers and other electrical equipment, are poisonous to people and wildlife. A document prepared for the Conference of the Parties of the Stockholm Convention in 2019 showed that only about 30 percent of Parties had supplied the obligatory reports on their progress in removing PCBs from use.[71]

Of those Parties, about 70 percent expected to eliminate PCBs by the 2025 deadline, although the share fell to 39 percent of responding countries in Africa. It seems likely that those member states that did not fulfil their national reporting obligations or participate in an additional survey are less likely to reach the goal; thus in the worst case scenario where all non-responders fail to meet their goals, only about 40 of the 182 Stockholm Parties might fulfil their 2025 obligation.

Arsenic, hexavalent chromium, and asbestos are likewise amongst the WHO's top 10 chemicals of global public health concern. Long-term arsenic exposure is linked to a wide range of health problems including cancers, cardiovascular, and kidney problems. Early childhood exposure to arsenic can also affect cognitive development.[72] Arsenic exposures, particularly in drinking water from industrial and natural sources, remain problematic in several low- and middle-income countries in south, southeast, and east Asia, most notably Bangladesh, India and China.[73,74] Hotspots in Latin America also exist.[75] Mining is another global source of arsenic pollution.[76,77] Food crops such as rice can be contaminated via groundwater or wastewater and are likewise potential sources of arsenic exposure.[78] Hexavalent chromium, often associated with the tannery industry, is also used as a pigment and elsewhere in industry where it can contaminate groundwater as well as create occupational risks.[79] Hexavalent chromium is genotoxic and a human carcinogen.[80] Asbestos, heavily regulated in high-income countries, is still used widely as a building material in low and middle-income countries, with the most common use as a roofing material (asbestos cement sheets) and water/wastewater plumbing.[81] Asbestos also continues to be mined in several countries including Brazil, China, Kazakhstan, and Russia.[82] Due to its use in the construction industry, laborers are at particular risk for asbestos-related disease including mesothelioma.[83,84] Russia is the world's largest asbestos producer and aggressively markets the mineral to low-income and middle-income countries, sometimes demanding the purchase of Russian asbestos as a precursor to entering into trade negotiations.[85] While asbestos related diseases are peaking in most industrialized countries, they are projected to increase in many LMICs over the next decades.[85] A global ban of asbestos is urgently needed.

More recent chemicals of concern include the perfluorinated compounds - PFOS and PFOA - widely used as water and stain repellents in clothing, household products, food containers, furniture, and carpets, and paints. These compounds are also used extensively in firefighting foams. Sources of human exposure include food, drinking water, dust, and air are all sources of human exposure. Litigation surrounding exposures in to PFOA in West Virginia USA have resulted in large awards.[86] Reviews of toxicity at the low concentrations typical of environmental exposures are in the early stages and indicate likely carcinogenic, immune, metabolic, neurodevelopmental, and reproductive risks.[87]

E-waste recycling is an important and growing source of chemical pollution, particularly in China and Ghana.[88] In 2019, 53·6 million tons of e-waste were generated worldwide, equivalent to 7·3 kg per person.[89] Due to higher consumption rates, shorter life cycles and fewer repair options, by 2030 74·7 million tons of e-waste will be produced worldwide.[89] E-waste is transported in large quantities to LMICs, where it is inadequately recycled, leading to exposures to toxicants including arsenic, cadmium, chromium, dioxin-line compounds, lead, mercury, polychlorinated biphenyls (PCBs) and flame retardants.[90,91] Exposure to these compounds from unsafe e-waste recycling has been associated with severe health impacts, including adverse birth outcomes, altered neurodevelopment, cancer, and respiratory and cardiovascular disease.[89]

Increased demand for electric vehicles has also lead to rising demand for metals used in battery production, notably the rare earth oxides lithium and cobalt.[92] Cobalt is known to have adverse effects on human neurological, cardiovascular, and endocrine systems.[93] The Katanga Copperbelt in DR Congo supplies the world with 60 percent of the global cobalt supply, with 15-20 percent delivered by artisanal miners.[94] Congolese artisanal miners and individuals living in and around mining communities have shown increased cobalt levels in blood and urine.[94]

Progress on Lead Pollution

Recent data from IHME finds that one in three children globally suffer blood lead levels above the US CDC reference level of 5 µg/dl.[95] Although the implications for society and economies of this finding are substantial, attention to lead poisoning in most LMICs, where most lead poisoning occurs, is minimal.

