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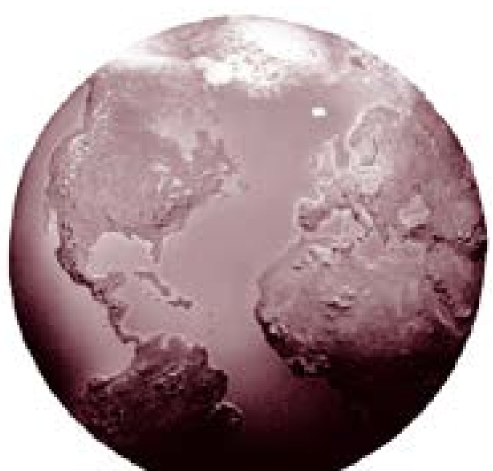
Contribution of Household Air Pollution to Ambient Air Pollution in Ghana: Using Available Evidence to Prioritize Future Action

HEI Household Air Pollution–Ghana Working Group



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Health Effects Institute

Boston, Massachusetts

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- Provides intensive independent review of HEI-supported studies and related research;
- Integrates HEI's research results with those of other institutions into broader evaluations; and
- Communicates the results of HEI's research and analyses to public and private decision makers.

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COMMUNICATION 19

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HEI Household Air Pollution–Ghana Working Group

INTRODUCTION

In 2017, 47% of the global population, an estimated 3.6 billion people, continued to rely on solid fuels for cooking. Solid fuels are a major source of exposure to household air pollution (HAP*) in the form of fine particulate matter ($PM_{2.5}$; particulate matter ≤ 2.5 µm in aerodynamic diameter) (Health Effects Institute 2019). A majority of these people live in sub-Saharan Africa (SSA), South Asia, and East Asia; in SSA, 80% of the population cooks with solid fuels including biomass, wood, and charcoal (Health Effects Institute 2019). In addition, a significant proportion of this population does not have access to an electric power grid, and uses biomass, kerosene, and diesel or gasoline generators for lighting. Taken together, these sources of residential energy make a significant contribution to HAP.

Household reliance on solid and liquid fuels is not just a problem for the households themselves; it is also a major source of ambient, or outdoor, air pollution with consequences for much broader populations (Chafe et al. 2014; Smith et al. 2014). A global analysis estimated that in 2010, cooking-related HAP contributed 12% of total population-weighted ambient $PM_{2.5}$ (Chafe et al. 2014). This contribution varied substantially across the world but was disproportionately higher in low- and middle-income countries; in southern SSA, the contribution was reported to be as high as 37%. In western SSA, the average contribution was estimated to be 10% of total ambient $PM_{2.5}$. When all residential energy use† was considered, a more recent estimate put the global contribution at 21%. Again, contributions were disproportionately higher in low- and middle-income countries and during the winter months (Weagle et al. 2018). In India and China, 24% and 19% of ambient $PM_{2.5}$, respectively, were attributed to residential solid fuel burning (GBD MAPS Working Group 2016, 2018).

The public health burden from exposures to HAP is well documented and substantial (Gordon et al. 2014; HEI Household Air Pollution Working Group 2018; Smith et al. 2014). The Global Burden of Disease (GBD) project estimated that, globally, 1.64 million deaths in 2017 were attributed to HAP from the burning of solid fuels for cooking alone (Health Effects Institute 2019). However, this estimate does not include the additional health burden linked to HAP's contribution to ambient air pollution. Therefore, it is likely to underestimate the total health burden associated with HAP in regions where solid fuel use is common. If we consider age-standardized death rates, a metric that takes into account the age distribution of the population, the indoor contribution of HAP to health burden is already higher in Ghana and western SSA than in China or India (Figure 1A). This is true despite the lack of estimation of the contribution of HAP to health burden via its impact on ambient air pollution (Figure 1B).

These estimates show that where household burning of solid fuels is prevalent, countries will not be able to achieve complete improvements in ambient air quality without addressing this important source. With expanding populations and increasing demand for energy in low- and middle-income countries, the energy choices made have critical implications for management of air pollution and for public health. The linkage between household energy choices and air quality has provided motivation in some countries to find cleaner energy solutions. For example, China has mounted an aggressive campaign to remove and replace coal stoves with cleaner energy sources to address serious air pollution levels in Beijing and across the northern region (Zhao et al. 2018). Air quality management efforts in other countries require a similar understanding of key sources of air pollution.

This document was made possible through support provided by Bloomberg Philanthropies (*www.bloomberg.org)*. The final contents of this document have not been reviewed by private party institutions, including those that support the Health Effects Institute; therefore, it may not reflect the views or policies of these parties, and no endorsement by them should be inferred.

* A list of abbreviations and other terms appears at the end of this volume.

† Residential energy use includes all household energy use for cooking and heating — including biofuel use, generators, and small combustion sources (Weagle et al. 2018).

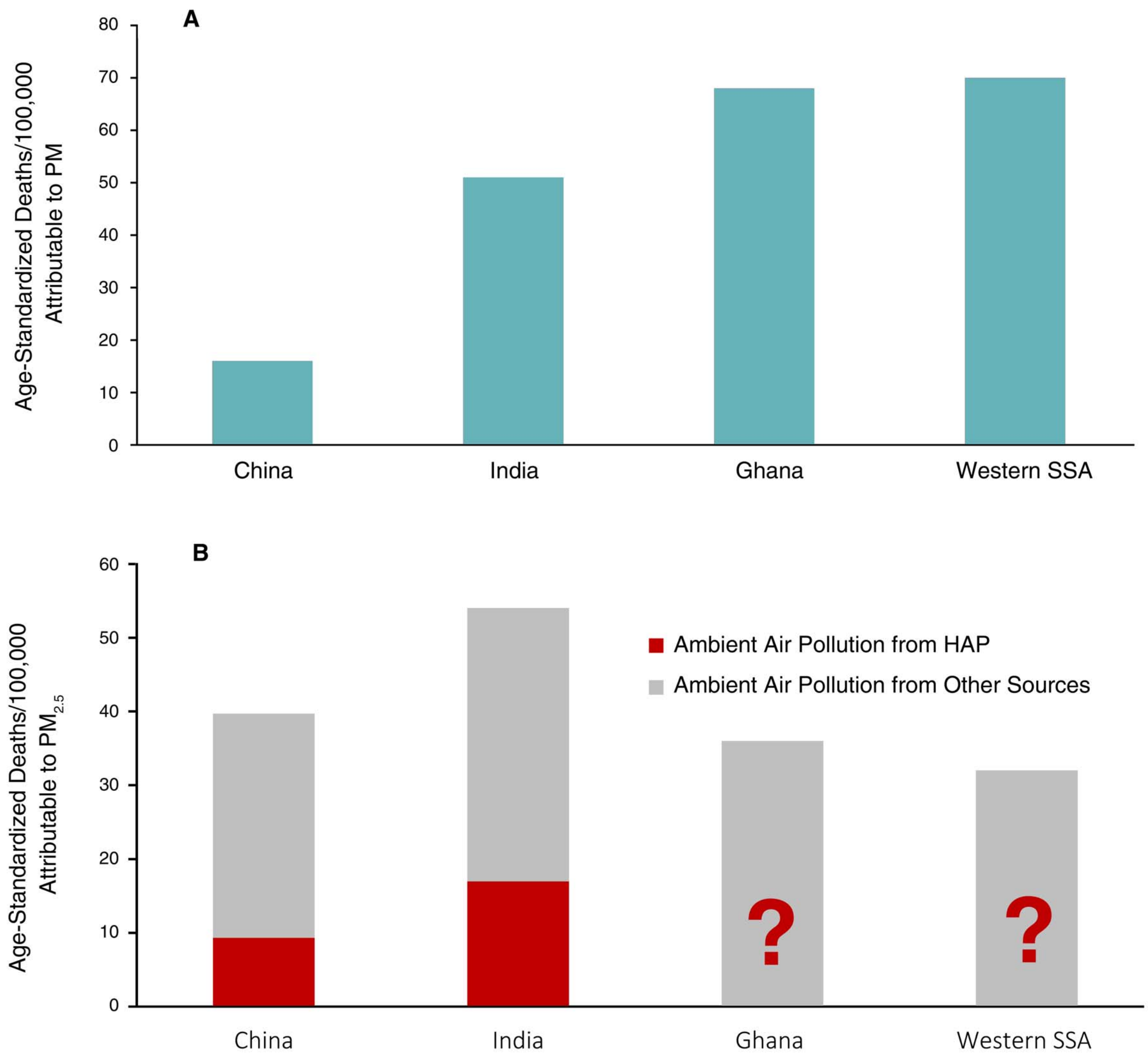


Figure 1. Contribution of HAP to age-standardized deaths per 100,000 people attributable to (A) solid fuel use for cooking (Health Effects Institute 2019; Stanaway et al. 2018); and (B) ambient $PM_{2.5}$ based on GBD 2017. In China and India, the contributions from HAP were estimated from their respective GBD MAPS studies, while in Ghana and western SSA, the fractional contribution of HAP to ambient air pollution has not been estimated (GBD MAPS Working Group 2016, 2018; Health Effects Institute 2019; Stanaway et al. 2018). Average $PM_{2.5}$ concentrations exceed the WHO guideline for healthy air (10 µg/m^3).

Across Africa, cooking and lighting with solid fuels and kerosene remain common and contribute significantly to ambient pollution. Other major sources of $PM_{2.5}$ emissions include desert dust, crop and savanna burning, road transportation, power production (including coal-fired power plants, gasoline and diesel generators, and others), industry, waste burning, and road dust (Crippa et al. 2018; De Longueville et al. 2010; Marais and Wiedinmyer 2016). According to one estimate at the continental scale (i.e., Africa), 71% of the total primary anthropogenic $PM_{2.5}$ emissions in 2012 were attributable to residential emissions, followed by 13% for agriculture, 12% for industry and processes, and 2% each for energy and transport (Crippa et al. 2018). Large-scale biomass burning was not included. With population and economic growth in the region, sources contributing to ambient $PM_{2.5}$ have been steadily increasing in recent years (Marais and Wiedinmyer 2016).

Within the African continent, meteorological factors also influence air quality. During the Harmattan season (November–March), transport of Sahara dust to the Gulf of

Guinea, including Ghana, is a major contributor to ambient $PM_{2.5}$ concentrations (De Longueville et al. 2010). Furthermore, within the same period (December–February), atmospheric mixing is severely restricted in this region due to natural inversions extending across West Africa, leading to a build-up of pollutants (Marais et al. 2014).

Several efforts are under way in Ghana and western SSA to quantify source contributions (including HAP) to ambient air pollution, but a comprehensive assessment of source contributions has not been completed in the region. Ghana provides a good case study, both because of the ongoing source apportionment work and because it has an active air quality monitoring network. Ghana has recently released a draft air quality management plan for the Greater Accra region and has undertaken sustained efforts to promote liquefied petroleum gas (LPG) use in households (see textbox). This is an opportune time to review how results from a range of different approaches, using different sources of available data, shed light on the contribution of HAP to ambient air pollution in Ghana, and to consider possible next steps.

OBJECTIVES

The goal of this analysis is to explore the resources available for estimating the contributions of HAP to ambient air pollution. The focus of this Communication is on the experience of Ghana and the larger western SSA region where the proportion of populations relying on solid fuels remains high (73% and 80%, respectively, in 2017) (Health Effects Institute 2019), and where an increasing number of relevant studies have been conducted. Data from the region further suggest that kerosene and other liquid fuels are also used in households and contribute to HAP. Where available, their contributions are also considered in the analysis.

