WHO Indoor Air Quality Guidelines: Household Fuel Combustion

Review 5: Population levels of household air pollution and exposures

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Summary

Background

Emissions from household fuel use affect indoor concentrations of pollutants as well as escape to the outdoors. Their impact on health, however, is most closely linked to the exposures they cause. While a number of studies provide empirical information on such exposures to household air pollution (HAP), this information has not been systematically integrated. This review provides a comprehensive review of the evidence for HAP exposures across all WHO regions while also describing methods and technologies used for HAP exposure assessment.

Objective and key questions

The aim of this review was to assess population levels of HAP and exposure. The following key questions were defined:

1. What are some of the key features of the HAP exposure setting?
2. What are some common methods and technologies used for estimating HAP concentrations or exposures?
3. How do selected household level determinants such as type of fuel or location of stove affect levels of HAP exposure are experienced by household members?
4. How do the pooled estimates of exposure from studies reviewed compare to pollutant specific WHO Air Quality Guidelines (AQGs)?

Methods

A systematic search for articles indexed in PubMed, Web of Science and Bioscience (Article indexes) using keywords and MeSH terms using PRISMA[1] guidelines, was mounted to revise an earlier version of a WHO global database on indoor air pollution (developed in 2003) with studies through 2011 (now termed as the Revised WHO Global HAP Database). In addition, recent reviews of studies conducted in developed countries were also identified. While all studies in the database were included to describe the HAP exposure setting and methods/technologies used for measurement, additional selection criteria were applied for studies used to generate pooled estimates. A total of 161 articles were selected from over 6800 citations, for inclusion in the database. The additional criteria that included specifications for pollutants, averaging time and quality assurance identified 46 PM studies and 27 studies for CO exposures. Pooled estimates were generated using the disaggregated arithmetic means and standard deviations (or 95% confidence intervals around the mean) provided by the studies

Findings

The pooled mean and pooled SD for 24-hr kitchen area concentrations of $PM_{2.5}$ in solid fuel using households are estimated to be 972 $\mu g/m^3$ (SD 876 $\mu g/m^3$) as compared to 148 $\mu g/m^3$ (SD 56 $\mu g/m^3$), in households using gas, electricity or kerosene as primary fuels. The corresponding 24-hr personal exposures in solid fuel using households are estimated to be 267 $\mu g/m^3$ (SD 297 $\mu g/m^3$) and 219 $\mu g/m^3$ for women and children respectively, with exposures in gas/electricity using households being comparable to the kitchen area concentrations. The pooled mean and pooled SD for 24-hr kitchen CO concentrations amongst solid fuel users are estimated to be

[1] PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses. See: http://www.prisma-statement.org/

8.60 ppm (SD 6.21ppm) while personal exposures are estimated to be 3.63 ppm and 2.69 ppm for women and children respectively. Estimates of concentrations and exposures for other PM fractions and CO across multiple fuel, stove and household configurations have also been generated. A small number of studies that provide highly resolved spatio-temporal information and/or exposure models have also been included in the evidence summary

Conclusions

This review provides a comprehensive description of the nature and magnitude of HAP exposures across all WHO regions. There is considerable variability in methods used by studies to measure area concentrations and/or exposures. Despite the uncertainty introduced while pooling across studies, **the evidence for high or extreme exposures in solid fuel using households in developing countries is unequivocal,** where people are exposed indoors and outdoors. The levels of exposure associated with solid fuel use in developed counties are much lower, although the use of solid fuels for heating can be a major source of ambient air pollution.

There are important gaps in the existing exposure evidence base. Considerable additional information is needed for example, to understand the drivers of the variability within solid fuel using households and the associated implications for fuel, stove or behavioural interventions. By quantifying the extent to which different cookstove and fuel interventions impact exposures, the available health-based pollutant specific AQGs may be used as a benchmark to develop technology or practice based guidelines to minimize risks from HAP to public health.

1. Introduction

Emissions from household fuel use affect indoor concentrations of pollutants as well as escape to the outdoors. Their impact on health, however, is most closely linked to the exposures they cause, which is a function of the pollutant levels experienced over time by the general population as well as by susceptible subgroups (such as young children, pregnant women, and the elderly). Exposure assessment is thus an essential part of assessing the impact of household air pollution (HAP) on health. It is also a critical component for risk management, which involves identifying ways to reduce people's exposure through the use of cleaner fuels, improved combustion stove technologies or behavioural interventions.

This review assesses evidence on exposure to HAP from empirical air pollution measurement studies conducted across WHO regions. While most studies describe the exposure situation in rural household settings of developing countries, a few also address urban settings and/or rural areas in developed countries. We provide a brief overview of measurement methodologies and the nature of exposure determinants together with summaries of measurement results from studies in both settings. In addition, we provide pooled estimates from studies in developing countries for household concentrations and personal exposures for $PM_{2.5}$ and CO (the most commonly measured indicator pollutants), in relation to the WHO interim and guideline values for air quality.

2. Methods

2.1 Definition of issues addressed in the review

A number of framing questions have been set out for this review in order to summarize the available evidence on population levels of household air pollution and exposures, and these include:

1. What are some of the key features of the HAP exposure setting?
2. What are some common methods and technologies used for estimating HAP concentrations or exposures?
3. How do selected household level determinants such as type of fuel or location of stove affect levels of HAP exposure are experienced by household members?
4. How do the pooled estimates of exposure from studies reviewed compare to pollutant specific WHO Air Quality Guidelines (AQGs)?

This review provides a descriptive summary of levels of air pollution and exposure, and was not deemed suitable for meta-analysis or GEPHI assessment.

GRADE domains were used to assess the overall quality of evidence. The summary estimates (accompanied by a thorough description of how information has been obtained, reviewed and pooled) are intended to provide context for Review 6 (Intervention impacts on HAP and exposure) where they are used to perform a comparative analysis across intervention options that seek to reduce HAP exposures.