Mexico recently added lead testing to its periodic health survey.[96] Elevated lead exposures have been long been highly prevalent in Mexico. In addition to traditional sources of exposure (mining and occupational), the key source of lead exposure is deeply embedded in Mexican culture: the use of lead-glazed ceramics to cook, store and serve food. The production process and the widespread use of lead in pottery in Mexico suggest that the prevalence of lead poisoning (LP: ≥5 µg/dL) should be high, but until recently there was no accurate estimate. In 2015 the first state-representative survey of blood lead levels in newborn infants was conducted in Morelos State. The prevalence of lead poisoning was found to be 14·7 percent (CI 95%: 11·1, 19·3) and in the most marginalized regions of the State reached 22·2 percent (CI 95%: 14·4, 32·5).[97] These results led the government to scale up the study to a national level through the National Survey of Health and Nutrition (ENSaNut). This is a household survey and represents a key new instrument in the design of health policy in Mexico. In 2018-19, the state-representative health survey ENSaNut included blood lead measurements (BLM) in 1-4-year-old children. The estimated national prevalence of LP was 17·4 percent (CI 95% 14·8, 20·0) representing 1.4 million children, with wide variation among states. While Puebla state, with a long tradition of use of lead-glazed ceramics, recorded a prevalence of 46·6 percent (CI95%: 30·7, 63·3), followed by San Luis Potosí (37·4 percent) and Tlaxcala States (35·6 percent), other states had zero or near-zero prevalence: Sinaloa (0 percent) and Tabasco (0·8 percent). These results were treated as a public health emergency and triggered the implementation of a national comprehensive plan to reduce population lead exposures derived from the use of lead-glazed ceramics. Strategies include lowering the blood-reference level, efforts to reduce and eventually eliminate the use of lead in ceramic production, social awareness strategies, and a hybrid individual and population-level blood-lead biomonitoring surveillance system to encompass susceptible sub-populations and the general population.

China has also made efforts to determine baseline exposures to lead.[98,99] From the late 1990s through 2009, average blood lead levels in urban Chinese children 0-6 years of age decreased from 7-10 µg/dL to 2·5-6 µg/dL. The prevalence of children with higher blood lead levels (>10µg/dL) also decreased substantially, from 30–50 percent to 1·5–15 percent. This decline in blood lead levels appears to have been associated with national efforts to decrease lead pollution, including the phase-out of leaded gasoline, a transition from coal fuel to diesel, natural gas, and clean energy alternatives, and closing or merging heavily polluting enterprises.[100] However, a recent review of 219 published articles found that blood lead levels in Chinese children remain high, with over 8 percent of 629,627 children showing blood lead levels higher than 10 µg/dL.[101] Based on these findings, efforts are underway to modify guidelines for childhood lead poisoning prevention in China.

Most low- and middle-income countries do not have blood lead or environmental lead monitoring systems in place.[102] Targeted, data-driven prevention of childhood lead poisoning is thus not possible except in the most obvious exposure circumstances. The international response to the problem of childhood lead exposure in low-income and middle-income countries has focused mainly on lead in paint.[103]

Progress on Mercury Pollution

Mercury is a highly toxic metal and its toxicity includes neurodevelopmental, neurotoxic, cardiovascular, reproductive and immunological effects.[104–107] Mercury exposure levels vary by population. The highest exposures occur at the source of emission amongst populations who come into regular contact with mercury occupationally, and amongst Arctic, small island, tropical riverine and coastal communities who have a high intake of fish and seafood contaminated with methyl-mercury, which, as a diffuse pollutant, migrates with air and water and bio-magnifies after penetrating the food chain.[108,109] In 2015, artisanal and small-scale gold mining activities (ASGM) were found to be responsible for 38 percent of global anthropogenic mercury emissions, followed by coal combustion (21 percent), non-ferrous metal production (15 percent) and cement production (11 percent).[110,111] ASGM is a main source of mercury release into aquatic systems, followed by disposal of mercury-containing products, domestic wastewater, metal production, and releases from industry.[112,113] New studies under the Minamata Convention are underway to better understand the contributions of oil and gas mining to the incidence of mercury to the environment.