The specific objectives of this analysis were to:

- Summarize and compare approaches that have been used to quantify the contribution of HAP and other sources of ambient air pollution for various geographic scales in Ghana.
- Discuss the current state of knowledge on the source contributions to emissions, air quality, and health and identify key knowledge gaps.
- Discuss the potential added value of other data or approaches not yet deployed fully in the region.
- Make recommendations for opportunities to improve estimates of HAP's impact on air quality and health burden for tracking progress on efforts to scale up clean energy.

Although this Communication focuses on Ghana, it is intended to be informative for other low- and middle-income countries where the use of solid fuels remains high and where the resources to develop these estimates are often constrained.

METHODS FOR SOURCE APPORTIONMENT

Effective air quality management requires a thorough understanding of the contribution of various sources to ambient air pollution.

OVERVIEW OF METHODS

The term *source apportionment* describes techniques used to quantify the contribution of different air pollutant sources to the air pollutant concentrations of interest. The focus of this Communication is on ambient $PM_{2.5}$ and its primary components (e.g., black carbon [BC] and organic carbon [OC]) as well as on various gaseous precursors (sulfur dioxide [SO_2], nitrogen oxides [NO_x], volatile organic compounds [VOCs], and ammonia [NH_3], among others). Particulate matter (PM) refers to solid particles and liquid droplets found in the air. Primary particles are released directly into the atmosphere (e.g., dust and BC from combustion of fuels), while secondary particles are formed in the atmosphere from primary gaseous emissions through chemical reactions. $PM_{2.5}$ emissions refer only to primary particles. Ambient $PM_{2.5}$ concentration includes $PM_{2.5}$ mass from both primary and secondary particles.

There are two broad approaches for estimating source contributions to $PM_{2.5}$: (1) *top-down*, or receptor-modeling approaches, and (2) *bottom-up,* or source-based approaches. The foundations for the two approaches are very different — they approach the analysis from different directions, starting with different building blocks. They also differ in the nature and geographic detail required for inputs, in the nature of estimates they provide, and in the economic and technical resources they need. For a detailed discussion on source apportionment methodologies, please refer to Johnson and colleagues (2011).

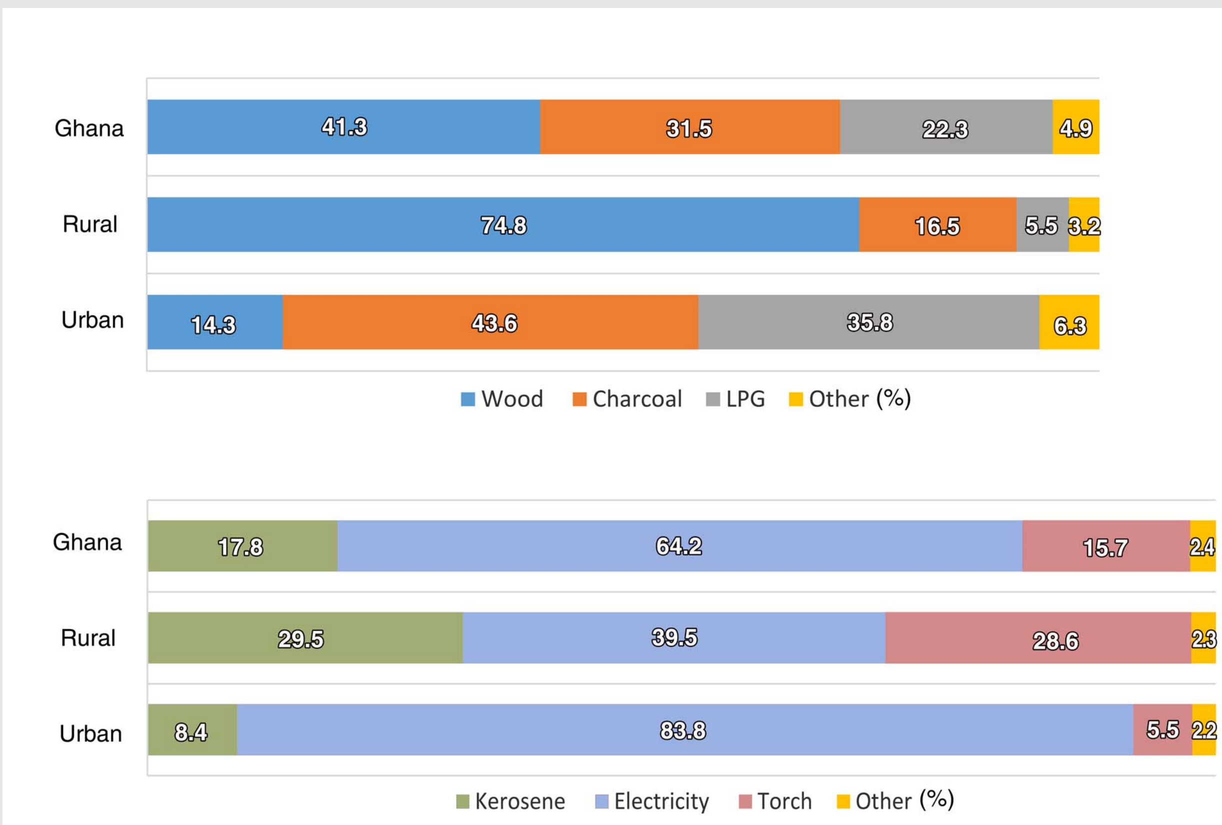
In top-down analyses, filter samples for PM ($PM_{2.5}$, PM_{10}, or both) are collected, weighed, and analyzed using chemical speciation methods. These data are then analyzed mathematically using receptor-modeling techniques that essentially attempt to parse out the various sources that contributed to overall PM concentrations using chemical *signatures* (referred to as *source profiles*) indicative of broad categories of sources (e.g., biomass burning or transport). For top-down modeling, both trace elements and

Ghana: Promoting Sustainable Energy and Decreased Household Air Pollution

Ghana has already begun to address the issue of clean energy access and air quality. An expansion of these efforts could address the adverse health effects of household air pollution (HAP). Some facts about Ghana:

- Ghana has the second largest economy in western sub-Saharan Africa (SSA) with a stable political structure and a stronger economy compared with neighbors in the region.
- Household air pollution is the 7th leading risk factor associated with disease burden (Stanaway et al. 2018); HAP contributed to 9,781 deaths in 2017.
  - HAP has been identified as the most impactful of the modifiable risk factors in Ghana.
  - Elderly Ghanaians disproportionately bear the burden of HAP; more than half of the HAP-related deaths are reported in individuals age 50 years and older.
- The government of Ghana is increasing efforts to promote both clean biomass and LPG (liquefied petroleum gas) cookstoves, spurred in part by the start of domestic LPG production from offshore oil fields (see the textbox figure for fuel-use statistics).*
  - Current policies include the Sustainable Energy for All Country Action Plan and the Rural LPG Promotion Policy. As part of the Sustainable Energy for All Country Action Plan, the national government has pledged to “promote the use of LPG” and provide “universal access to electricity.” These developments are motivated by energy and climate concerns rather than by air pollution.
- In 2018 the Greater Accra region adopted a draft Air Quality Management Plan; while this plan addresses ambient air pollution, it does not include specific action items on household air pollution.

* An estimate based on the Ghana Living Standards Survey, 2014, reported that 76% of Ghana’s population relies on solid fuels for cooking (World Health Organization 2018). In this Communication, results from the GBD 2017 analysis (Stanaway et al. 2018) have been reported for consistency.



Textbox Figure. Fuel use statistics for Ghana: (A) cooking and (B) lighting. (Based on Ghana Living Standards Survey, 2014 [World Health Organization 2018].)

organic compounds can be used as markers for specific sources, although for combustion sources, organic compounds (referred to as *molecular markers*) offer more specificity and reliability. Some of the trace elements (e.g., copper, zinc, and iron) are emitted from a range of sources, making it difficult to apportion the PM to sources with a high degree of confidence. For example, in Ghana, elements including calcium, iron, zinc, copper, nickel, and manganese were reported as markers for both 2-stroke engines and gasoline vehicles; a subset of these (copper and zinc) were also used to identify industrial emissions (Ofosu et al. 2012, 2013). In the case of biomass burning, potassium is emitted whenever biomass is burnt, whether in an open fire or in a kitchen. On the other hand, organic (molecular) markers can be highly specific to particular sources. When used in top-down modeling studies, these markers can help in distinguishing between combustion sources in particular. For example, certain organic compounds (hopane and sterane) are associated with vehicular emissions and can be used to tease out the differences between diesel and gasoline contributions from vehicles. However, receptor-modeling studies often cannot provide a breakdown of the contribution from different source categories or subcategories (e.g., diesel use in generators vs. vehicles) since the markers are often similar. For further details on top-down source apportionment methods, please refer to Watson and colleagues (2002).

An additional factor that needs to be considered in interpreting results from top-down analyses is that the results are sensitive to the location of the monitoring sites from which the samples are collected. Monitoring sites may be located for the purpose of studying particular sources (e.g., road traffic or industrial emissions). Therefore, careful analysis is required to determine the representativeness of these sites for estimating source contributions to other locations in the study area.

In bottom-up analyses, on the other hand, the starting point is the sources themselves. Inventories of the sources and their emissions are inputs for atmospheric chemical transport models (CTM), which are used to model both total ambient $PM_{2.5}$ concentrations and the contribution of individual sources across appropriate time and geographic scales. Because these methods start with individual sources, they can provide more specific insights into contributions within the broader categories available to top-down methods. However, they typically require substantially more input data and assumptions compared with a top-down approach.

Despite their underlying differences, bottom-up and top-down analyses can allow researchers and policymakers to gain a comprehensive understanding of the source contributions to air pollution for a particular region, country, or city that is critical for determination and prioritization of mitigation efforts. Ideally, results from the two types of studies will complement one another, identifying similar sources.

In summary, there are significant methodological differences between top-down and bottom-up approaches:

- **Scale.** Top-down methods are typically applied at the local (city/town/village) scale, while bottom-up methods have been applied across local, national, and regional scales. However, within the bottom-up models, there are significant differences in the resolution (see Table 1 for differences in top-down and bottom-up methods used in Ghana).
- ***Assessment of Health and/or Climate Impacts.*** Top-down methods are typically used for source attribution and estimation; bottom-up methods have been used to estimate health impacts and to evaluate effectiveness under different scenarios.
- ***Speciation Methods and Attribution of Sources.*** In the case of top-down models, source specificity often depends on the methods chosen for chemical analysis. For example, while dust and combustion sources can be separated using elemental markers alone, it is often hard to separate diesel, gasoline, and kerosene combustion unless molecular markers are used. This last step requires a sophisticated suite of instruments. Additionally, extraction of filter samples for chemical analysis can be time- and labor-intensive. Bottom-up methods, however, can be used to model detailed contributions from the different categories within each sector. (See Table 2 for examples of sources included in analyses in Ghana.) Also, while top-down methods can be used readily for estimating the contribution of dust, careful consideration is required to model the impact of dust in bottom-up approaches.
- ***Computing Power and Time.*** This is very relevant in the case of bottom-up approaches. Both full-scale and adjoint models can be used for modeling PM concentrations and source contributions. The GEOS-Chem Adjoint model (*http://wiki.seas.harvard.edu/geos-chem/ index.php/GEOS-Chem_Adjoint*), for example, allows a quicker analysis than the full-scale GEOS-Chem model (*http://acmg.seas.harvard.edu/geos/*) (varying from almost instantaneous results to 10–15 minute runs) depending on the complexity of the model (e.g., time scale of the analysis, frequency of outputs [annual, every 5 years, every 10 years], and modeling methodology used for each source sector). In comparison, a full run of the GEOS-Chem model requires a much longer time commitment. On average, it would take about one week to run a full year of the lower resolution version of the full-scale model (2° × 2.5°, latitude × longitude), and it will need 4–8 CPUs;