2.2 Search Terms and Databases

Well over a hundred studies over the last three decades have assessed household air pollution exposures in developing countries. However, merging results from individual studies has been challenging because of differences in measurement protocols, types of summary measures reported, the types/ nature of household level determinants explored and quality control criteria used for sampling/analysis. To overcome this challenge a global indoor air pollution (IAP) database, was first prepared in 2003, that documented the results of these measurements from 70 studies from developing countries of Asia, Latin America and Africa *(1)* with a subsequent version that included 110 studies primarily from China *(2)*. The database, developed using Microsoft Access® 2000, allows researchers to extract and analyze findings within and across studies, and export the files to a statistical program for more in-depth analysis. Articles are abstracted in consistent and simple ways studies so that data across studies could be used to generate profiles that represent larger geographical regions within and outside a country.

Over the last several years, however there has been a continuous evolution of methods and protocols for assessing HAP *(3)*. The quantum and quality of information collected has also become considerably more detailed. Results from large-scale studies (conducted over hundreds of households under multiple exposure configurations) that examine temporal, spatial, or multi-pollutant patterns, in addition to day-to-day or seasonal variability in concentrations and exposures have recently become available from many countries. In view of this progress and to inform the WHO HAP-IAQG (Household air pollution- Indoor Air quality Guidelines) process on

the exposure evidence from HAP studies, the earlier version of global IAP database (cited above) was updated to cover studies reported in peer-reviewed literature until 2011. The global IAP database has also been renamed as the Global HAP database to enable inclusion of a broader range of exposure assessment studies within this setting.

The following search terms were used with the PubMed (National Library of Medicine and National Institute of Health) and Science Direct (Elsevier) bibliographic search engines to identify publications for inclusion within the revised global HAP database.

MeSH Terms: [Air Pollution; Indoor]

Key words:

- Rural / Developing Countries/Less Developed countries/ Household/ Domestic/Village
- Solid fuels/ Biomass Combustion/ Bio Fuels/Household combustion/ Household energy
- IAP/Indoor Pollution/ Indoor Air Quality
- Kitchen/Cooking/Stove/Open fire/Improved Cook stove/Wood stove/Bio-mass stove
- Biomass / Wood / Dung / Coal / Agriculture residues/Crop residues/Kerosene/Clean Fuels/LPG
- Concentration / Exposure/Exposure Assessment/Personal
- Exposure/Environmental Exposure/ Particulate Matter/ PM/ Particles/ CO/Carbon monoxide/Volatile Organic Compounds/Sulphur Dioxide/Nitrogen Dioxide/Aromatic hydrocarbons

Further, exposures to household air pollution from solid fuels in developed countries were addressed through recent reviews (and accompanying cross-references) that describe results from quantitative measurements. Developed country studies are currently not included in the global IAP Database.

2.3 Eligibility Criteria

To address questions 1 and 2 all studies (identified through the searches described above) that provided details pertinent to household air pollution exposures in relation to fuel use were included. This allowed the generation of a broad narrative on the exposure situation and a descriptive review of the methods used to generate such information.

To address questions 3 and 4, the following additional screening criteria were applied to articles available in revised Global HAP Database for inclusion in evidence summaries, taking cognizance of the fact the final pollutant specific WHO HAP-IAQGs would be based on what is already included in previous WHO AQGs.

Accordingly, the evidence summary was generated from studies that**:**

- Measured pollutants included in the WHO outdoor AQG / WHO AQG for specific pollutants
- Reported average concentrations or exposures over a relevant averaging period specified in guidelines (such as 24-hrs for PM_{10}, $PM_{2.5}$ and CO). This is based on the rationale that while many studies report concentrations/exposures over shorter periods such as cooking periods, it would not be possible to link to health effects without

additional epidemiology supporting such a measure of exposure. Since available guidelines specify the health relevant averaging periods, it seemed most appropriate to base the evidence summaries on studies that not only report a relevant pollutant but also the relevant exposure averaging period.

- Provided adequate details of sampling criteria, sampling methods (including specification of sampling devices, flow rates, calibration procedures etc.), analytical methods (including specification of analytical instrumentation, sensitivity and wherever applicable specificity of method), calibration standards and corrections for measurement errors (such as co-locating or calibrating against gravimetric samplers for nephelometric or light-scattering devices used in measuring PM).

2.4 Extraction methods

Information was extracted from each of the included studies to populate data fields created for the revised global HAP database using Microsoft Access® 2010. Data fields are based on the templates created for the previous version of the database [3] and include fields describing the overall study as well as disaggregated information on methods and measurement results for specific pollutants. The revised database may be found in Balakrishnan et al., "Global Household Air Pollution Database: Household concentrations and exposures from cooking fuels" Version 2.0, September 2012, Sri Ramachandra University, University of California Berkeley, World Health Organization.[2]

For generation of a pooled estimate studies that provided the arithmetic mean (AM) and standard deviation(SD) for area concentrations and/or exposures were included (as most studies reported AM and SD, as compared to reporting geometric mean and geometric standard deviation). A pooled estimate for the mean and the SD were generated for PM and CO as follows:

$$\bar{X}_{pooled} = \sum_{i=1}^{n}(N_i \times \bar{x}_i) / \sum_{i=1}^{n} N_i \qquad S_{pooled} = \sum_{i=1}^{n}(N_i - 1)S_i / \sum_{i=1}^{n}(N_i - 1)$$

For studies that provided the 95% confidence interval around the AM, the SD was estimated using:

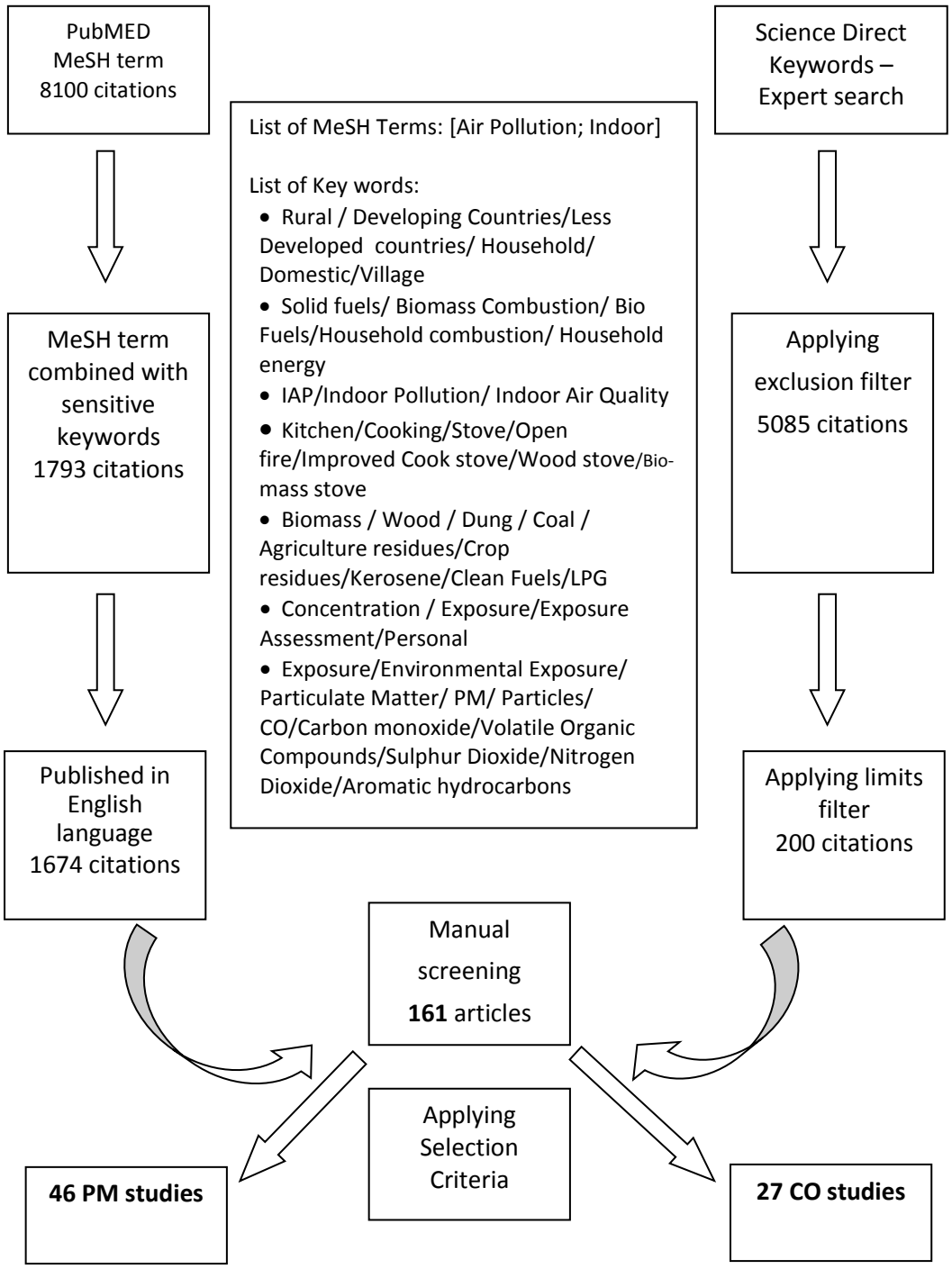
$$SD = \frac{\sqrt{n}(\bar{x} - LCL)}{t_{\alpha/2;n-1}}$$

[2] See the following for details of studies: http://www.who.int/indoorair/health_impacts/databases_iap/en/

2.5 Flow Chart

A flow chart describing the full search process is provided in Figure 1.

Figure 1: Flow chart describing the search process for compilation of the revised Global HAP database and evidence summaries for PM and CO