The Minamata Convention calls for international and national action on mercury to protect health and the environment and includes a financing mechanism for the implementation of the Convention.[110] Agreed upon in 2013, it entered into force in 2017 and has been ratified by 130 countries. The Convention includes a non-punitive compliance mechanism that helps countries to fulfil their obligations. The main funding tool is the Global Environment Facility (GEF), especially via its Chemicals and Wastes and “Planet Gold” program. The World Bank supports several projects to control pollution, for example its “Pollution Management and Environmental Health” program. UN Environment Program also hosts the “Global Mercury Partnership”, which aims to protect human health and the global environment from the release of mercury and works closely with stakeholders to assist in the timely ratification and effective implementation of Convention objectives.

The great strengths of the Minamata Convention are its clear agenda, with health as a priority issue (§ 1 and § 16), its globally binding construction, and the inclusion of a sustainable funding mechanism through GEF. However, like other UN treaties, decision-making under the Convention depends on the consensus of their partners, causing delays and curbing ambition and new approaches. Interventions are also typically implemented as time-limited projects rather than as sustainable, comprehensive, long-time interventions.[114] Intervention efforts are also limited by lack of data on sources and long-term biomonitoring, particularly in low- and middle-income countries.[115]

Phasing out mercury demands strong collaborative efforts among scientists, policymakers, and mercury users. To change attitudes and behaviours, knowledge transfer, microfinance, legalisation, and especially, participation of those ASG miners who are at the end of the value chain are needed above all.[116,117] It is vital to recognise that those individuals and corporations who profit most from extractive activities such as mining are in industrialized countries and that they consistently outsource the health and environmental risks of mercury extraction and use to low-income and middle-income countries.

While in recent years, great strides have been made by both scientists and policy makers to reduce mercury emissions and human exposure, intensified collaboration across sectors, exchange of knowledge, training and awareness raising, and participation of the affected parties is needed to improve further urgently needed actions to minimize the persistent health hazards from global mercury pollution.

Progress on Asbestos Pollution

The asbestos minerals – actinolite, amosite, anthophyllite, chrysotile crocidolite, and tremolite – are a group of naturally occurring fibrous silicates. Asbestos can withstand fire, heat, and acid. It has great tensile strength. It provides thermal and acoustic insulation. For these reasons, asbestos came into use in the 19th century, was heavily used through much of the 20th century, mainly in insulation and construction materials, and is still used today. Chrysotile, 'white asbestos', accounts for 95 percent of all asbestos ever used and is the only form in use today.[118]

All forms of asbestos are now recognized to cause asbestosis, a progressive, fibrotic lung disease. All forms of asbestos also cause multiple cancers including malignant mesothelioma, lung cancer, laryngeal cancer, ovarian cancer, and possibly gastrointestinal cancers.[119] Asbestos has been declared a proven human carcinogen by the International Agency for Research on Cancer and by national regulatory bodies in many countries. There is no safe level of exposure.

The health hazards of asbestos were first recognized in the early 20th century with the diagnosis of asbestosis among asbestos-exposed workers. The first reports of cancer in workers exposed to asbestos were published in the UK and the USA in the mid-1930s. A landmark 1964 publication by Irving Selikoff confirmed the association between asbestos and cancer and had major impacts on regulatory policy.[120] In the years following publication of this report, asbestos consumption in the USA fell by more than 99 percent. Similar declines took place over the following two decades in most other high-income countries as well as in many low-income and middle-income countries, and asbestos is now banned in 44 countries, including all EU member states. After lag periods of 10-20 years (reflecting the long latency of asbestos-related cancers), substantial reductions in asbestos-related mortality have resulted in these countries.[121]

Despite wide knowledge of asbestos' dangers, many countries still use, import, and export asbestos, and annual world production remains at about 2 million tons. Russia is by far the leading producer nation, followed by China, Kazakhstan, Brazil, Zimbabwe, and Colombia.[118] China is the largest consumer, followed by India, Russia, Kazakhstan, Thailand, Ukraine, and Uzbekistan. The 2019 Global Burden of Disease study attributes over 230,000 global deaths to asbestos, a number that almost certainly is an undercount of the true burden.[122] In low-income and middle-income countries, where too often there exists little or no protection of workers and communities, asbestos may be expected to cause epidemics of lung cancer, mesothelioma, and other malignancies that will extend over much of this century.[121]

Repeated efforts to control international trade in asbestos under the Rotterdam Convention have failed, because of the Convention's requirement for unanimity among all Parties to the Convention, a legality that has enabled a few asbestos-producing nations to block the desire of more than 100 other countries to end the asbestos trade.[121] Russia aggressively markets asbestos to low-income and middle-income countries, sometimes demanding the purchase of Russian asbestos as a precursor to entering into trade negotiations.

