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Highlighting Uncertainty and Recommendations for Improvement of Black Carbon Biomass Fuel-Based Emission Inventories in the Indo-Gangetic Plain Region

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Abstract Black carbon (BC) is a major contributor to hydrological cycle change and glacial retreat within the Indo-Gangetic Plain (IGP) and surrounding region. However, significant variability exists for estimates of BC regional concentration. Existing inventories within the IGP suffer from limited representation of rural sources, reliance on idealized point source estimates (e.g., utilization of emission factors or fuel-use estimates for cooking along with demographic information), and difficulty in distinguishing sources. Inventory development utilizes two approaches, termed top down and bottom up, which rely on various sources including transport models, emission factors, and remote sensing applications. Large discrepancies exist for BC source attribution throughout the IGP depending on the approach utilized. Cooking with biomass fuels, a major contributor to BC production has great source apportionment variability. Areas requiring attention tied to research of cookstove and biomass fuel use that have been recognized to improve emission inventory estimates include emission factors, particulate matter speciation, and better quantification of regional/economic sectors. However, limited attention has been given towards understanding ambient small-scale spatial variation of BC between cooking and non-cooking periods in low-resource environments. Understanding the indoor to outdoor relationship of BC emissions due to cooking at a local level is a top priority to improve emission inventories as many health and climate applications rely upon utilization of accurate emission inventories.

Keywords Biomass fuel · Black carbon · Cookstove · Emissions · Indo-Gangetic Plain · Inventories · Ventilation

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Introduction

Approximately half of the world's population utilizes biomass fuels including wood, dried animal manure, crop residues, and charcoal for cooking or heating, most of which are in developing nations [1–3]. The extensive worldwide use of traditional open-fire biomass cookstoves is cause for concern due to the high particulate matter concentrations produced within the home [4–6]. A substantial body of literature has linked indoor air pollution from biomass fuels to several chronic illnesses including ischemic heart disease, chronic obstructive pulmonary disease (COPD), lung cancer, and acute lower respiratory infections (ALRI) [1, 3, 7–11, 12•, 13]. The World Health Organization estimated in 2012 that 4.3 million premature deaths occur worldwide annually as a result of exposure to indoor air pollution created by biomass fuels during cooking [11, 14, 15].

Increase in ambient air pollution associated with biomass burning can result in additional health effects as well as impacting climate change. A significant portion of the particulate matter generated from cooking with biomass fuels is comprised of black carbon, a climate change agent, which is produced during incomplete combustion [16••, 17, 18]. In addition to residential biomass fuels used for cooking and heating, other sources of black carbon include power plants, industrial facilities, cars, and trucks, as well as forest and wild fires [18]. Black carbon alters the environment by directly heating surfaces due to deposition resulting in changes in surface albedo (i.e., decreasing surface reflectivity) and contributing to the accelerated melting of Arctic sea and land ice, glaciers, and seasonal snow covers [19]. Recent studies have estimated that black carbon is the second or third largest overall contributor to global warming, surpassed only by CO_2 and methane [19, 20]. The production of black carbon from the burning of biomass fuels is a major contributor to climate change [18]. However, black carbon has a much shorter residence time relative to greenhouse gases; thus, mitigating sources of black carbon is an attractive target for producing significant results quickly in the efforts to combat climate change [19, 21].

Focusing on the Indo-Gangetic Plain

Of the total global annual black carbon emissions, ~20 % are believed to be a result of biomass burning during cookstove use [22]. In South Asia, biomass cooking alone is believed to contribute about two thirds of black carbon emissions [23]. An area identified as a regional hotspot for production of black carbon emissions from biomass fuel use is the Indo-Gangetic Plain (Fig. 1) [19]. In this region, black carbon entering the atmosphere and its subsequent deposition on glaciers and snow pack is thought to be a significant contributor to the changing climate [25].

The Indo-Gangetic Plain, covering 255 million hectares (630 million acres) that encompasses most of northern and eastern India, is one of the most densely populated regions in the world. Its inhabitants, comprised of people across South and East Asia, are reliant upon the annual glacial and snow pack melt from the surrounding mountains in the Himalayan-Hindu Kush region as a source of fresh water and contributor to the overall hydrological, or precipitation, cycle [16••, 19, 26]. However, these glaciers along with the annual snow pack are experiencing an accelerated retreat and are threatening the water supply for this region [26, 27]. While greenhouse gases play a role in contributing to the glacial retreat, the pace of the retreat indicate that other factors beyond just greenhouse gases (e.g., black carbon deposition) are contributing to this changing climate [26]. Within the Himalayas, it has been estimated that black carbon is responsible for as much as 50 % of the total glacial retreat observed to date [23]. In addition to the diminishing presence of glaciers and snow pack, changes to the cyclical seasonal patterns in South Asia are becoming more evident. For example, alterations in intense precipitation events and deviation of monsoons from typical periods illustrate these changes [16••, 25, 28]. This instability is threatening the livelihoods of nearly one billion people, including farmers who rely on this fertile land to feed a considerable segment of the global population [17, 29].