3. Results

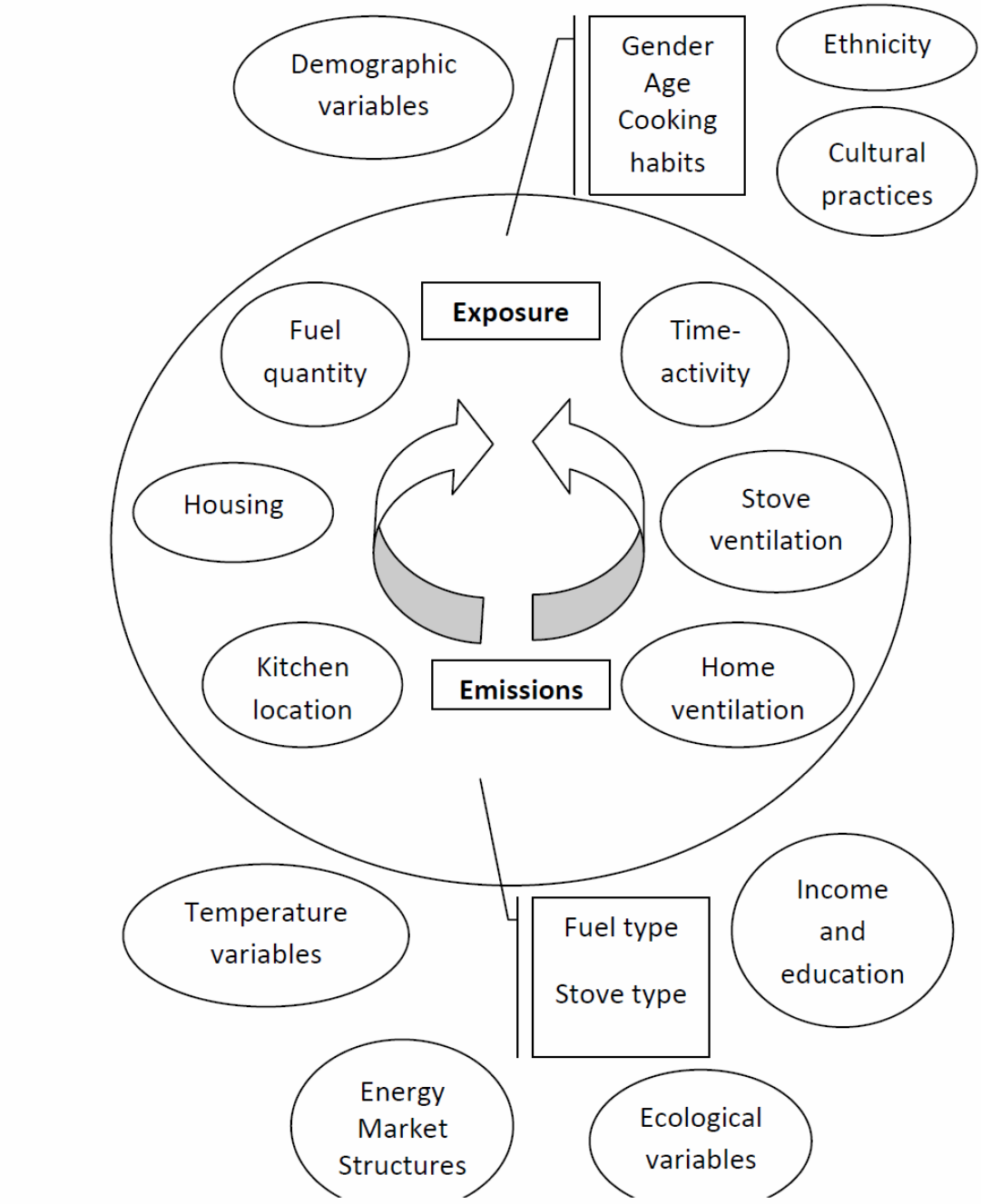
3.1 Household air pollution: a brief description of the exposure setting

Air pollution varies over space and time, and people experience different pollution levels in the various places that they spend time, throughout the day and over a lifetime. As such, exposure is determined by the (i) levels of air pollution in the environments where people spend their time, with a focus on 'microenvironments', which are spaces where pollution levels in the specified time window are assumed to be relatively uniform, or has constant statistical properties and (ii) by the amount of time people spend in these microenvironments.

Despite a rapid increase in urban populations in both developed and developing countries, some of the highest exposures to air pollution continues to be experienced within households in rural areas of developing countries, where the majority of people spend their time *(4)* and (as described in later sections) experience the greatest pollution levels on account of use of household solid fuel for cooking. In these settings, multiple variables have been shown to influence such HAP exposures either directly or indirectly. Some variables such as household income, education, together with energy market structures, socio-cultural preferences and geographical location affect HAP exposures indirectly through their influence on household energy choices. Many household level variables such fuel, stove or meal type together with household layout, family size, fuel quantity, location of cooking and ventilation have been shown to directly influence household concentrations with additional contributions from time–activity profiles of individual household members for personal exposures.

In developed-country settings, most exposures related to household fuel use are attributed to use of solid fuels for heating. The use of solid fuels for heating is dependent upon local energy markets and economies with examples of increased use of these fuels during periods of economic hardship. Further, exposures in these settings are often on account of infiltration of polluted ambient air indoors and are usually less influenced by household level variables. Figure 2 provides a schematic to describe many of these variables that are likely to influence HAP exposures at individual, household or community levels.

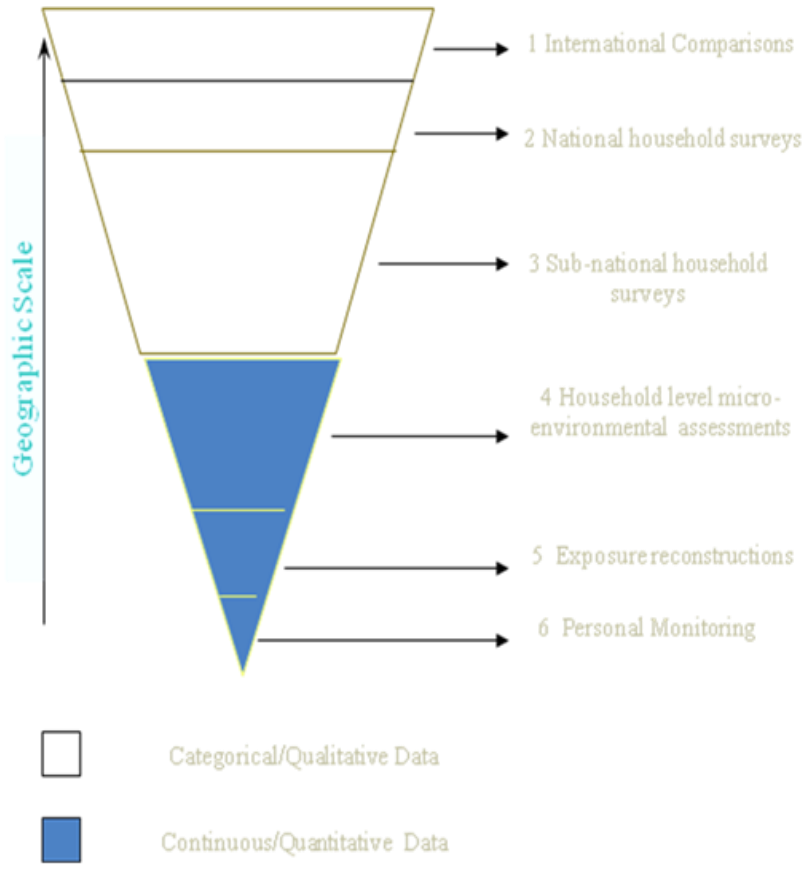
Figure 2: Major categories of variables likely to influence to HAP exposures at individual, household or community levels (adapted from *(5)*) Reproduced with permission