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Supplementary materials: Summary of HPAP Process and Outcomes to date

The aims of the Health and Pollution Action Plan process are to:

1) Identify and evaluate the health impacts of pollution within a country;
2) Prioritize pollution issues based on the magnitude of their health impacts;
3) Identify and implement interventions to reduce exposures to the sources of pollution and related health effects.

HPAP process

After initial discussions and responding to a formal request from the relevant ministry (often the ministry of health), an official working group is established in collaboration with key ministries and local agencies, including academics and knowledgeable NGOs.

The HPAP is led by a government agency and is structured to bring together agencies and parties who usually do not interact. HPAPs provide an opportunity for different stakeholders to share and review national reports, policies, journal articles and other relevant information on health and pollution. The objective of the process is to achieve a consensus through consultation, building on existing interventions, and identifying potential areas of collaboration. The initial HPAP process is completed at a final validation workshop where it is approved by the relevant agencies and other critical stakeholders.

The outputs are project proposals which can be commenced with local resources. The final HPAP report and project proposals are also used to generate support for wider action from the national government and external partners.

The following table provides a summary of HPAPs completed or nearing completion, based on information from the Global Alliance on Health and Pollution (GAHP). The progress, scope and outcomes of the HPAP in each country differ according to local conditions, enthusiasm of key parties and availability of resources.

Country (donor)	**Priority Issues identified**	**Concept Notes/Project Proposals developed**
Colombia (co-led by UNIDO and Pure Earth, funded by the EU and USAID) Completed Dec 2018	Ambient urban air pollution ($PM_{2.5}$) National capacities to address endocrine disruptors Pesticide contamination of food Sites contaminated by chemicals	Developing the country's roadmap for the reduction of $PM_{2.5}$ emissions and building technical capacities for monitoring and follow-up. Elaboration of a strategy for the prevention/mitigation of health risks associated with Endocrine Disruptors among vulnerable populations in Colombia

		Strengthening of the country's institutional coordination for the inspection, monitoring and control of pesticide residues in food National Contaminated Sites Identification and Screening Program (aims to establish the first database in Colombia)
Ghana (led by UNIDO, funded by EU and USAID) Completed May 2019	Municipal Waste Management Industrial Pollution Toxic Pollutants of all forms at contaminated sites	Sustainable Waste Management Pilot in Kumasi National Contaminated Site Identification and Assessment Project: updating the existing database and identifying and screening additional sites. The project will also generate a Ghana pollution map and pilot remediation at 2 pilot sites. Resource Efficient Cleaner Production (RECP) in the Chemu catchment area to enhance their operational productivity while at the same time reducing their impacts on the Chemu Lagoon.
Kyrgyzstan Completed May 2019	Air pollution in Bishkek Water pollution in the Issyk-Kul Oblast	Reducing harmful pollutants from transport in Bishkek Upgrading water quality monitoring of Lake IssykKul by improving and modernizing water quality monitoring of Lake Issyk-Kul and its main tributaries
Madagascar	Household air pollution	Pilot-Scale Household Air Pollution Reduction. Aim is to identify and to begin to implement interventions that can measurably reduce HAP

Completed Oct 2018	Ambient urban air pollution ($PM_{2.5}$) Identification and assessment of chemical contamination	Upgrading Transportation Fuel Quality. Roadmap illustrating the costs and benefits of upgrading the quality of fuel imported to Madagascar and the functional steps the government and private sector would take. National Contaminated Site Identification and Screening Program to identify and screen sites across the country where soil and water pollution pose public health risks
Philippines Completed March 2019	Outdoor Air Pollution Wastewater and Sanitation Occupational Exposure Indoor Air Pollution Soil Contamination	Mitigating Pollution from the Transport Sector Continuing to reduce Water Pollution in Manila Bay Reduction of lead exposures from used lead-acid battery recycling activities Improvement of Indoor Air Quality from Household Energy Use
Tanzania (led by UNIDO and funded by EU and USAID) Completed Feb 2019	Water and waste water pollution Indoor air pollution Outdoor air pollution Exposure to chemicals from agriculture	Air Quality Management for Improving Human Health and Environment in Urban Cities and Municipalities Wami-Ruvu Basin Water Quality Improvement Project Reducing exposure to Heavy Metals and other Toxics in Small Scale Mining