Changes in cookstove technology have been proposed to reduce emissions in order to reduce deforestation, improve efficiency, and mitigate the consequences to health and climate. Organizations such as the Global Alliance for Clean Cookstoves of the United Nations Foundation, working in partnership with other agencies, governments, and the private sector, have invested significant resources to replace traditional, open-design cookstoves with new, alternative stove technology [30–32]. Alternative stoves are designed to reduce the amount of household air pollution and fuel consumption, increase thermal efficiency, and/or redirect particulate matter to the exterior environment via the use of a chimney. The potential for increase in particulate matter emitted outdoors to exacerbate climate change by increasing the amount of black carbon released to the atmosphere is receiving less attention than the potential for improved health associated with reduced household air pollution (Grieshop, Personal Correspondence). Assessing the impact of current and alternative cooking technologies on climate change will require accurate emission inventories for both particulate matter and black carbon. This paper gives an overview of how emission inventories are generated for cookstove-related black carbon in ambient air. Furthermore, we highlight uncertainty in the approaches utilized as well as give recommendations on research priorities that are receiving insufficient attention yet are integral to improving emission inventories in the Indo-Gangetic Plain region.

Emission Inventories: Development and Uncertainty

Climate change models concerned with particulate matter and black carbon fate and transport in the Indo-Gangetic Plain rely on emission inventories that have been generated via several methods, including estimates based upon emission factors developed in laboratories, demographic data including population and fuel-use estimates, remote sensing applications, and source-receptor apportionment models reliant upon measurements (e.g., atmospheric or ice core samples) [22, 25, 26, 33]. Most inventories that assign black carbon emissions originating from indoor biomass use are based upon some variant of