3.2 Exposure assessment methods for household air pollution

Several methods and technologies have been used estimate exposure to household air pollution. In the absence of a regulatory framework in most countries (stipulating for example, a specific protocol for routine monitoring), the choice of the method has been dictated by research needs such as characterization of exposures for a population or landscape, linking exposures with specific health risks, assessing the impact of an intervention, deriving dose-response relationships, or others. In developing-country settings, approaches used to estimate exposure have varied from simple reporting of household fuel use on questionnaires to multi-year monitoring efforts with thousands of direct exposure measurements with methods varying by precision and geographic scale, as well as cost /resource intensity. Since studies in developed-country settings have mostly used routine ambient air quality monitoring methods with only a few examining household-level concentrations, the focus of this section is on the hierarchy of **methods employed by HAP studies conducted in developing countries**. We briefly describe each of these levels shown in Figure 3 (adapted from *(6)*).

Figure 3: The exposure assessment pyramid: a hierarchy of exposure assessment methods used by HAP studies in developing countries with modeling methods straddling across multiple or all levels (adapted from *(6)*) Reproduced with permission



3.2.1 Qualitative exposure assessment through use of questionnaires or survey information

As direct quantitative measurements of HAP exposure are generally limited to a specific project or study area due to the resources and time required, a common approach to making broader estimates of exposure has been to use qualitative indicators as proxies or predictors of exposure levels. Previous burden of disease estimates, for example, have relied on this approach *(7)*. Commonly used indicators include, fuel/stove type, housing type, kitchen type and location, cooking location (indoor/outdoor), and others. The benefit of such an approach is that data on these many of these indicators are often available from census or other large-scale demographic surveys (tier #1; Figure 3), or can be relatively easily obtained with additional simple surveys at modest costs (tiers #2, 3; Figure 3). Conversely, they do not provide information on the ways that different exposure indicators are linked (for e.g. to what extent fuel-use patterns in the community or households may relate to actual air pollution concentrations or exposures).

3.2.2 Micro-environmental monitoring and exposure reconstruction

Air pollution measurement studies with devices set in stationary positions in the house or in the ambient environment (tier #4, Figure 3) afford more accuracy but are much higher in cost as compared to studies using survey based data. Since these studies provide only household concentrations, exposures are reconstructed by using a combination of micro-environmental concentrations measured in locations where the study participant spends most of his/her time (or where significant contributions are expected to come from), and integrating across the time spent in those environments *(8-11)*. This approach allows for more flexibility with monitoring equipment, as it is not worn on the participant, although the placement of the equipment must be carefully selected to represent the exposure of a person in the given environment. A key challenge is obtaining accurate time-activity pattern data, which is commonly gathered via either a questionnaire or a time-activity diary with some recently developed methods which can make quantitative measures of location with data logging motion detectors *(12)*.

3.2.3 Direct measurements of personal exposures

The most direct method for monitoring personal exposure is to use instruments that can be placed on a participant, preferably in the breathing zone (tier #5, Figure 3). Direct measurement of personal exposure is generally considered to provide the most accurate estimate and has been employed in several household energy studies *(13-16)*. Direct measurement can be especially critical for understanding exposure patterns typical of the household energy sector, which are characterized by highly variable contributions from a variety of factors. Direct measurement on individuals however, requires multiple considerations to be addressed. For example, monitoring equipment is restricted to what can be reasonably worn by participants, and there must be extra QA/QC steps taken to track that the monitors are worn. This can be especially difficult for infants, small children, pregnant women or the elderly, for whom only the smallest monitors are feasible and in many cases are not consistently clothed (often affecting passive sampling methods). Another limitation of personal sampling is that monitors may alter behavior and therefore exposure.

Further, in addition to the research question being asked, the estimation of personal exposure must take into account factors that make assessment s in the household setting uniquely

challenging. Populations are often dispersed and sometimes in relatively remote locations, which can complicate the deployment and management of equipment and field teams. The specific populations being studied may require extra care to ensure that cultural and social norms are not violated as part of study protocols (for e.g. how, or if at all, equipment may be worn can depend on what is considered socially acceptable as well as the style of local clothing).

The sources that drive exposure also complicate exposure measurement as they are typically highly variable in their magnitude, duration, and periodicity. Concentrations in a typical kitchen, for example, can vary by orders of magnitude from minute to minute as shown in Figure 4 and Figure 5 *(17, 18)*, as well as spatially across small distances as shown in Figure 6 *(19, 20)*.