	Exposure to heavy metals from mining activities	Reduction of Indoor Air Pollution and its impact on Health of Women and Children in Vulnerable Rural and Urban Communities Sound management of pesticides in agronomy for protection of human health in Tanzania
Thailand Completed May 2019	Ambient air pollution in Northern Thailand Chemical contamination	Pathways to beat air pollution to deliver health benefits in Thailand National Contaminated Site Identification and Screening Program
Kalimantan Province, Indonesia Completed May 2020	Smoke pollution from forest and land/peat fires Mercury pollution in Small Scale Gold Mining (ASGM) Pesticide pollution in agriculture and plantations	Reducing the health impacts of Smoke Pollution from Kalhutra (Forestand Peatland fires) by streamlining the coordination system of the relevant local agencies; collecting data on health impacts and economic losses; and then develop community education and awareness to take action in areas prone to Kalhutra Strategy for the mitigation of health risk associated with mercury pollution among the vulnerable population in Central Kalimantan, including to assist local governments in RAD (Regional Action Plans) for Removing Mercury, which was initiated by DLH together with Artisanal Gold Council. This project will help build the capacity of local governments to collect data and increase awareness of the dangers of mercury for the environment and health in vulnerable areas or populations. Developing Central Kalimantan Province's roadmap for reducing health risks of pesticides pollution by building the technical capacity for the development of program

		intervention and raising awareness of the community and employees of the plantations. The government is expected to gradually increase public awareness to switch to using natural or more environmentally friendly pesticides.
Senegal Completed Sep 2020	Heavy metals pollution (lead and mercury) Pesticides pollution Effects of pollution on Health in Senegal	Decontamination Project for Saint-Louis and Richard-Toll Pesticide Storage Site Study on the prevalence of Asthma in the school environment in Dakar in relation to indoor and outdoor air pollution Project to assess the exposure of women and children to mercury in gold panning areas in the Kédougou region Project to assess stakeholders (operators, recyclers and garages) and practices in the used oil and battery sector, and to raise awareness of good practices.
In Progress Bangladesh Tajikistan Azerbaijan	Priority issues have been identified through the HPAP process in each country but final acceptance and validation by all stakeholders has not yet been formalised	Selection and approval of interventions and projects will be finalised when the HPAP has been validated and reviewed by the Government.

Supplementary materials: Analysis of country framework documents

This supplemental section provides details and references on the text analysis processes.

Latent Dirichlet Allocation Analysis Methods

Latent Dirichlet Allocation is a machine learning algorithm capable of modeling a text document's subject matter. Through repeated sampling and optimization of Dirichlet parameters, it provides a continuous probabilistic distribution of words over a certain number of topics.[1] Simply put, it models the probability that a word appears in each of the topics and the probability that a topic appears in each of the documents. More details specific to the two applications are provided below.

All data and analysis were performed in R and utilized Latent Dirichlet Allocation (LDA).[2] We also used several R packages: "textmineR" for LDA analysis[3], "SnowballC" for word stemming[4], and "pdftools" for reading pdf files[5], as well as "tidyverse"[6] and "dplyr"[7] for data cleaning and visualization.

World Bank Group, UN, and SDG Country Strategy Document Assessment

Collection

We collected 537 World Bank documents (written between 1995-2020), 136 Asian Development Bank (ADB) documents (written between 1995-2020), 23 Inter-American Development Bank (IADB) documents (written between 2015-2019), and 164 African Development Bank (AfDB) (written between 1999 – 2020) to form a "composite" grouping of the World Bank group documents. We added ADB and AfDB country partnership frameworks to the pool of World Bank frameworks if they represented a country that was not already represented for that year in the World Bank documents. We did not include IADB frameworks in this composite because its shorter timeframe might promote over-representation of certain countries in more recent years.

Similarly, we collected 207 UN documents (written between 2000 – 2020) and 112 Sustainable Development Goal (SDG) country voluntary reviews (written between 2016 – 2020). The UN documents were used for primary analysis.

Latent Dirichlet Allocation (LDA)

LDA, performed with every year of country frameworks, can provide the probabilities for whether "pollution," "biodiversity," and "climate" would appear in each framework and amongst all frameworks for each year. This included finding the probability the word would appear for each topic, and each topic's frequency, for each of the country frameworks and in total. We present these probabilities as the estimated "percent of total subject matter dedicated" to that term.