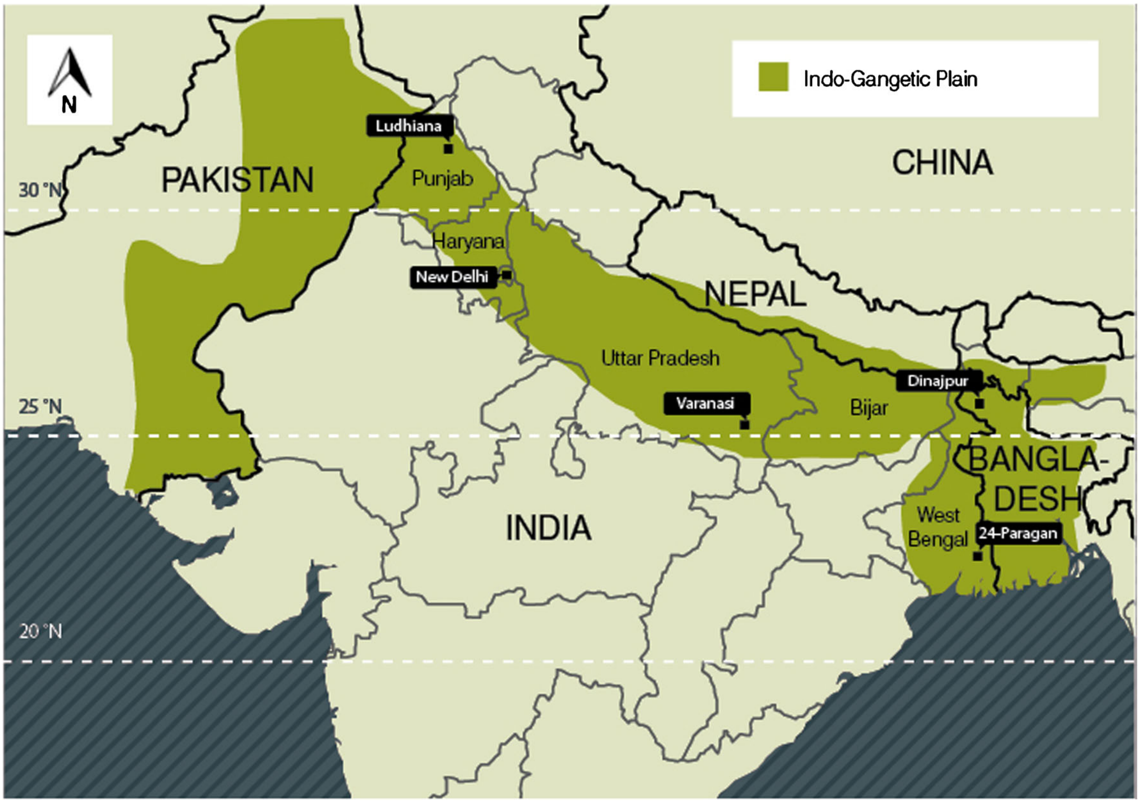

Fig. 1 *Shaded area* indicates location of Indo-Gangetic Plain region (source: [24])

source apportionment models, controlled lab or field experiments, satellite imagery analysis, and theoretical calculations [20, 26, 34]. Due to the lack of in situ data, two issues that exist are (1) emission estimate profiles for particulate matter and black carbon are subject to large uncertainty and (2) related but independent is that the models created are not validated with in situ data. Subsequently, this results in climate change prediction models having considerable variability [25]. Significant inconsistency exists for published black carbon emissions in the Indo-Gangetic Plain, with regional scale emissions having two- to fivefold uncertainty [16••, 25, 35]. In addition to the presence of uncertainty in the accuracy between model emission inventory projections and actual emissions, precision between models is also impacted due to the lack of in situ data.

Determination of cookstove-related emission inventories in the Indo-Gangetic Plain for particulate matter and black carbon utilize two main methods that can be classified as either being top down or bottom up approaches [36•, 37], illustrated in Fig. 2. Bottom up approaches utilize findings from published estimates (i.e., emission factors, concentration, etc.) for particulate matter or black carbon generated from various types of fuel and cookstove use along with demographic information to characterize the amount of these pollutants that are in the atmosphere. Specific to the Indo-Gangetic Plain, substantial findings have been published characterizing particulate matter emissions from fuel sources and cookstove types in this region [7, 12•, 16••, 38–45]. Several emission inventory estimates have utilized cookstove particulate matter emission factor estimates (e.g., mass of particulate matter produced per mass of fuel used) to generate outdoor air concentration projections in this region [22, 34, 37, 46••, 47, 48]. These emission inventory estimates can be inaccurate due to a variety of factors including utilization of emission factors developed in a lab-based setting or ignoring the barrier of the house itself, which could limit the amount of emissions emitted into the atmosphere [49••]. In contrast, the top down method uses outdoor pollution source-receptor apportionment models, possibly integrating remote sensing, ambient, and other regional measurements, to generate cookstove related particulate matter and/or black carbon emission inventories. Several groups have developed black carbon emission inventory estimates utilizing top down methods for the Indo-Gangetic Plain region [25, 37, 48, 50–56].

Noticeable discrepancies exist with respect to determining the origin of black carbon emissions using these two approaches [57]. For instance, one report highlighted that top down approaches indicate that biomass fuels are the main source of black carbon emissions in this region with fossil fuels accounting for 10–30 % of black carbon emissions; in contrast, bottom up approaches indicate that fossil fuels comprise 50–90 %