Figure 4: Typical CO concentrations in a rural Mexican kitchen, which are characterized by large peak events during cooking (adapted from *(17)*) **Reproduced with permission**

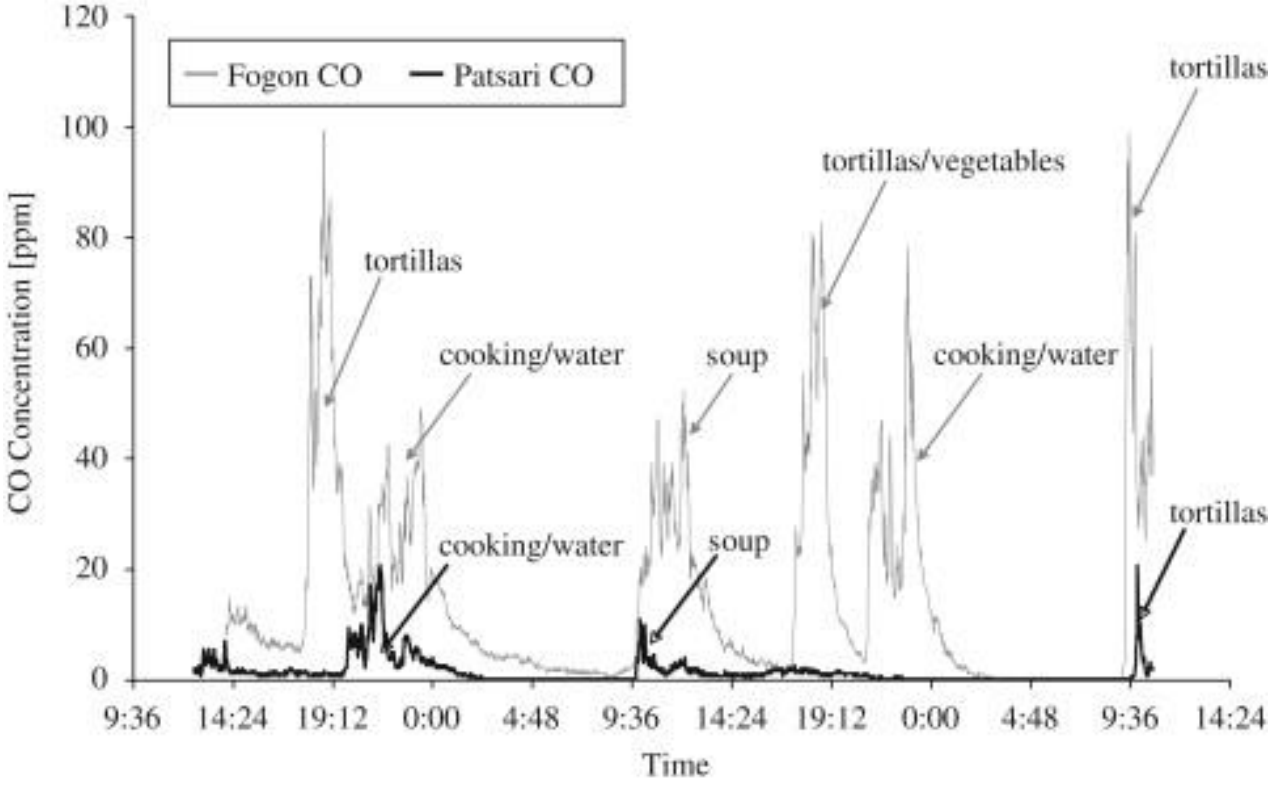
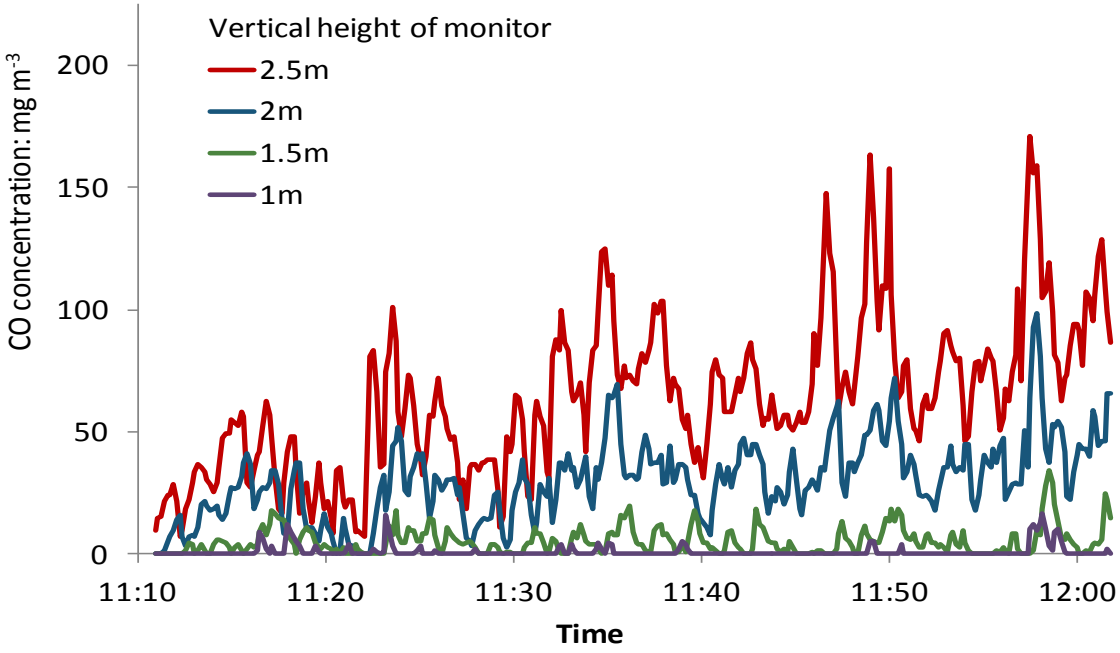
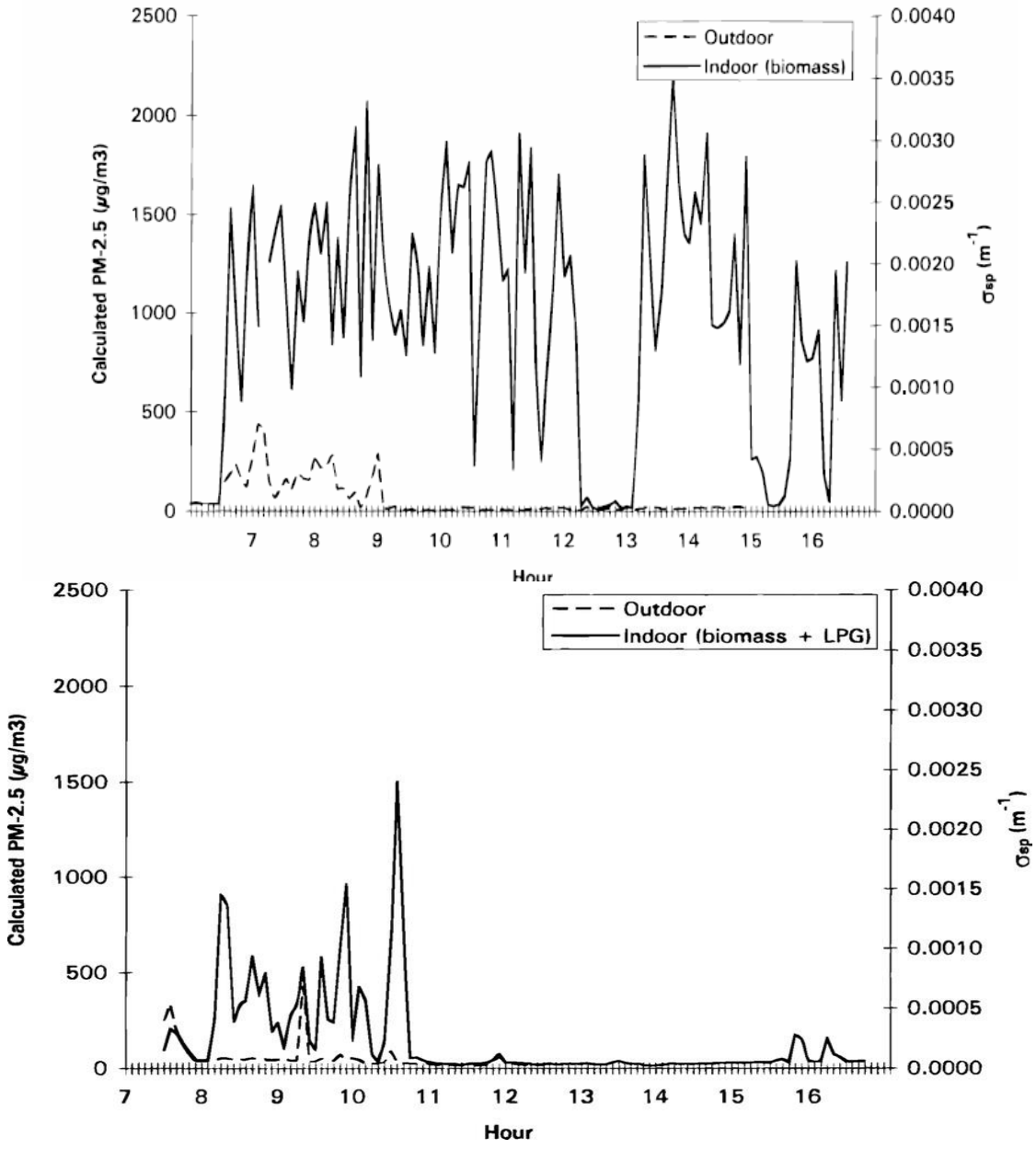