Table 1. Summary Matrix of Various Top-Down and Bottom-Up Studies Focusing on PM in Ghana

	Top-Down		Bottom-Up			
	Various Authors	SPARTAN[a]	DICE-Africa[b]	UEinfo	LEAP-IBC	GBD MAPS[c]
Features						
Emissions inventory (*local/national/ regional/global*)	N/A	N/A	Regional	Author's calculations for household sector and EDGAR-HTAP for the remaining	Developed with Environmental Protection Agency Ghana & Energy Commission Ghana	N/A
Emissions inventory (*gridded/non-gridded*)	N/A	N/A	0.1° × 0.1°	District level and gridded (0.1° × 0.1°) for national and 0.01° × 0.01° for the Greater Accra region	National total gridded to 2° × 2.5° for conversion to population-weighted $PM_{2.5}$ concentrations	0.5° × 0.67° (0.1° × 0.1° for $PM_{2.5}$)
PM measurement (*speciation*)	Gravimetric (XRF, carbon speciation)	Gravimetric (FRM measure-ment), AOD	Only in cases where emission factors were determined	N/A	N/A	N/A
Geographic scale (*local/national/regional/global*)	Local	Global/Local	Continental	Local (urban) and district level	National[d]	National/subnational
Temporal scale	24 hr–48 hr[e]	9-day samples	Depends on the CTM; annual	Annual	Annual	Annual
Base year	N/A	N/A	2006, 2013	2015	2010	
Scenario analysis	N/A	N/A	2030	2030	2040[f]	Analysis has not been conducted in Ghana
Air Quality Analysis & Source Identification						
Model(s)	PMF, Other	N/A	GEOS-Chem	WRF-CAMx	GEOS-Chem Adjoint	GEOS-Chem, nested regional models (e.g., South Asia, East Asia)

Table continues next page

AOD = aerosol optical depth; CTM = chemical transport model; FRM = federal reference monitor; GBD = global burden of disease; N/A = not applicable; PMF = positive matrix factorization; QA/QC = quality assurance/quality control; XRF = x-ray fluorescence.

[a] Currently, there are no SPARTAN sites in Ghana.

[b] DICE-Africa, in itself, is a stand-alone emissions inventory. Other studies have utilized the inventory to conduct bottom-up analysis.

[c] While this is a bottom-up methodology, it has not yet been applied in Africa.

[d] An urban scale version is under development.

[e] Weekly samples were collected in one study.

[f] The year 2040 has been used for analysis in Ghana. The actual end year of the analysis depends on the user; many choose 2030 as this is the time horizon of key plans (e.g., Ghana Nationally Determined Contribution), and others choose longer-term projections of emissions (e.g., 2100).

Table 1 (*Continued*). Summary Matrix of Various Top-Down and Bottom-Up Studies Focusing on PM in Ghana

	Top-Down		Bottom-Up			
	Various Authors	SPARTAN[a]	DICE-Africa[b]	UEinfo	LEAP-IBC	GBD MAPS[c]
Air Quality Analysis & Source Identification (*continued*)						
Air quality metric	$PM_{2.5}$ and its components (μg/m^3) and source contributions to total $PM_{2.5}$ (μg/m^3 and %)	$PM_{2.5}$ and its components (μg/m^3)	N/A	kg/capita emissions for pollutants and $PM_{2.5}$ (μg/m^3)	Annual average population-weighted $PM_{2.5}$ (μg/m^3)	Population-weighted $PM_{2.5}$ (μg/m^3) and source contributions
Model validation/ adjustment	N/A	Standard QA/QC	Long-term trends of air pollutants from UV-visible instruments (GOME, SCIAMACHY, OMI) used to assess inventory	Information not available	Based on satellite data (van Donkelaar et al. 2016)	Satellite and ground data
Impact Assessment						
Climate and short-lived climate pollutants	N/A	N/A	Work under way	N/A	Absolute global temperature change due to Ghanaian emissions, relative to 2010	N/A
Human health *(source contribution to health burden)*	N/A	N/A	Analysis at continental scale (Lacey et al. 2017)	Based on GBD methodology (work under way)	$PM_{2.5}$	$PM_{2.5}$
Agriculture (*crop losses, crop productivity*)	N/A	N/A	N/A	N/A	Ozone	N/A

AOD = aerosol optical depth; CTM = chemical transport model; FRM = federal reference monitor; GBD = global burden of disease; N/A = not applicable; PMF = positive matrix factorization; QA/QC = quality assurance/quality control; XRF = x-ray fluorescence.

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Table 2. Comparison of Sources Addressed Using Top-Down and Bottom-Up Approaches in Ghana[a,b]

Sector	Source Category	Top-Down	Bottom-Up: DICE-Africa	Bottom-Up: Urban Emissions	Bottom-Up: LEAP-IBC
Residential/ household				Own calculations & EDGAR-HTAP inventories	Ghana EC & Ghana EPA inventories
Fuel types include LPG, charcoal, other biomass (cooking) and kerosene, electricity, solar lamps (lighting)	Cooking	X (source profiles now available for biomass, charcoal, and LPG)	X (fuelwood, charcoal, kerosene, crop residue burning)	X (fuelwood, coal, cow dung, biogas, LPG, charcoal, kerosene, crop residue burning)	X
	Lighting	(source profiles now available for kerosene lighting)	X	X	X
	Heating				X
	Diesel/gasoline generators		X	X	X
	Other				X
Agricultural					
	Crop burning		X	X	X
	Other (e.g., diesel consumption)				X
Industry					
	Manufacturing				X
	Restaurants				X
	Oil refining		X (ad-hoc oil refining by individuals as opposed to oil companies, largely restricted to the Niger Delta)		X
	Charcoal production		X	X	X
Waste burning					
	Municipal solid waste				X
	Electronic waste	X	(under way)		X

Table continues next page

EDGAR-HTAP = Emissions Database for Global Atmospheric Research; Ghana EC = Ghana Energy Commission; Ghana EPA = Ghana Environmental Protection Agency.

[a] Note that the top-down and bottom-up methodologies use varying levels of details on sources, and even within the bottom-up approaches, studies have used different combinations of sources.

[b] X indicates that the source has been included in the study.

Table 2 (*Continued*). Comparison of Sources Addressed Using Top-Down and Bottom-Up Approaches in Ghana[a,b]

Sector	Source Category	Top-Down	Bottom-Up		
			DICE-Africa	Urban Emissions	LEAP-IBC
Energy generation					
	Power plant (coal)				X
	Power plant (oil)				X
	Hydroelectricity				X
Dust					
	Crustal dust/ Sahara dust	X			
	Road dust (paved and/or unpaved)	X			X
Transportation		X			
Includes fuel types (gasoline/diesel/other) and	Public and private transportation	X	X (motorcycles and vehicles)	X	
Engine type (2-stroke/4-stroke) and emissions (Euro I/II/III/IV)	Off-road equipment (diesel/kerosene)				X
Other					
Savanna and forest fires					X
Sea salt		X			
Gas flaring (natural gas)			X	X	

EDGAR-HTAP = Emissions Database for Global Atmospheric Research; Ghana EC = Ghana Energy Commission; Ghana EPA = Ghana Environmental Protection Agency.

[a] Note that the top-down and bottom-up methodologies use varying levels of details on sources, and even within the bottom-up approaches, studies have used different combinations of sources.

[b] X indicates that the source has been included in the study.

the run time for nested grid high-resolution full-scale models is even longer (weeks to a month). The memory requirements for storing GEOS-Chem meteorological fields and emission inventory data are also relatively high (can reach a few terabytes), although GEOS-Chem can now run on the cloud through Amazon Web Services.* There are costs associated with running the model, but they are relatively low.

*An Amazon Web Services hub is expected on the continent in 2020 (*https://aws.amazon.com/blogs/aws/in-the-works-aws-region-in-south-africa/*). The availability of cloud services largely mitigates the memory and IT needs. This could pave the way for greater use by African institutions.

These methods are now discussed in the context of specific studies conducted in Ghana and western SSA.

APPLICATION OF SOURCE APPORTIONMENT METHODS IN GHANA

As part of expert consultations begun in July 2018, an expert panel identified several studies thought to be (1) informative about the state of knowledge on source contributions to ambient air pollution and adverse health outcomes in Ghana and West Africa and (2) instructive for other countries about the opportunities and limitations of the range of existing and emerging methods.

Table 1 summarizes the studies identified by the panel according to the type of the methods used, comparing their key characteristics (including the geographic scale, the use of emission inventories and model types) and impact assessments (health, climate, and agricultural).

Top-Down Modeling Approaches

We examined six top-down studies conducted in Ghana by government and independent researchers between 2005 and 2017 (Aboh et al. 2009; Ofosu et al. 2012, 2013; Piedrahita et al. 2017; Zhou et al. 2013, 2014). They focused on the analysis of filter samples of PM_{10} and/or $PM_{2.5}$ from monitors located in the Greater Accra region and in Northern Ghana. The locations and other details of the studies are summarized in Table 3. As is typical of many top-down analyses, these studies were intended to represent the local scale, that is, a town or a city. A comprehensive top-down analysis of PM sources, using the full suite of methods, has not yet been conducted in Ghana.

Across all studies, PM filter samples were weighed to estimate total $PM_{2.5}$ concentration. The samples were analyzed for several elemental species, and for elemental and organic carbon, to identify sources. Only one study reported detailed speciation of organic components (Piedrahita et al. 2017) (see Table 3). All but one of the studies applied multivariate receptor models, primarily the positive matrix factorization (PMF) model, to identify sources that contributed to ambient $PM_{2.5}$ concentrations. That study (Aboh et al. 2009) has been excluded from further discussion. The chemical mass balance model has not yet been applied in Ghana; it requires source fingerprint datasets (also called source profiles) that were not available in Ghana until recently.

Bottom-Up Modeling Approaches

We also examined three bottom-up analyses in Ghana that represent the range of information that these methods can provide.

DICE-Africa. Diffuse and Inefficient Combustion Emissions in Africa (DICE-Africa) represents the first high-resolution (0.1° × 0.1°, or about 11 km × 11 km at the equator) emissions inventory for Africa (years 2006 and 2013) that included emissions from the residential use of solid and liquid fuels. These emission sources included charcoal, kerosene, fuelwood and crop residue burning, generators (diesel or gasoline), charcoal production, vehicles and motorcycles (diesel or gasoline), artisanal oil refining, and gas flaring (see Table 2) (Marais and Wiedinmyer 2016). This inventory was developed to address a number of important sources that had not been accurately represented in the global emission inventories used to characterize air pollution in Africa available at the time. In contrast with large stationary sources that are easier to identify, this analysis includes a broad set of smaller inefficient combustion sources that are typically dispersed across the country or region. Pollutants in the inventory include SO_2, NO_x, NH_3, carbon monoxide (CO), BC, OC, and nonmethane volatile organic compounds (NMVOCs).

To develop the inventory, the authors needed several inputs that are standard for inventory development but that did not always exist for Africa: an accurate spatial map of the sources spread across a geographic area, the rate of fuel-of-interest burned for each type of source (*activity factor*), and the amount of air pollutant released for a given source (*emission factor**). Data on activity factors were gathered from the U.N. Energy Statistics database and were combined with national datasets (as needed) and locally relevant emission factors (developed for this project). Global inventories, by contrast, typically rely on emission factors that have mostly been derived from data in Europe and North America and may not accurately represent source emission factors in other parts of the world. As was noted in this analysis and elsewhere, information on emissions factors in Africa is very limited. As a consequence, use of global emissions factors can contribute to important uncertainties in the final analyses (Crippa et al. 2018; Marais and Wiedinmyer 2016). Further, the availability of ground-based measurements, which are important for validation of inventories, is very limited in Africa.