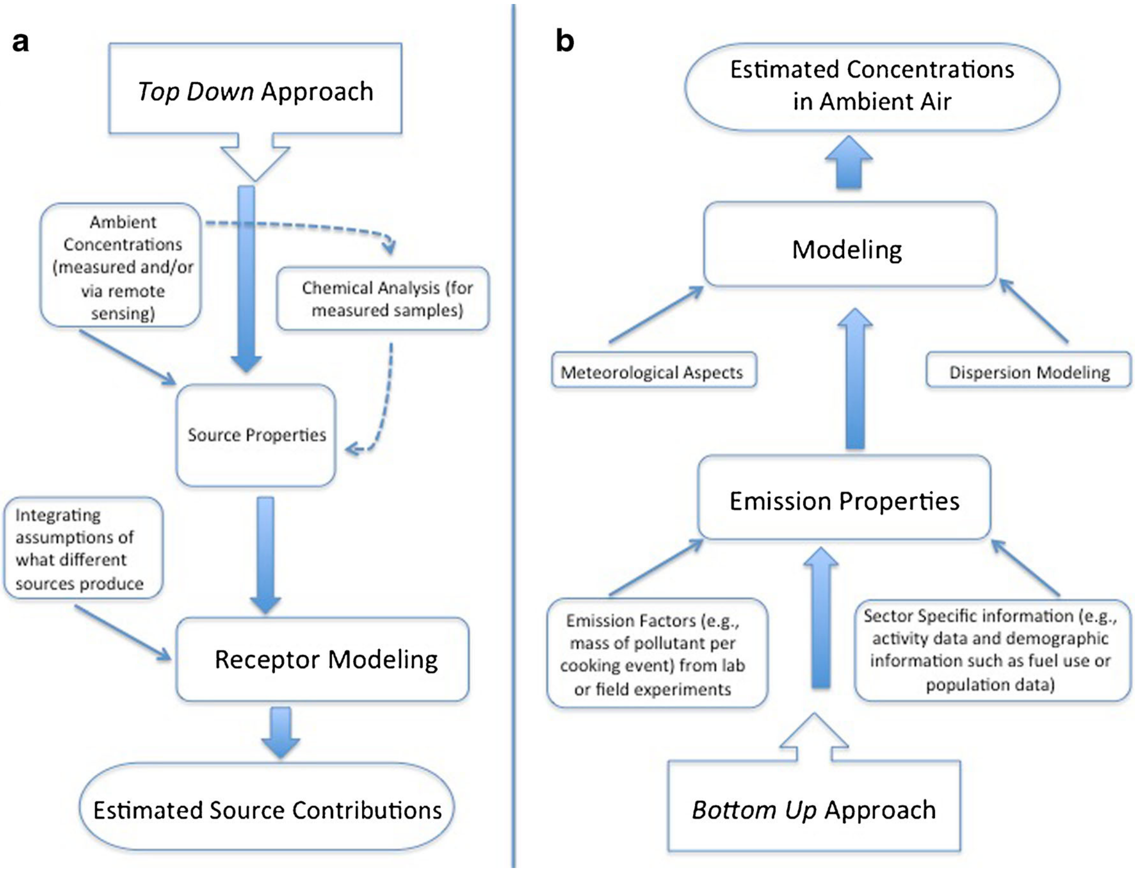

Fig. 2 Approaches to emission inventory development. Methods are **a** top down and **b** bottom up

of black carbon emissions with the remainder from biomass and other sources [57]. Both top down and bottom up approaches do not typically incorporate an understanding of the indoor to outdoor relationship with respect to what is expelled into the atmosphere during cooking vs. non-cooking events. Specifically, village homes act as a barrier limiting the amount of emissions that are released into the atmosphere [49••], thus developing a more robust understanding of the relationship between indoor to outdoor black carbon emissions due to biomass combustion use is essential to resolving these discrepancies. However, limited field-based estimates exist examining this relationship particularly at the village or local scale [16••, 58]. A recent study conducted in northern India found a diurnal pattern of ambient black carbon concentration that coincided with indoor biomass cooking during the morning and evening meal preparation periods (shown in Fig. 3) [16••]. Figure 3a, b shows the changing black carbon concentrations over a 24-h period for indoor and outdoor measurements, respectively. Figure 3c highlights how indoor black carbon emissions (in red) increase during cooking periods and how outdoor black carbon concentrations (in blue) at village level elevate during the same periods. While this study found an association demonstrating the indoor to outdoor relationship, it utilized a single outdoor air sampler to represent black carbon concentration across a large area, limiting the study's ability to understand small-scale spatial variation. Improving the understanding of small-scale variation is important because it will allow for better characterization of cookstove biomass-related emissions and lay the groundwork for improving existing methods used for emission profile generation, such as remote sensing applications.

Future Direction

Accurate black carbon emissions estimates created by the use of biomass fuels in cookstoves are needed to allow agencies and organizations to properly assess the impact of black carbon production, between traditional and alternative cookstoves. Understanding this impact will allow for resources to be allocated in a more reliable, effective, and efficient manner with respect to cost, human health, and mitigating climate change. Furthermore, understanding the contribution cookstoves play in the creation of these emissions, specifically