After performing this analysis separately for each year, we regrouped documents into a 2015-2020 pool and repeated this analysis for "water," "toxic,", "radioactive," "pollution," "pesticides," "particulate," "metal," "mercury," "household," "fossil," emission," "chemical," "burn," "ambient" to provide an overview of each word's percent of subject matter from 2015.

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Supplementary material: Methods for media analysis

Methodology - Media Coverage of Pollution

Factiva, a media database owned by Dow Jones, was used for data analysis. Factiva aggregates content from both licensed and free sources from nearly every country worldwide.

Broad search parameters used as follows:

- Date range: 7/15/2010 to 31/12/2020
- Language: English only
- Regions: All

Media sources:

- As opposed to creating a custom media list that involves some subjectivity, we utilized an established Factiva list of top news sources
- This list was modified to remove less relevant types of coverage, including: press releases, recurring pricing and market data, obituaries, sports, calendar postings, personal announcements, letters, weather news, food items and routine traffic reports
- Republished news stories were NOT excluded, in order to account for the impact of stories that run in a wire or influential source and are further reported across additional outlets
- Unless otherwise noted, the searches were conducted within the entire article vs. the headline/lead paragraph only

Detailed Search terms

Coverage of modern disease-causing pollution over the 10-year timeframe

1. The search terms used for this portion are:

(pollution OR pollutant* OR emission OR waste OR toxic* OR exposure). Then, within the same paragraph one of the following: (ambient OR chemical OR air OR soil OR water OR radioactive OR pesticide OR herbicides OR insecticides OR particulate OR coal OR industr* OR burn OR fuel OR factory OR environment* OR ozone OR hydrocarbons OR arsenic OR mercury OR lead OR metal OR electronic OR slash OR mining OR petroleum OR vehicle* or electric* OR agricultur* OR exhaust OR urban OR gas)

Note: When removing the "same paragraph" requirement, meaning an article was counted if a term from the first list and a term from the second list appeared anywhere within the article, the article count rises to ~9.5 million. The proximity requirement helped narrow down relevance.

2. To assess which portion of the coverage contained modern disease-causing pollution as a key focus vs. passing mention, we ran the same search limited to the headline and first paragraph of each article vs. the full article search. This amounted to just under ~1.5 million articles, or nearly 27% of the overall coverage.

To determine the frequency with which modern pollution is linked to disease in coverage, we further limited the core initial search to those mentioning one of the terms as follows: disease* OR death or disability OR health OR kill* OR fatal*

Coverage was also assessed to determine the portion including mention of regulations, legislation, interventions, policy, or reform. This accounted for over 34% of the broader set of coverage on modern disease-causing pollution. The top 5 regions for these stories were: U.S., UK, India, China and Canada (same top 5 list as the broader set of coverage, though in this subset, UK surpassed India)

The core search was also assessed when limited to “developing economies” vs. “all regions” and this accounted for ~28% of the coverage globally

“Developing economies” is defined in Factiva as countries listed as low-income, lower-middle-income, or upper-middle-income economies per the World Bank.

Why do estimates of mortality attributable to air pollution differ?

The Lancet Commission report relies on estimates of mortality and disease burden attributable to past exposure to ambient ozone and $PM_{2.5}$ and $PM_{2.5}$ exposure from household air pollution from the use of solid fuels for cooking from the Global Burden of Disease project (GBD 2019). Over the past decade the GBD results, and the methods used to produce them, have become the global benchmarks for such estimates and analyses, providing a consistent time-series of global and national estimates that begins in 1990 and which is updated annually and which incorporate updated input data and methodology. As the epidemiologic evidence has grown, other estimates of global $PM_{2.5}$-attributable mortality have been published by WHO and by independent research groups. All estimates to-date report global mortality attributable to ambient $PM_{2.5}$ on the order of millions of annual deaths and the importance of $PM_{2.5}$ as a major health risk factor requiring concerted action is now widely accepted by the public and policy makers. However, published estimates of the number of attributable deaths may vary several-fold due to differences in analysis years, analytic methods and assumptions (Evangelopoulos et al. 2020; Burnett and Cohen 2020).

Air pollution mortality and burden estimates include three main inputs: exposure, exposure-response functions describing air pollution relative risks as a function of exposure, and baseline rates of mortality. In addition, burden estimates must specify a counterfactual, a level of exposure at which risk is minimized. Differences between these inputs are responsible for the majority of differences in resulting burden estimates. The Table summarizes these differences for five recent global assessments.