While the DICE-Africa emissions inventories provide a good starting point for understanding sources of $PM_{2.5}$ emissions, additional modeling analyses are required to better understand the spatial and temporal pollutant concentrations and the population exposures. After the development of inventories, source contributions to regional air pollution have been estimated using the GEOS-Chem CTM. DICE-Africa has been used to calculate projections for air quality and health impacts of future emissions control scenarios (2030) in Africa (Lacey et al. 2017). Led by Panel member Dr. Eloïse Marais assessments of the health effects of present-day and future emissions in Africa are ongoing.

UEinfo (Urban Emissions). In this ongoing analysis supported by the Clean Cooking Alliance, the focus is solely on residential emissions in Ghana (*www.urbanemissions.info/*). Investigators conducted a bottom-up assessment of $PM_{2.5}$ emissions for 2015 and for a set of future scenarios in 2030 (see Table 1 for a summary). The analysis relies on a combination of the authors' own estimates for household emissions and the Emissions Database for Global Atmospheric Research (EDGAR)-HTAP inventory for other

* An emission factor is defined as "a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant" (U.S. EPA 2019). For example, an emissions factor for coal burning would be represented as kilograms of particulate emitted per megagram of coal burned.

Table 3. Summary of Top-Down Studies in Ghana

Study / Location	Year(s)	Sampling and Analysis	
Aboh et al. 2009			
Greater Accra region (Kwabenya)	February 2006–February 2007 (Harmattan and non-Harmattan period)	Pollutants	Ambient $PM_{2.5–10}$, $PM_{2.5}$
		Sample duration	24 hr
		Samples (*N*)	171
		Speciation	Elements (EDXRF); black carbon (BC)
		Model	PCA
Ofosu et al. 2012			
Ashaiman (semi-urban town)	February 2008–August 2008	Pollutants	$PM_{2.5}$
		Sample duration	24 hr (sampling period was 12 hr or 16 hr due to logistical constraints)
		Samples (*N*)	Not available
		Speciation	Elements (EDXRF); carbon speciation (IMPROVE TOR)
		Model	PMF
Ofosu et al. 2013			
Navrongo	February 2009–February 2010	Pollutants	$PM_{2.5-10}$, $PM_{2.5}$
		Sample duration	24 hr
		Samples (*N*)	110
		Speciation	Elements (EDXRF); carbon speciation (IMPROVE TOR)
		Model	PMF
Zhou et al. 2013			
Accra	September 2007–August 2008	Pollutants	Ambient PM_{10}, $PM_{2.5}$
		Sample duration	48-hr samples/6 days
		Samples (*N*)	199 ($PM_{2.5}$), 197 (PM_{10})
		Speciation	Elements (EDXRF); BC (smoke stain reflectometer)
		Model	PMF
Zhou et al. 2014			
Accra[a]	November 2006–August 2007	Pollutants	Ambient and cooking area $PM_{2.5}$
		Sample duration	48 hr
		Samples (*N*)	80
		Speciation	Elements (EDXRF), BC (smoke stain reflectometer)
		Model	PMF
Piedrahita et al. 2017			
Kassena-Nankana (northern Ghana)	November 2013–September 2014	Pollutants	Ambient $PM_{2.5}$
		Sample duration	One week
		Samples (*N*)	50; 25 for organics — used for source apportionment
		Speciation	Carbon speciation (NIOSH TOT); organics (subset of samples, GC-MS)
		Model	PMF2

EDXRF = energy dispersive x-ray fluorescence; GC-MS = gas chromatography-mass spectrometry; IMPROVE = Interagency Monitoring of Protected Visual Environments; NIOSH = National Institute for Occupational Safety and Health; PCA = principal component analysis; PMF = positive matrix factorization; TOR = thermal-optical reflection; TOT = thermal-optical transmission.

[a] The study included other sites outside Ghana, but those are not listed here for brevity.

emissions. Population-based fuel-use data were extracted at the district level from the 2010 Ghana Census (Ghana Statistical Service 2012). For the policy analyses, population projections for the 2030 scenarios were derived from *populationpyramid.net*. Meteorological data (3D wind, temperature, pressure, relative humidity, and precipitation fields) were derived from the National Center for Environmental Prediction global reanalysis database and processed through the WRF meteorological model at a 1-hour temporal resolution. Household emissions were split into four categories: cooking, lighting, space heating, and water heating. For the capital city of Accra, the emission inventory was gridded at a finer resolution (0.01°, equivalent of 1 km). A photochemical dispersion model, CAM_x (Comprehensive Air Quality Model with Extensions) was used to study the movement of source emissions on a regional scale, the formation of secondary sulfate particulates (part of $PM_{2.5}$), and how these contribute to $PM_{2.5}$ levels and to health impacts across urban and rural areas. Scenario analysis was completed using the SIM-air (Simple Interactive Models for better air quality) framework. The detailed methodology is described in detail elsewhere (Guttikunda et al. 2019).

LEAP-IBC. Long-range Energy Alternatives Planning-Integrated Benefits Calculator (LEAP-IBC) is an integrated planning tool designed to help governments jointly assess (1) greenhouse gases (GHG), short-lived climate pollutants (SLCPs), and other air pollutant emissions; (2) build mitigation scenarios; and (3) understand how emission reductions benefit climate, health, and crops. It is a flexible system for the development of inventories and scenarios that reflect national circumstances and is designed to be used by practitioners in developing countries.

In Ghana, LEAP is extensively used within national institutions primarily for energy and climate planning. A LEAP dataset is maintained and updated by the Ghana Energy Commission (Ghana EC) for energy planning (using activity data from the Ghana Living Standards Survey and other national datasets); it is implemented in partnership with the Ghana Environmental Protection Agency (Ghana EPA). As part of the development of a National Action Plan to reduce SLCPs, analysis was conducted for the base year of 2010. The LEAP dataset on energy sources was combined with additional information on nonenergy sector emission sources from the Ghana EPA in order to create an emissions inventory for all major energy and nonenergy source sectors. Pollutants included in the inventories were primary $PM_{2.5}$, OC, BC, NH_3, SO_2, NO_x, NMVOCs, CO, carbon dioxide, and methane. Subsequently, analysis was conducted to evaluate a range of mitigation measures, including those outlined in the Ghana Nationally Determined Contribution (*www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Ghana%20First/GH_INDC _2392015.pdf*), as well as additional measures that focus on major SLCP sources using the LEAP-IBC model.

LEAP's initial output is in the form of emissions (e.g., total emissions of air pollutants or GHGs). The emissions output was then input into the GEOS-Chem Adjoint model to estimate national population-weighted annual ambient $PM_{2.5}$ concentrations for the base year (in this case, 2010). These results were then combined with an integrated exposure response (IER) function and baseline mortality rates for relevant disease outcomes to estimate the number of deaths attributable to $PM_{2.5}$ exposures nationally. Once the baseline model was developed, additional analyses were conducted to assess the changes in air pollution, health, and climate impacts that might result from specific mitigation measures, for example, achieving the government's target to have 50% of Ghanaian households on LPG by 2030.

A major difference between the LEAP-IBC program and the two other analyses discussed above (i.e., DICE-Africa and UEinfo) is the use of locally developed emissions inventories, which are developed and maintained by the Ghana EPA and the Ghana EC. The activity data were collected by the Ghana EPA and EC at the national level. However, the analysis relied on default global emission factors, which, as discussed earlier, are not always representative of local emissions.

The LEAP-IBC analysis developed in Ghana was focused on the development of the national SLCP planning, and there is significant overlap with air quality management. Ghana EPA, the developer of the analysis, is also responsible for air quality management and climate change planning in Ghana. The national SLCP plan is an air quality effort that was designed to identify measures with air quality and climate benefits.

Overall, the LEAP-IBC tool is a flexible system for the development of inventories and scenarios that reflect national circumstances. It is designed to be used by practitioners in developing countries. Any particular application of LEAP-IBC to develop an analysis of emissions now and in the future depends on the availability of local activity data, locally relevant emission factors, and well-grounded consistent projections of how activity and emissions will change over time under different policy scenarios.

OTHER METHODS AND RESOURCES

In addition to the methodologies discussed above, which have already been applied in Ghana, other methods exist but either have not yet been applied or are emerging as resources for source apportionment.

HEI GBD MAPS

The HEI Global Burden of Disease from Major Air Pollution Sources (GBD MAPS) methodology shares several elements similar to those of other bottom-up approaches, but there are some important differences (see Table 1). GBD MAPS follows a four-step process to estimate the disease burden associated with exposure to ambient $PM_{2.5}$ under baseline conditions and under 3–4 future energy and emissions control policy scenarios (Figure 2). In the first step, detailed multipollutant emissions inventories for $PM_{2.5}$, SO_2, NO_x, BC, OC, NMVOCs, and other pollutants for major sources or sectors are generated at the district level using data from published literature and government reports. These are compiled on a 0.5° × 0.67° grid scale. In order to estimate the fractional, or percentage, contribution of individual sources, global and nested (e.g., South Asia version for India) GEOS-Chem models are first used to model total ambient $PM_{2.5}$ concentrations using all sources in the emissions inventories. Then, sensitivity analyses are conducted in which emissions from individual major sectors or sources are removed (or, in essence, shut off), and the models are run again. The difference between the total and sensitivity simulations provides an estimate of that sector's contribution to ambient $PM_{2.5}$. These spatially resolved fractional contributions of the different source sectors are then applied to the gridded ambient $PM_{2.5}$ concentrations estimated as part of the GBD project. The GBD concentration estimates combine satellite-based estimates with the GEOS-Chem model to provide information on the relationship between aerosol optical

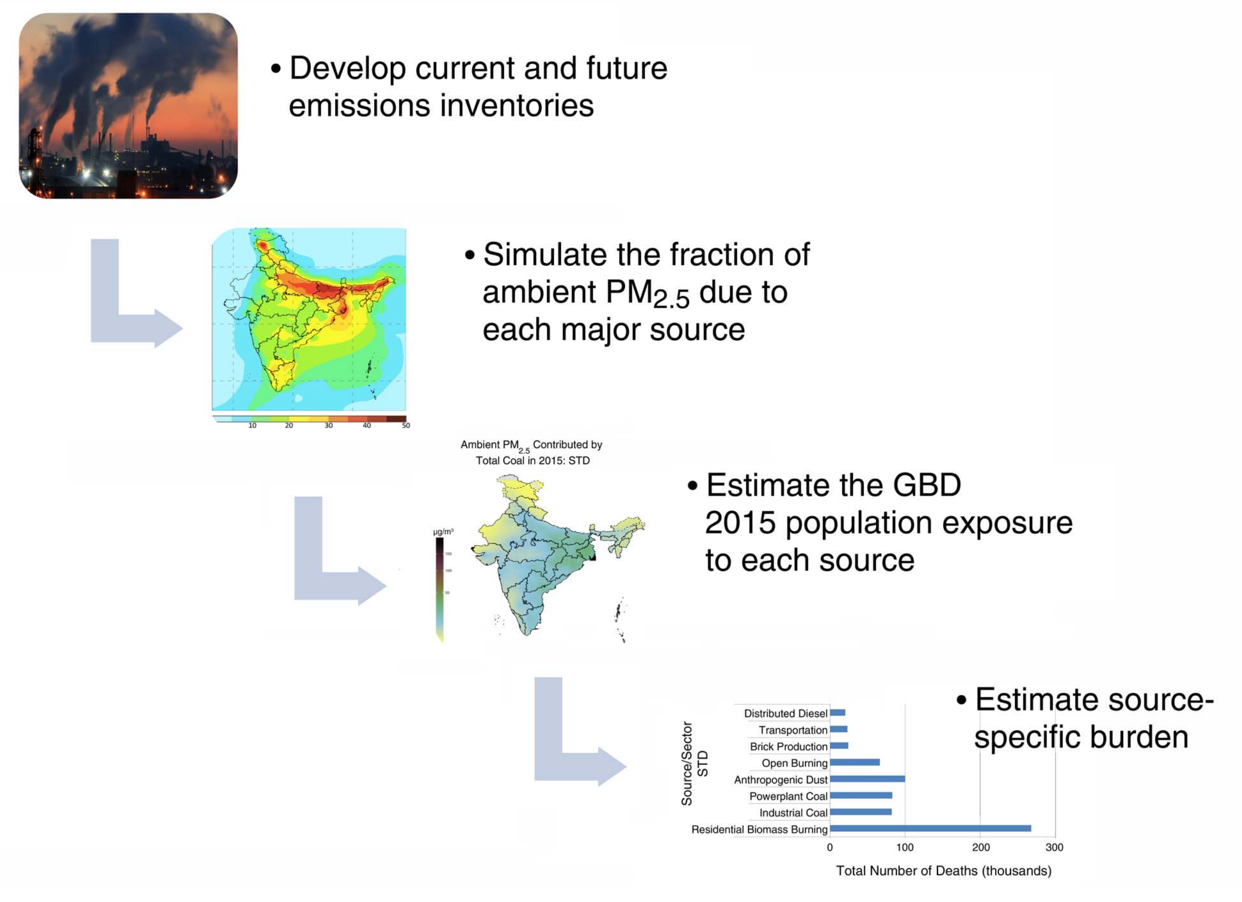

Figure 2. Methodological approaches for GBD MAPS project.