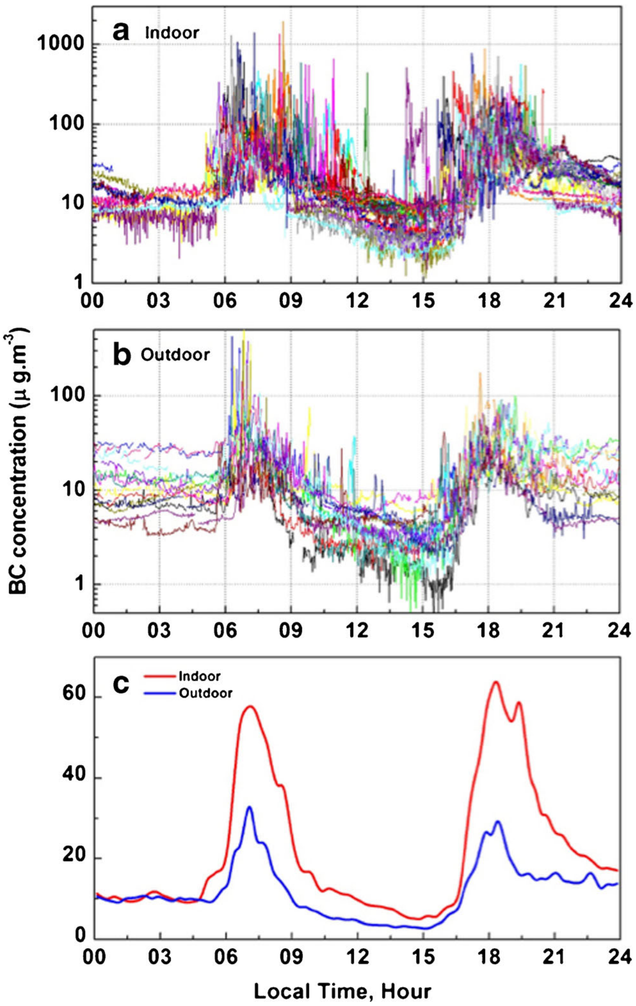

Fig. 3 Diurnal pattern of black carbon concentration for a study conducted in a rural Indian village (*a*) indoors for 26 homes, (*b*) outdoors at a central village location, and (*c*) comparison between multiple homes indoors (*red*) and one central location outdoors (*blue*) (republished with permission from Dr. Rehman from: Rehman IH, Ahmed T, Praveen PS, et al. Black carbon emissions from biomass and fossil fuels in rural India. Atmos Chem Phys Discuss. 2011 Apr 7;11:10845–74) [16••]

from data collected in situ, is critical towards obtaining accurate estimates and improving emission profiles overall.

Research Opportunities and Recommendation

Many areas requiring additional focus have been acknowledged and repeatedly highlighted to improve emission inventories, such as developing more robust estimates around emission factors for different stove-fuel combinations, improving speciation of emitted particulate matter, and better quantification and attribution to regions and economic sectors where formal monitoring may not exist [20, 59]. Current projections of black carbon emission inventories in ambient air produced by biomass fuels are also limited by their understanding of the fraction of black carbon that exits the home during cooking, affecting local air quality and subsequently being transported to climate sensitive regions. Limited studies have sought to establish exfiltration estimates in this region [46••, 49••], making it another key area that must be addressed to improve the understanding between indoor to outdoor emissions in this region. In addition, attention should also be given to the need to assess, in situ, the indoor to outdoor relationship during cooking and non-cooking events at a local level. In particular, conducting concurrent sampling indoors and outdoors with a high spatial resolution within village and rural areas is integral to improving the characterization between indoor and outdoor particulate matter and black carbon emissions attributable to household cooking. Assessing indoor to outdoor relationships for pollution has been extensively studied in industrialized countries [60–66]. This understanding, combined with studies conducted in various low-income countries [16••, 58], can inform future field-based work with regard to sampling design, data collection, and analysis in the Indo-Gangetic Plain region. In addition, identifying and measuring other factors that could contribute to the overall emissions and thus act as potential confounders is also worth emphasizing, such as meteorological conditions (e.g., wind speed or direction), traffic patterns, point sources emanating from industrial sites, and ventilation of village homes. Characterization at a local scale will ultimately allow for better prediction of cookstove biomass-related emissions at locations not sampled, particularly in underrepresented rural areas. Developing a better understanding of ambient particulate matter and black carbon concentration characterization during periods of cooking and non-cooking at a local, small-scale level is essential to improving emission inventory profiles that are utilized in many climate change applications.

Conclusion

Improving black carbon emission inventories is needed to assess the impact of current and future cooking practices in the developing world. Several areas have been highlighted as requiring additional research and refinement to improve upon black carbon emission inventories attributable to cooking with biomass fuels. Our recommendation, highlighting the need to improve upon the characterization between indoor and outdoor emissions during cooking and non-cooking periods at a local village-scale level, should also become a research priority, as this will have direct implications to the improvement upon these emission inventories. Ultimately, having accurate emission inventories, particularly in the Indo-Gangetic Plain, is critical to many health and climate applications.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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- •• Of major importance

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