Ground-level air pollution monitoring alone is insufficient to provide comprehensive global $PM_{2.5}$ exposure estimates, especially in LMICs. Therefore, GBD $PM_{2.5}$ exposures are estimated from a combination of satellite retrievals linked to chemical transport models which are then calibrated to available ground measurements. Calibration can include a relatively simple geographically-weighted regression (Brauer et al. 2012) or more complex Bayesian hierarchical models such as DIMAQ, now used by both GBD and WHO (Shaddick G et al. 2018) which also provides uncertainty estimates. DIMAQ estimates are updated annually and new estimates differ from earlier versions in the set of satellite-based estimates, ground monitoring inputs and in the year of estimation. Other analyses have relied solely on chemical transport models such as EMAC and GEOS Chem to provide global $PM_{2.5}$ estimates (Lelieveld et al. 2019; Vohra et al. 2021). These model outputs do not provide uncertainty estimates and are typically not calibrated to $PM_{2.5}$ ground-level measurements but comparisons may be included to document agreement. The inputs to such models are not updated on a regular basis and as a result the mortality estimates that use their output typically reflect levels in a single year. Differences between exposure estimation methods and uncertainties in these estimates have been estimated to be relatively minor contributors to overall uncertainty compared to that from the exposure-response functions (Ostro B et al. 2018). However, in earlier estimation years (e.g. 1990 – 2000) and in locations such as northern Africa that are impacted by windblown mineral dust or regions with sparse ground monitoring, estimates of exposure can exhibit large uncertainty.

The exposure estimates are inputs into non-linear exposure-response functions which relate relative risks to a given level of exposure. The exposure -response function must address two major sources of uncertainty in current knowledge: how large are the relative effects on mortality across the full distribution of global exposures, and which causes of death are affected by air pollution. How these uncertainties are addressed accounts for the majority of reported differences in estimated mortality and disease burden. The GBD estimates are based solely on epidemiologic studies of a limited number of specific causes of death for which there is broad scientific consensus for a causal effect of air pollution (Table). As new causes (e.g. neonatal mortality via the impact of $PM_{2.5}$ on birthweight and gestational age added in GBD 2019) may be included in annual GBD updates the specific causes may also differ between analyses. In order to estimate disease burden globally, including locations with concentrations beyond those included in epidemiologic studies, and to jointly estimate the burden attributable to household air pollution, GBD has used an exposure-response function that combines relative risk information from studies of ambient $PM_{2.5}$, and other sources of $PM_{2.5}$ (household air pollution, secondhand and active smoking) using parametric functions developed to fit the data (Burnett et al. 2014). The use of $PM_{2.5}$ relative risks from non-ambient sources typically produces highly non-linear functions in which the increase in the relative risk is markedly reduced, and may even cease, at high levels of exposure. In more recent iterations of the GBD, and with the publication mortality studies in China and South Asia (Yin P et al. 2017; Yusuf S et al. 2020), the use of non-linear splines with explicit prior constraints has allowed for more flexible risk functions without the inclusion of risk inputs based on active smoking (removed for GBD 2019) or secondhand smoking (removed for GBD 2020) and produce somewhat larger relative risks. GBD's choice of counterfactual level, or TMREL, is designed to reflect current uncertainty about the lowest levels at which $PM_{2.5}$ causes increased mortality. Annual updates also incorporate new epidemiologic studies and methodologic improvements in fitting the risk functions. Notably, within the GBD the same risk relationships are used for both ambient and household air pollution to explicitly avoid double-counting from combined exposures. Recent WHO estimates have used GBD exposure-response functions but have typically lagged the GBD in the included diseases and in the disease-specific risk function that is applied (Evangelopoulos et al. 2020; Table).