depth (AOD) and surface $PM_{2.5}$. Annual average $PM_{2.5}$ measurements and other information (chemical composition and geography) are used in a Bayesian hierarchical model to provide global estimates of $PM_{2.5}$ at a 1° × 1° resolution (about 11 km × 11 km at the equator). The combination of these concentrations with gridded population data produces an estimate of exposure (i.e., population-weighted $PM_{2.5}$). These exposure estimates in turn are used with IER curves from the GBD project that define the quantitative relationship between exposure and health outcome, for example, to provide estimates of the burden of disease (mortality, disability-adjusted life-years, and respective rates) attributable to each source for a particular year.

A notable difference between this approach and that of LEAP-IBC is that the full-scale GEOS-Chem models used in the GBD MAPS analyses account for the complex atmospheric physics and chemistry between precursor emissions and ambient particle concentrations, whereas the GEOS-Chem Adjoint versions rely on simplified linear relationships. The impact of the simplifications on the accuracy of the predictions is not well studied for applications in this region and thus is a source of uncertainty. HEI has completed GBD MAPS studies in China and India at the national and subnational levels (GBD MAPS Working Group 2016, 2018) and is currently supporting a global analysis.

Satellite Data

Newer satellite-based methods and associated ground-based monitoring networks are emerging that show promise for supporting consistent approaches to estimating sources regionally and globally.

SPARTAN The Surface PARTiculate mAtter Network (SPARTAN) is comprised of a global network of ground-level $PM_{2.5}$ and PM_{10} monitors across more than 20 sampling sites. These sites are situated primarily in highly populated regions and are collocated with existing ground-based sun photometers* that measure AOD (Figure 3) (Snider et al. 2015, 2016). The goal of SPARTAN is to use ground-monitoring data for the development of satellite data-based $PM_{2.5}$ estimates. Data from the network have also been used to support global-scale bottom-up source attribution (Weagle et al. 2018). The instruments, a three-wavelength nephelometer and an impaction filter sampler for both $PM_{2.5}$ and PM_{10}, collect samples automatically and do not require significant manual intervention. These measurements provide, in a variety of regions around the world, the key data required to evaluate and enhance satellite-based $PM_{2.5}$ estimates used for assessing the health effects of aerosols. Hourly $PM_{2.5}$ concentrations are inferred from the combination of weighed filters and nephelometer data. SPARTAN filters are analyzed for mass, BC, water-soluble ions, and metals. The data are made publicly available, and potentially could be used for top-down source apportionment analysis, as well as for validation analyses. Currently, there are two sites in Africa — Ilorin (Nigeria) and Pretoria (South Africa) — and there are plans to add a site in Addis Ababa (Ethiopia) in mid-2019.

TROPOMI. The TROPOspheric Monitoring Instrument (TROPOMI), onboard the Sentinel-5P satellite platform, was launched into orbit in 2017. It provides daily global high-resolution (7 km × 3.5 km) measurements of air pollutants visible in the shortwave-infrared, near-infrared, and UV-visible wavelengths. These include NO_2, CO, formaldehyde (a proxy for NMVOCs), ozone, methane, and SO_2. This offers an opportunity to assess high-resolution emissions inventories, using CTMs to relate TROPOMI measurements of the sum of a pollutant throughout a vertical column of air to the amount of the precursor pollutant emitted.

Others. The NASA MAIA (National Aeronautics and Space Administration Multi-Angle Imagers for Aerosols) project aims to quantify the size, composition (sulfate, nitrate, OC, BC, and dust), and concentrations of PM with a focus on using the data for epidemiological studies at the urban level in 12 major cities worldwide, including at least one African city. This is expected to generate valuable data in the African context, but the project launch is still a couple of years away.

Several unrelated research efforts are working toward improving air quality forecasting capabilities (e.g., MAP-AQ program at the National Center for Atmospheric Research, Boulder, CO, and the Atmospheric Monitoring Service under the Copernicus Programme in Europe). While these aren't the focus of discussion in this analysis, they can provide valuable information for improving our understanding of air quality in the continent.

RESULTS

Both top-down and bottom-up methods have been applied in Ghana, but no single method has been applied that provides a comprehensive view of all sources in Ghana. This Communication therefore compares reported estimates qualitatively and, where possible, quantitatively to provide a better understanding of the current state of

* The sun photometers are maintained across the world as part of the NASA AERONET (AErosol RObotic NETwork) program: *https://aeronet.gsfc.nasa.gov/*. There is one NASA AERONET site near Accra, Ghana.

Figure 3. SPARTAN sites as of December 2018. (Courtesy of Randall Martin; *www.spartan-network.org.)*

evidence on the contribution of HAP to ambient $PM_{2.5}$ concentrations.

Some studies (e.g., DICE-Africa) were initially designed only to develop more comprehensive emissions inventories, which is an important starting point for bottom-up approaches. Although contributions of primary HAP emissions as a percentage of total emissions do not necessarily translate into the same percentage contributions to ambient $PM_{2.5}$ concentrations, both kinds of estimate are presented here to provide some perspective on the potential importance of HAP emissions for air quality.

Across all methodologies, residential emissions were identified as a key source for $PM_{2.5}$ emissions. In case of top-down analyses, the use of biomass and solid fuel was consistently identified as a contributor to ambient $PM_{2.5}$ concentrations. Estimates from the two types of methodologies also differ because they address different geographic scales; the top-down methods have quantified source contributions for ambient $PM_{2.5}$ at the local scale, while a bottom-up analysis produced national- or regional-level estimates.

AMBIENT AIR QUALITY IN GHANA

The various studies provide broad agreement that $PM_{2.5}$ levels in Ghana exceed the World Health Organization (WHO) Air Quality Guideline for health (10 μg/m^3) (WHO 2006). Top-down studies using ground-based PM monitoring data have reported average (24-hr or weekly) $PM_{2.5}$ concentrations ranging between 21.6 and 40.8 μg/m^3 (Aboh et al. 2009; Ofosu et al. 2012, 2013; Piedrahita et al. 2017; Zhou et al. 2013, 2014). Modeling approaches produced similar estimates; the LEAP-IBC method predicted annual average ambient $PM_{2.5}$ levels of 33 μg/m^3 for 2010. The GBD 2017 study, which relies on global satellite and ground-level measurements worldwide, more recently estimated the national average $PM_{2.5}$ concentration in Ghana to be 35 μg/m^3, while the regional average for western SSA was 59 μg/m^3 (Figure 4) (Health Effects Institute 2019).

PRIMARY $PM_{2.5}$ EMISSIONS IN GHANA

The Ghana LEAP-IBC analysis estimated that residential sources (including household cooking, lighting, and heating) contributed ~65% of total national primary $PM_{2.5}$ emissions in 2010 (see Figure 5). The investigators found that solid fuel use in rural areas was driving the trends, with more than 80% of the total residential emissions coming from rural households. Other major sources identified by the Ghana LEAP-IBC analysis included road transport and road dust (13.9%), open fires (8.9%), and industry (5.1%).

DICE-Africa reported the $PM_{2.5}$ emissions as its individual components (OC and BC), which are often used to identify different types of sources as well as precursors to $PM_{2.5}$ (SO_2, NO_x, NH_3, etc.). Residential fuel use was the

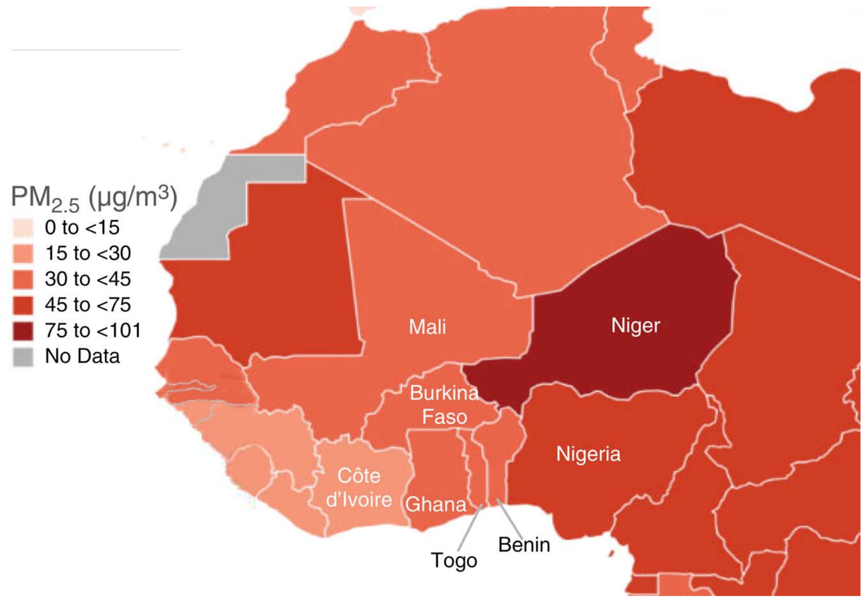

Figure 4. Ambient $PM_{2.5}$ concentrations in western SSA. (Health Effects Institute 2019.)