Figure 5: Minute-by-minute concentrations of CO, showing the stratification across four vertical heights in an Indian kitchen during a cooking event (adapted from *(20)*) **Reproduced with permission**



The sources of exposure include not just stoves (often multiple within a home), but also lighting devices such as kerosene wick lamps, neighbor and neighborhood pollution, and in peri-urban areas there are substantial contributions from traffic and industrial sources. Exposure patterns also change over time. Seasonal impacts on fuel type used, food types and availability, and whether stoves are used indoor or outdoor affect exposure patterns. All of these factors impact both the approach that is used to estimate exposure, as well as what can be justifiably inferred from the results of a given exposure study.

Figure 6: Simultaneous particle light scattering extinction coefficients and estimated $PM_{2.5}$ concentrations inside and outside a kitchen with only biomass used for cooking (top panel) and with both biomass (morning meal) and LPG (evening meal) were used for cooking (bottom panel) (adapted from *(21)*) Reproduced with permission



3.2.4 Short- and Long-term exposure assessment

Direct measures of exposure to household air pollution are usually limited to specific time-points, which can provide a reasonable indication for short-term exposure. In such cases where exposure monitoring is limited to single cross-sectional or before/after measurement of a

sample group, the temporal changes in exposure in relation to time-varying exposure determinants (as described in section 3.2.3) may not be adequately addressed and fail to capture representative exposures for the sample or population.

Larger epidemiological studies looking at health impacts of household air pollution often need to rely on long-term exposure assessment with enough direct measurements over sufficiently long time periods together with models to addresses heterogeneity within or between individuals and groups. However, only few such studies have been conducted. In the RESPIRE study in Guatemala *(22)*, over 500 children and 500 mothers were monitored every three months for up to 18 months with passive diffusion CO tubes. McCracken et al *(23)* applied a mixed model approach with this data set, which used both individual short-term exposure measurements and group-level characteristics (e.g. housing characteristics, stove type, altitude) to predict the measured long-term exposure. The mixed model approach demonstrated the need to have longitudinal data on both individual and group level measures to reliably predict long-term exposures. A study in The Gambia *(24)* also reported modeling long-term exposure (1 year), using a mixed-effect approach, and found that adding housing characteristics to individual short-term CO exposure helped models better explain between-child CO exposure variance. For exposure studies related to a specific intervention, the usage patterns of a new technology such as a stove are often complex, changing over time due to behavioral adaptation and physical conditions of the new technology *(25, 26)*. While this dynamic usage of stove technologies makes assessment of impacts more complicated, the usage patterns are clearly critical for understanding a technology's overall impact on long-term personal exposure.