As an alternative approach for the estimation of mortality attributable solely to ambient $PM_{2.5}$ Burnett et al (2018) developed the Global Exposure Mortality Model (GEMM). The GEMM is based entirely on studies of ambient $PM_{2.5}$ and also includes studies from China and South Asia, which allows GEMM to estimate relative risks at the highest levels of global ambient $PM_{2.5}$ without incorporating estimates from non-ambient sources. But as a result, the GEMM cannot be applied to simultaneous estimation of household air pollution relative risks and burden of disease. The GEMM is constrained to be non-linear, with smaller increases in the estimated relative risk at higher concentrations as $PM_{2.5}$ levels increase. GEMM estimates are also based on studies of non-accidental mortality and when applied to burden estimation also include a much broader aggregation of diseases than the GBD; typically all NCDs plus LRI. This group of mortality causes includes major global causes of death, such as Alzheimers disease, not currently included in GBD estimates and for which aggregation may not be globally applicable given differences in the relative importance of causes of death between regions (Burnett and Cohen 2020; Hystad, Yusuf and Brauer 2020). With regard to the counterfactual level, published GEMM estimates have assumed that mortality effects continue down to the lowest level reported in published studies, a level that is the minimum of the counterfactual distribution used in GBD. Taken together these differences result in estimates of attributable mortality that are two-fold greater than GBD's (Burnett et al. 2018; Lelieveld et al. 2019; Table)

A recent report by Vohra et al. (2021) reported estimates of global mortality attributable to $PM_{2.5}$ from fossil fuel combustion. Like GEMM, the non-linear exposure-response function is based solely on studies of ambient $PM_{2.5}$ (Vodonos et al. 2018) but unlike in GEMM and GBD, multiple estimates from the same study population are included in the model in a manner which contributes to highly imprecise estimates of attributable mortality (Table). The model also includes no explicit prior constraints on extrapolation as $PM_{2.5}$ levels increase and the estimates are based on the mean reported levels in each study, a maximum of 47 $\mu g/m^3$, with no clear approach to extrapolation to much the higher levels observed in some LMICs. The estimates are based on mortality from all-natural causes, an aggregation broader than either GBD or GEMM, and therefore also subject to the same concerns as GEMM regarding global applicability. Taken together these differences result in estimates of attributable mortality that are two to 3-fold greater than GBD's and 15 percent greater than GEMM despite the narrower focus on $PM_{2.5}$ from fossil fuel combustion (Table).

Though the differences in estimates between the GBD and other models have received periodic attention in the press, the differences are less important than the fact that they all point to a major global health problem now centered, and increasing, in many LMICs. The GBD estimates are the most conservative among them, being based on disease-specific risk functions reflecting standardization with other GBD risk factors and incorporating quantitative evidence scoring criteria, and for that reason may, as the GEMM has suggested, underestimate the full magnitude of $PM_{2.5}$-attributable mortality. Reducing the current uncertainties will require continued research, including large cohort mortality studies in settings with high exposures and analyses of the relationship between $PM_{2.5}$ and other major causes of death.

Table

Source of Estimate	$PM_{2.5}$ Exposure Estimate	Exposure-Response Relationship	Baseline Mortality source	$PM_{2.5}$ Counterfactual Level	Causes of Death	Year of mortality estimate	Global Attributable Deaths (million) (95% UI)
GBD 2019 (2020)	Ambient $PM_{2.5}$ DIMAQ2 (2019)	MR-BRT	GBD 2019	2.4-5.9 $\mu g/m^3$ uniform distribution of lowest and 5th % ile estimates from selected cohort studies	LC, IHD, Stroke, COPD, LRI, T2D, NNM	2019	4.1 (3.4-4.8)
Burnett et al. (2018)	Ambient $PM_{2.5}$ DIMAQ (2017)	GEMM	GBD 2015	2.4 $\mu g/m^3$ lowest estimated exposure in selected cohort studies	All NCDs and LRI	2015	8.9 (7.5-10.3)
WHO (2018)	Ambient $PM_{2.5}$ DIMAQ2 (2019)	IER GBD 2015	WHO Global Health Estimates (2018)	2.4-5.9 $\mu g/m^3$ uniform distribution of lowest and 5th % ile estimates from selected cohort studies	LC, IHD, Stroke, COPD, LRI	2016	4.2 (3.6-5.0)
Lelieveld (2019)	Ambient $PM_{2.5}$ EMAC Global chemistry model	GEMM	WHO Global Health Observatory (2017)	2.4$\mu g/m^3$ estimated $PM_{2.5}$ levels without fossil fuel combustion/anthropogenic emissions	All NCDs and LRI	2015	8.8 (7.1-10.4)
Vohra et al. (2021)	$PM_{2.5}$ from fossil fuel combustion GEOS Chem chemical transport model	Meta-analytic summary rate ratio from 53 studies (Vodonos et al. 2018)	GBD 2015	11 $\mu g/m^3$ estimated $PM_{2.5}$ levels without fossil fuel combustion	All natural causes ages >14 yr.	2012	10.2 (-47.1-17.0)

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