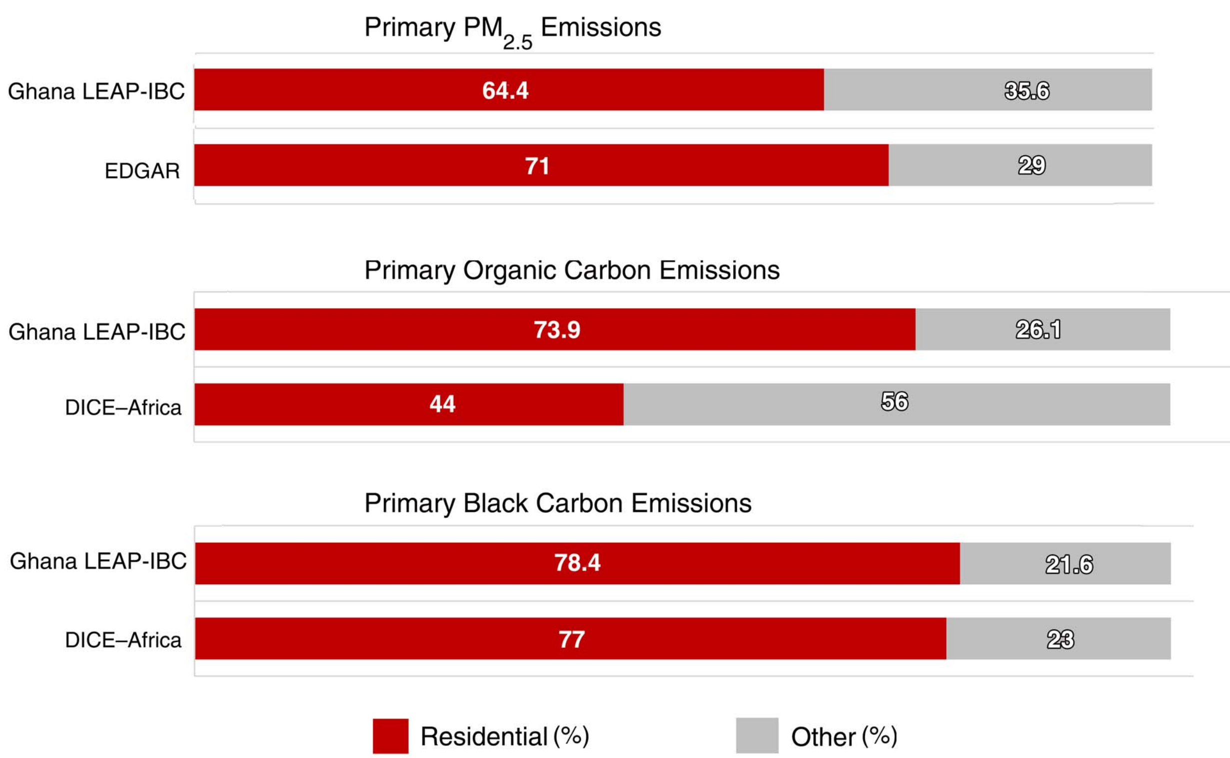

Figure 5. Percentage contribution of residential emissions to total $PM_{2.5}$ emissions in Ghana. Contributions from other sources are combined and represented as "Other." (Data from Crippa et al. 2018 and Marais and Wiedinmyer 2016.) EDGAR percentages represent the African continent.

second largest contributor (44%) to total OC emissions in Ghana, just behind vehicles (42%) (Figure 5). Analyses for BC point to residential fuel use as the largest contributor (77%), followed by other sources (charcoal use [10%], commercial biofuel use [8%], and vehicles [5%]) (Figure 5). In contrast, per LEAP-IBC analysis, the residential sector was found to contribute 73.9% and 78.4% of the total OC and BC emissions, respectively. As noted in Table 2, DICE-Africa does not include all the PM sources that are considered in LEAP-IBC.

UEinfo has not yet finalized its estimates of the percentage of $PM_{2.5}$ emissions from HAP, but ultimately, like other bottom-up methods, its analysis enables mapping those contributions at the local level throughout Ghana (see Figure 6A). Its preliminary work suggests substantially higher emissions rates for cooking-related PM in the major urban areas. DICE-Africa reported similar results for $PM_{2.5}$ precursor pollutants (Figure 6B).

SOURCE CONTRIBUTIONS TO AMBIENT $PM_{2.5}$ IN GHANA

Across the country, emission patterns are driven by fuel use. This includes solid fuels for cooking but also other fuels, such as kerosene, for lighting. Air quality is tied not only to solid fuel use in cooking but also to all residential uses. To date, direct estimates of the contribution of sources to ambient air pollution concentrations have been reported only by the top-down studies relying on $PM_{2.5}$ monitoring data representing relatively small areas (Table 4). These estimates of biomass combustion contributions are not specific to residential use of solid fuels for cooking; they can include other forms of biomass combustion as well (e.g., open fires, commercial activities). Other significant contributors include dust — both dust and resuspended road dust — (16%–39%) and emissions from transportation (15%–35%) and industry (~10%). Specifically, in Accra, between 15% and 42% of the ambient $PM_{2.5}$ was attributed to biomass burning (related to biomass as fuel for cooking), while in case of the cooking area (i.e., within the home) between 39% and 62% of the $PM_{2.5}$ was attributable to biomass burning (Zhou et al. 2014). However, results from receptor-modeling studies are locally specific; that is, they can be biased by the location (e.g., a study with roadside locations will invariably show a higher contribution from traffic). So location of the monitoring stations needs to be taken into account when interpreting results.

The Ghana LEAP-IBC analysis estimated natural background emissions (predominantly desert dust) to be the largest contributor (65%) to annual average population-weighted $PM_{2.5}$ concentrations across Ghana, followed by rest-of-the-world emissions (21%) and then by local emissions (14%) from within Ghana. LEAP-IBC also uses these percentages to apportion the percentage of deaths attributable to ambient $PM_{2.5}$ to $PM_{2.5}$ from natural background, rest-of-the-world, and national emissions. This finding is consistent with a global analysis, which attributed nearly 60% of total deaths in Ghana to natural dust (Lelieveld et al. 2015).

This evidence makes clear that air pollution in Ghana is a regional challenge with sources such as desert dust and open burning influencing regional air quality. DICE-Africa also estimates that pollution from Nigeria, another major country in western SSA, has a major impact on regional air quality (Marais and Wiedinmyer 2016). Recent analysis in the southern West African region has also pointed toward high regional background concentrations for air pollutants (Brito et al. 2018).

HEALTH IMPACTS ASSOCIATED WITH EXPOSURE TO $PM_{2.5}$

The implications of exposure to air pollution for public health in Ghana are important. The Ghana LEAP-IBC analysis estimated that approximately 9,100 deaths were attributable to total ambient $PM_{2.5}$ exposure in 2010. No estimate was provided specifically for the contribution of household fuel use. The recent GBD 2017 estimated significantly higher burdens — 9,780 deaths — due to exposure to HAP from solid fuel use and 5,190 deaths attributable to ambient $PM_{2.5}$ pollution (Health Effects Institute 2019; Stanaway et al. 2018).

It is also important to note that between 2005 and 2017, the percentage of people using solid fuels for cooking in Ghana declined from 91% to 73%; by extension, the estimated number of early deaths also declined (from 11,300 to 9,780) (Health Effects Institute 2019), providing further evidence for the need to reduce HAP exposures. The 2017 GBD study ranked HAP as the seventh largest risk factor based on its health burden in Ghana (Stanaway et al. 2018). In India, for example, where approximately 60% of the population relied on solid fuels for cooking, an estimated 24% of the mortality burden from ambient air pollution was attributed to HAP (GBD MAPS Working Group 2018). In Ghana, if a substantial component of the burden of disease from ambient air pollution were also attributed to residential cooking with solid fuels, HAP's total impact would compete with premature birth to be the sixth leading risk factor for adverse health outcomes in the country.

FUTURE SCENARIOS

Two of the methods used in Ghana, the Ghana LEAP-IBC and the UEinfo analyses, offer the opportunity to explore the implications of alternative energy policies on

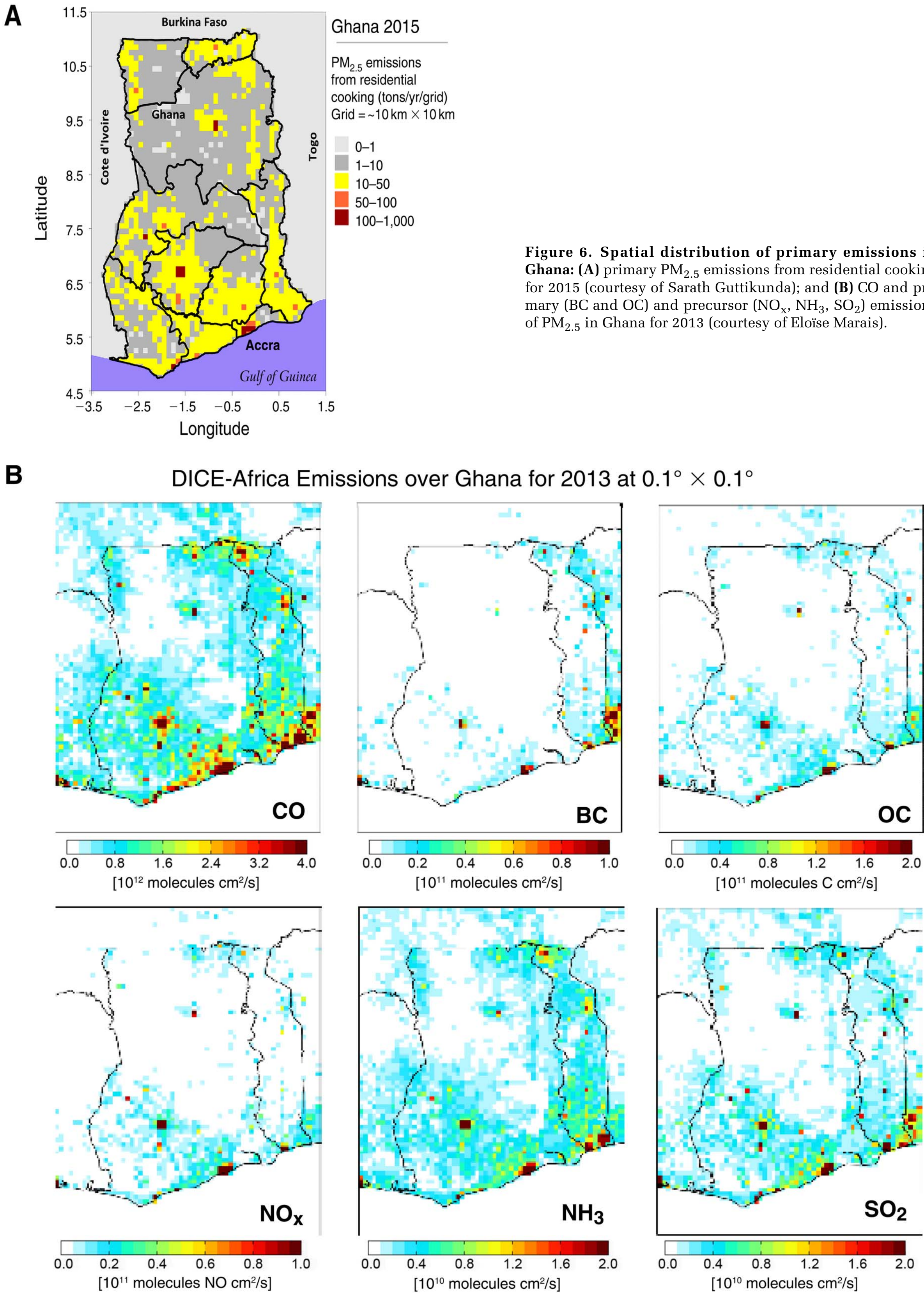

Figure 6. Spatial distribution of primary emissions in Ghana: (A) primary $PM_{2.5}$ emissions from residential cooking for 2015 (courtesy of Sarath Guttikunda); and **(B)** CO and primary (BC and OC) and precursor (NO_X, NH_3, SO_2) emissions of $PM_{2.5}$ in Ghana for 2013 (courtesy of Eloïse Marais).

Table 4. Source Contribution Estimates for Ambient $PM_{2.5}$ Based on Top-Down Studies[a]

Study	Location	Year(s)	Results
Aboh et al. 2009	Greater Accra region	February 2006–February 2007	Excluded from discussions since it does not include specific fractional contributions to ambient $PM_{2.5}$.
Ofosu et al. 2012	Ashaiman	February 2008–August 2008	*Fractional Source Contribution (%)* Fresh sea salt (16); Aged sea salt (6.2); **Biomass combustion (9.5);** Industry (11); Soil dust (18); Two-stroke engines (5.1); Diesel emissions (18); Gasoline emissions (16)
Ofosu et al. 2013	North Ghana	February 2009–February 2010	*Mean Source Contribution (μg/m³)* Soil dust: 12.3 (35.9%); Resuspended road dust: 5.5 (16%); **Biomass: 5.4 (15.8%)**; Two-stroke engines: 3.4 (9.9%); Gasoline combustion: 3.7 (10.9%); Diesel combustion: 3.9 (11.5%)
Zhou et al. 2013	Accra	September 2007–August 2008	**Fresh biomass burning: 10.6–21.3 (μg/m³)** for $PM_{2.5}$ Sea salt: 2–13.9 (μg/m³) (~25% at one site) for $PM_{2.5}$ and 6.4–27.5 (μg/m³) in PM_{10} (14%–30%) Crustal: 9.5–10.5 (μg/m³); 17%–38% for $PM_{2.5}$ and 16%–46% for PM_{10} Solid waste burning, road dust & vehicles, aged biomass particles. Specific numbers not cited.
Zhou et al. 2014	Accra[b]	November 2006–August 2007	Ambient **Biomass burning (fresh smoke + aged particles): 7–37 (μg/m³) (15%–42%)** Crustal dust: 29%–39% Other Results are available for cooking-area PM, but aren't discussed here.
Piedrahita et al. 2017	North Ghana	November 2013–September 2014	**Biomass combustion (including local wood burning);** dust; regional biomass burning; vehicular emissions (including evaporative emissions)

[a] Biomass combustion is **bolded**.

[b] The study included other sites outside Ghana, but those are not listed here for brevity.

emissions, ambient air quality, and health. To date, the most complete work has been done by the Ghana LEAP-IBC analysis as part of the development of Ghana's National Short-lived Climate Pollutant Action Plan. The Ghana LEAP-IBC analysis predicted that air pollution would get worse under a *business-as-usual* analysis, with in-country emissions nearly doubling from 14% to 23% in 2040. Primary $PM_{2.5}$ emissions from the residential sector could also double from 60 kilotons in 2010 to 110 kilotons in 2040, with consequences for increased air pollution and public health burden. Under a scenario that assumed greater penetration of improved cookstoves and 50% of households cooking with LPG by 2050, the number of deaths attributable to ambient $PM_{2.5}$ was estimated to decline substantially (the health burden from HAP exposure was not quantified in the Ghana LEAP-IBC analysis).

In comparison, according to an International Energy Agency (IEA) analysis, under the current regime, $PM_{2.5}$ emissions are expected to grow by nearly 20% by 2040 given the increasing energy demand over the next few decades (IEA 2016). Improvements in electricity access and provision of LPG as a cooking fuel would help reduce the emissions associated with residential energy use.

ONGOING WORK IN GHANA

A variety of initiatives are currently under way in Ghana and other African countries that can pave the way for better estimates for air quality as well as for source apportionment. Key projects are listed below:

- *Air quality monitoring and top-down source apportionment*: Air quality monitoring sites in Ghana were established in the early 2000s with support from the U.S. Environmental Protection Agency, the U.S. Agency for International Development, and the United National Environmental Program as part of the Air Quality Management Capacity Building project. The sites have been running since then; currently there are 14 sites in and around Accra. However, the data are not publicly available and must be purchased from the Ghana EPA.

  With sponsorship of the World Bank and in collaboration with the Ghana EPA, air quality monitoring and source apportionment studies in the Greater Accra Region are expected to commence in early 2019. Source profiles are being developed for cooking emissions (with biomass, charcoal, and LPG), waste burning, kerosene lighting, and back-up diesel generators. These profiles will be utilized for undertaking the receptor-modeling studies in the future. Expert Panel members Dr. Michael Hannigan and Dr. Allison Hughes are involved in this project.
- *Urban LEAP-IBC application in Accra*: The Stockholm Environment Institute, Ghana EPA, and the Ghana EC are currently extending the LEAP-IBC analysis in Ghana to the urban scale (0.25° × 0.31°). This involves developing an emissions inventory for Accra that is separate from the rest of the country, with the aim of evaluating the effect of Accra's draft air quality management plan on air quality in the city. The urban IBC module for Accra will use coefficients from GEOS-Chem Adjoint, run at a much finer resolution than the national scale analysis. The smaller geographic scale will facilitate comparison of the modeling results with the monitoring data that are collected in Accra by the Ghana EPA. The project is expected to be completed in the spring of 2019
- *REACCTING* (Research on Emissions, Air quality, Climate, and Cooking Technologies in Northern Ghana): As part of the REACCTING project, emission factors (PM mass/fuel unit burned) have been estimated for a number of sources. These include cooking (with biomass, charcoal, and LPG), trash burning, kerosene lighting, and back-up diesel generators.
- *DACCIWA* (The Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa): This project is quantifying the influence of anthropogenic and natural emissions on the atmospheric composition over southern West Africa and assessing their impacts on human and ecosystem health and on agricultural productivity.
- *HEI GBD MAPS Global*: This project is undertaking a worldwide estimation of sectoral source contributions to air pollution and the associated impacts on national disease burden for all 195 countries included in the GBD project. It is designed to provide consistent baseline estimates of HAP and other source contributions to ambient air pollution in individual countries across the world.

DISCUSSION

KEY SOURCES OF $PM_{2.5}$ IN GHANA

Ghana now has a range of results stemming from different methodologies whose evidence consistently points toward HAP as an important source of ambient air pollution, particularly in rural areas where rates of reliance on solid fuels is extremely high. Although comparing results from top-down and bottom-up methodologies in this context is difficult because of differences in the scale of the assessments (local vs. national or regional), it is clear that household solid fuel use is a significant contribution to the ambient $PM_{2.5}$ and to the health burden associated with such exposures.

However, gaps remain with respect to a comprehensive understanding of the role of solid fuel use in different contexts. In many low- and middle-income countries, solid fuels are also used for open community cooking or by roadside vendors and hawkers. In such instances, how should such sources and "household air pollution" be differentiated, and how should the role of HAP as a source of ambient air pollution be interpreted? Also, in areas with limited energy access, household solid fuel use for cooking–heating–lighting might be closely linked, and at least with top-down methods, such assessment is not feasible.

DATA LIMITATIONS

A common theme that emerges across top-down and bottom-up approaches is the limited availability of data related to air pollution (including emissions and ground air quality) across the SSA region. While Ghana is relatively rich in terms of data and studies compared with other countries in the region, the emissions inventories are limited, particularly in rural areas. Detailed activity data for the country may not be in the public domain, may not be accurate, or may be incomplete. For example, country-level activity factor data are available from the United Nations energy statistics database, but the metadata required for indicating the accuracy, completeness, and collection methodologies are limited. Assumptions and estimates made in the absence of data can further increase uncertainties in the results. For some of the sources, detailed emissions factor data for relevant precursor pollutants are not currently available (e.g., in the case of kerosene, emission factors are available for OC, BC, and CO but not for NMVOCs). Several key sources in Africa (e.g., electronic waste burning) are missing from global inventories. Specific gaps in the context of Ghana include the lack of data on electronic waste burning (both activity and emission factor data), installed diesel or gasoline generator capacity, diesel and gasoline use, and quality of fuel for vehicles and generators. Finally, the quality and resolution of the emissions inventory can determine the type and quality of subsequent analyses when using the bottom-up approach.

Marais and Wiedinmyer (2016) have also highlighted that different studies have reported different emissions trends. For example, while the differences are relatively small for BC, they are substantial for OC, CO, and NMVOCs. Models utilizing the different emissions estimates can produce vastly different results for $PM_{2.5}$ concentrations and source contributions (Figure 7).

As discussed earlier, accurate emissions inventories are critical for bottom-up modeling efforts. Recent studies in the region, including DICE-Africa are helping to build databases for pollution emissions in Africa. As part of ongoing projects, REACCTING and DACCIWA emission factors have been generated for sources including solid fuel combustion (charcoal and wood), waste combustion (open burning of waste), charcoal production, and vehicles (Coffey et al. 2017; Keita et al. 2018). Such datasets are expected to provide a more accurate determination of key sources for PM in African countries. For the development of emissions inventories, it is also critical to leverage regional efforts and develop plans that are practically feasible. This idea is also bolstered by the fact that despite multiple studies pointing toward the significant regional contributions, there are limited regional inventories.

Key sources of uncertainty in the case of receptor models include source profiles (and interpretation of source contributors), while uncertainties in emissions estimates (i.e., emission inventories) are the largest contributor to total uncertainties in bottom-up models. Some of these issues are only beginning to be addressed in Ghana. Looking beyond Ghana, it is reasonable to assume that corresponding data many not even be available for other African countries.

RESEARCH AND TECHNICAL CAPACITY

Cost

Approximate costs for executing a top-down study depend on the scale of the study and whether or not laboratory facilities need to be established. Overall, such a study can be an expensive endeavor. The instruments alone cost between $20,000 and $250,000, and there are additional costs for operations, maintenance, and staffing. Overall, it is reasonable to assume that a relatively good study would require at least $125,000 to $150,000 and could be completed in 1.5–2 years.

The determination of costs for bottom-up studies includes a variety of considerations including scale (grid size), whether or not to use primary surveys, and availability of computation facilities. Development of emissions inventories primarily requires computation power ($1,000–$3,000 with recurring costs for cloud-based services) and trained technical staff. In some cases, additional efforts such as field surveys and access to paid databases might be required, which can add to the costs. However, some methodologies, such as those developed as part of DICE-Africa, are scalable in theory and can be applied to other countries including South Africa, Nigeria, Rwanda, and Kenya. Such analyses can typically be completed in 1–1.5 years.

Technical Capacity

Both top-down and bottom-up analyses require technical expertise. Staff running such programs need to be well trained and, in some cases, experienced in handling and interpreting such data.

Research Priorities

As has been noted above, progress is being made in terms of improving data, but challenges remain. Key research priorities include:

- *Development of accurate emissions inventories*: It is critical to develop accurate activity factors (number of

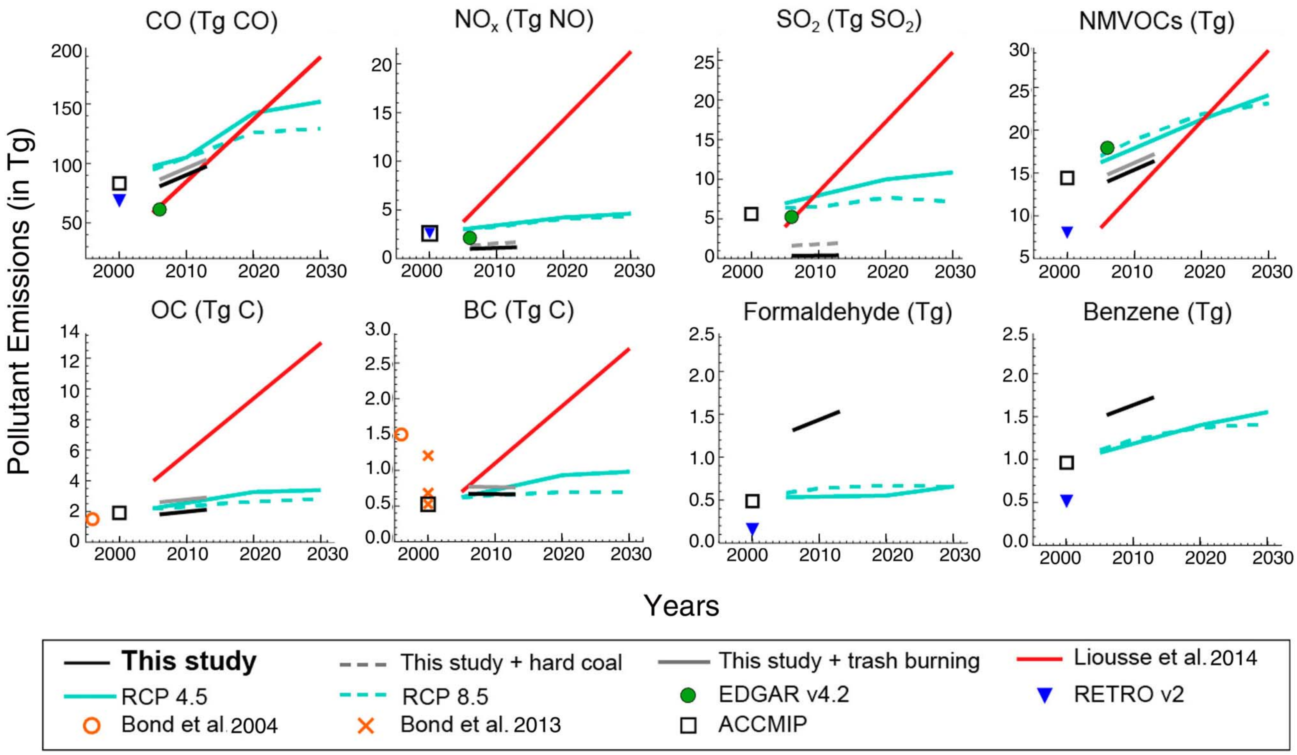

Figure 7. Comparison of emissions estimates for Africa. RCP = Representative Concentration Pathways; RETRO = REanalysis of the TROpospheric chemical composition over the past 40 years; ACCMIP = Atmospheric Chemistry and Climate Model Intercomparison Project. (Adapted from Marais and Wiedinmyer 2016. Copyright 2016 American Chemical Society.)

vehicles including motorcycles, types of vehicles, quality of vehicles, quality of fuel, number and capacity of generators and the fuel used) for developing emission inventories. Activity factors should be reported at a finer scale than the country level (county, province, or municipal area) to improve spatial mapping of emissions. This, in turn, can help reduce uncertainties in model estimates for $PM_{2.5}$ concentrations and sources.

- *Locally relevant emission factors*: Emission factors need to be developed locally, and the measurements need to address all $PM_{2.5}$ precursor pollutants (e.g., for kerosene use, only CO, OC, and BC emission factors are available).
- *Improvement in ground-based monitoring data*: There is an urgent need to augment ground-based air quality measurements and increase access to data, both for analytical and validation purposes.

APPLICABILITY IN OTHER GEOGRAPHIES

Ghana is currently undertaking several initiatives on air pollution and climate change. However, for countries and regions at an earlier stage in this process, Ghana's experience holds important lessons:

- In countries where no data currently exist, existing global assessments (e.g., Chafe et al. 2014; Lelieveld et al. 2015; Weagle et al. 2018) or assessments under development (e.g., HEI GBD MAPS Global) can be a good starting point for understanding and communicating the importance of residential energy contributions to ambient $PM_{2.5}$.
- Modeling tools like LEAP-IBC, which is currently being used in more than 30 countries, can be effectively used to develop local technical capabilities for building local emissions inventories that can be iteratively improved. Such tools can also be used to explore the implications of specific policies for air quality and health.
- In the long term, availability of ground-based measurement data and detailed source emissions inventories can lead to more detailed analyses of specific source contributions and the associated health burden.

Across all types of programs, collaboration with international scientists and organizations can leverage local scientific and government resources to improve the evidence base and build capacity in the long run. Although the local context needs to be considered for any of these activities, it is reasonable to assume that some of the fundamental challenges will be similar. In most cases, the investment in a comprehensive emissions inventory, together with a robust air quality monitoring network, should be seen as the first step in strengthening the local evidence base.

CONCLUSIONS AND RECOMMENDATIONS

Opportunities exist to apply both top-down and bottom-up methodologies to help identify the most cost- and health-effective clean energy interventions for HAP. Both top-down and bottom-up methods can be used for source apportionment and air quality management; however, both involve a substantial investment in equipment, technology, and human resources that can vary based on the scope and scale of the analysis. Targeted investments in enhanced monitoring and emissions data, coupled with refined bottom-up analyses, have the potential to capture the benefits of clean energy interventions and to motivate positive and sustained action, particularly in settings like Ghana where limited air quality data are available.

What Are the Opportunities to Spur Action on HAP and to Improve Estimates of Household Air Pollution's Contribution to Ambient Air Pollution and Burden?

1. Communicating the Importance of HAP as a Contributor to Ambient Air Pollution in Ghana. The current global and national evidence reviewed in this Communication point to HAP from residential fuel use as an important contributor both to total $PM_{2.5}$ emissions and to ambient $PM_{2.5}$ concentrations.

In the near term, this evidence creates an opportunity for strategic communications of the results in Ghana, bolstered with additional policy and/or economic analyses, in order to influence policy action on household energy. Strategies to address HAP have two scales of broad benefit — directly to households relying on solid fuels and indirectly to others who would benefit from improved ambient air quality.

Key stakeholders to be addressed fall into two categories: (1) policy makers focused on improving ambient air quality and (2) policy makers involved in the development and implementation of the national energy plan. Other stakeholders, including academics and civil society groups can also be targeted for briefings to build broader support for the issue.

Key messages include:

- HAP is the seventh biggest risk factor for health burden — it contributed to 9,780 deaths in Ghana in 2017.
- Residential energy use is the biggest driver for $PM_{2.5}$ emissions and is among the most modifiable risk factors. Policies to address this source will have significant benefits for air quality and public health.
- Top-down studies in the Greater Accra region indicate a significant contribution of biomass combustion to outdoor air pollution (15%–42%), including household solid fuel use.
- Overall, provision of LPG for cooking and improving access to clean energy can help reduce air pollution.
- Air quality management plans in Accra (and, more broadly, in Ghana) need to include considerations for residential solid fuel use.

This may also be an opportune time to assess public perceptions and media coverage of air pollution, its leading sources, and resulting health effects. If public perceptions and media coverage are not well correlated with the available evidence base, there may be a need to increase public awareness of the issues. The political will to promote clean household energy is likely to be dependent on a public demand for better air quality.

2. Support for Sustained Development and Improvement of Emissions Inventories for Ghana and the West African Region. Development and improvement of comprehensive inventories of emissions sources, both within countries and regionally throughout western SSA, are essential for characterizing sources and their impacts on air quality, health, and climate. All of the bottom-up analyses described in this analysis show that the accuracy, completeness, and comparability of the methods' findings depend in larger measure on the critical foundation of emissions and activity data.

In particular, there is a need for local, detailed emissions inventories focusing on key sources, including household energy use, at a fine spatial scale.

3. Support for an Expanded Air Quality Monitoring Program in Ghana. Air quality monitoring is a critical component of national and regional air quality management programs. Representative monitoring networks provide reliable information to track air quality and the effectiveness of interventions over time; they can also be used for validation and evaluation of bottom-up methods. Through the ongoing program in the Greater Accra region, Ghana is in the process of expanding its current air quality monitoring infrastructure. Future efforts could focus on expanding monitoring across the country. Detailed guidance is available for countries embarking on establishing or expanding air quality monitoring programs (Awe et al. 2018).

Data from strategically placed ground-based air quality monitoring stations can also be used to improve satellite data-based estimates for air pollutants and to support source apportionment at the national and regional levels. The SPARTAN monitoring network is currently providing data for such analyses globally. It could be expanded in Ghana, given the presence of a necessary NASA AERONET monitoring site north of Accra.

4. Harmonization of Ongoing Efforts and Better Coordination Among Researchers in the Region. While there is an increasing number of studies in Ghana and the region, there has been little or no coordination across programs. There are useful near-term opportunities to leverage existing (and ongoing) work to improve the understanding on source contributions to $PM_{2.5}$ and estimates of the air pollution-related health burden.

Sponsors of all of the efforts should gather and support (and provide resources to) a team of analysts (either from the government or from a private institution) to take the lead in coordinating and harmonizing these efforts. Some of the data gaps are being filled through the projects discussed here (i.e., DICE-Africa, the Ghana LEAP-IBC analysis, and UEinfo), as well as through other analyses. However, a more complete and harmonized assessment — led by an agreed-upon team, in collaboration with the Ghanaian government — is critical in designing national policies. The team's work should also consider steps to build local capacity for long-term sustainability of such efforts.

5. Support for Regional Action. The evidence reviewed for this Communication makes it clear that air pollution in Ghana is part of a regional challenge that will ultimately require regional solutions. Desert dust and pollution from surrounding countries both have substantial impacts on Ghana's air quality. Regional (western SSA) approaches to developing emissions inventories and ground-level monitoring systems may provide better value for the money than focusing on city- or country-specific analyses in Ghana alone. Such efforts would benefit from cooperation across countries in the region; Ghana could act as an anchor for a coordinated regional assessment of air pollution sources.

How Could Expanding Other Approaches in Ghana Better Inform and Motivate Action?

More comprehensive country-specific bottom-up modeling approaches can provide more realistic estimates of source contributions and analysis of the impact of policy alternatives. The GBD MAPS studies conducted in China and India (GBD MAPS Working Group 2016, 2018), and similar studies elsewhere, rely on more detailed atmospheric chemistry and meteorology as well as more geographic detail on the origins and impacts of sources on air quality and health. Like the LEAP-IBC tool, these approaches can be used to model and explore alternative energy and pollution-control scenarios, and they are very useful for both policy planning and evaluation. However, the quality of the results is dependent in large part on the quality of the detailed emissions inventories described in point 2 of the previous section.

From the Ghana experience, it now seems clear that a more consistent and coordinated approach to building technical and resource capacity at the local and national level is not only possible, but preferable for supporting data-driven policy action on household energy use. Ultimately, such efforts cannot be successful without addressing the longer-term needs for technical and financial capacity development to sustain effective in-country programs.

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ABBREVIATIONS AND OTHER TERMS

AOD	aerosol optical depth
BC	black carbon
CAMx	Comprehensive Air Quality Model with Extensions
CO	carbon monoxide
CTM	chemical transport model
DACCIWA	the Dynamics-Aerosol-Chemistry-Cloud Interactions in West Africa
DICE-Africa	Diffuse and Inefficient Combustion Emissions in Africa
EDGAR	Emissions Database for Global Atmospheric Research
EDXRF	energy dispersive x-ray fluorescence
GBD	Global Burden of Disease
GBD MAPS	Global Burden of Disease from Major Air Pollution Sources
Ghana EC	Ghana Energy Commission
Ghana EPA	Ghana Environmental Protection Agency
GHG	greenhouse gas
HAP	household air pollution
HTAP	hemispheric transport of air pollution
IEA	International Energy Agency
IER	integrated exposure–response
LEAP-IBC	Long-range Energy Alternatives Planning-Integrated Benefits Calculator
LPG	liquefied petroleum gas
MAIA	multi-angle imagers for aerosols
NASA	National Aeronautics and Space Administration
NH_3	ammonia
NMVOC	nonmethane volatile organic compound
NO_x	nitrogen oxides
OC	organic carbon
PM	particulate matter
$PM_{2.5}$	fine particulate matter (particulate matter ≤2.5 µm in aerodynamic diameter)
PM_{10}	particulate matter ≤10 µm in aerodynamic diameter
PMF	positive matrix factorization
REACCTING	Research on Emissions, Air Quality, Climate, and Cooking Technologies in Northern Ghana
SIM-air	Simple Interactive Models for better air quality
SLCP	short-lived climate pollutant
SPARTAN	Surface PARTiculate mAtter Network
SO_2	sulfur dioxide
SSA	sub-Saharan Africa
TROPOMI	TROPOspheric Monitoring Instrument
UEinfo	Urban Emissions
VOC	volatile organic compound
WHO	World Health Organization
WRF	Weather Research and Forecasting

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