Thus, the timing of a short-term exposure assessment is a critical component of study design and key for understanding the exposure estimates within the broader context of long-term health impacts and the benefits of interventions targeted at HAP exposure reductions. While modeling approaches, specifically those making use of both individual-level measurements and group level characteristics, show promise in providing estimates of long-term exposure, there is a need for the continued development and validation of approaches to estimate long-term exposure for HAP.

3.2.5 Measurement of biomarkers of exposure

Biomarkers of exposure are often considered to be a more reliable measure of absorbed dose (tier# 5, Figure 3), due to inter-individual differences in the translation of exposure to dose that may be caused by factors such as ventilation volume and rate. Personal monitoring and area measurements of environmental markers, typically carbon monoxide (CO) and $PM_{2.5}$, have traditionally been used to assess exposure to solid fuel (primarily biomass) smoke. However, these exposure assessment procedures are subject to limitations. These include the cumbersomeness and inconvenience associated with deploying monitoring equipment, difficulties in obtaining biological samples, storage and preservation of samples, accounting for confounding exposures (e.g. tobacco smoke, diet) and sometimes substantial differences in individual metabolism. Because of these limitations few biomarkers have been assessed with regards to biomass smoke exposure. Biomarkers that have been evaluated can include:

- Exhaled breath CO or blood carboxy- hemoglobin (COHb)
- Urinary hydroxylated polycyclic aromatic hydrocarbons (OH-PAHs), methoxyphenols (MPs), and levoglucosan.

Exhaled CO has been shown to be correlated with environmental CO in high exposure situations *(27)* and can be measured in the field with relatively easy-to-use and inexpensive devices. Similarly blood COHb has been shown to be correlated with exposure reductions accompanying interventions (COHb among 20 subjects fell from a pre-intervention range of 1.1 to 13.9% to a post-intervention range of 0.7 to 1.3% in Mexico *(28)*). Blood COHb can also be measured relatively easily by spectrophotometry. Non-invasive techniques including transcutaneous measurement of COHb are being explored although it remains to be validated *(29)*.

Hydroxylated polycyclic aromatic hydrocarbons (OH-PAHs) are the most used, and seem to show good responses in the exposure settings relevant to the residential combustion of biomass fuel in developing countries *(30, 31)*. However, confounding exposures may bias results since these biomarkers are not unique to biomass smoke exposure or even to the inhalation route. Other sources of PAHs include cigarette smoke, diet and industries. Consequently, the utility of OH-PAHs may be limited except in very high exposure situations.

Methoxyphenols (MPs) are products of the pyrolysis of lignin in wood *(32)*. They are composed of two classes of compounds: the syringols which are more predominant in hardwoods and the guaiacols which are more predominant in softwoods. Consequently, MP composition in urine may be reflective of the type of wood that was combusted*(33)*. Peak excretion of MPs have been reported to occur within 6 hours in an experimental study in which subjects were exposed to wood smoke *(34)*. There are also significant associations between the average 12-hour creatinine adjusted concentrations of MPs with the highest response (ratio of peak MP concentration to background concentration), and air concentrations of $PM_{2.5}$ and levoglucosan, a major organic product of combustion of wood*(35)*. This indicates that some of the MPs or a combination of them may be useful biomarkers of exposure to biomass smoke. However, diet is also a source of MPs in the environment. Further, the utility of MPs in relatively low exposure situations may be limited. A particulate matter exposure of 760 $\mu g/m^3$ has been suggested as a threshold at which MP as a biomarker of acute exposure to wood smoke may become useful. Finally, MPs are applicable to smoke exposures due to wood and coal, and may not be useful for exposures to other smoke due to the combustion of other biomass fuels such as grass and animal waste.

Levoglucosan is a product of the pyrolysis of cellulose during the combustion of vegetation, and *(35)* a major organic constituent of smoke due to biomass burning. Although, results from a smoke exposure study in mice suggest that levoglucosan may be a suitable biomarker of exposure to wood smoke,*(36)* results from human studies were not so promising*(37, 38)*. Exposure in one of the studies was within the range of exposures that has been reported for women who use inefficient cookstoves in indoor environments in developing countries. However, exposure periods in both studies were relatively short. No research has been conducted with levoglucosan for exposures to biomass smoke in the indoor environments where inefficient cookstoves are being used in developing countries. Similar to MPs, diet could be a significant source of levoglucosan. Therefore, it may also be less useful in low exposure situation. Finally, the half-life of levoglucosan in humans has not been reported in the literature.

With exception of breath CO and blood COHb, other biomarkers are thus at a stage of needing additional research before being used routinely in HAP exposure assessment studies (although even CO biomarkers are not widely used in HAP exposure assessment studies).

3.3 Technologies for measuring HAP exposure concentrations

Commonly used technologies reported in HAP exposure assessment are summarized in Table 1. Personal particulate matter (PM) exposures have most often been measured gravimetrically with pump and filter systems, which provide a direct measure of particulate matter and are considered a reference method. The currently available systems are not well-suited for child or infant exposure as they are bulky and cumbersome, and require careful handling, transport, and analysis of the filters. Other studies have reported PM exposures estimated from nephelometers, which are based on detecting light scattered by particles. Nephelometers can be easier to deploy for personal sampling, though in most cases still too large for small children or infants, and can record continuous concentrations, which can be important for understanding the contributions driving average exposure. Nephelometers are sensitive to differences in the optical properties of different aerosols, and thus need to be carefully calibrated against a reference method in the target aerosol to produce accurate concentration estimates. Black carbon concentrations have also been measured, and can be done with relatively simple reflectometry analysis of filters collected for particulate exposure *(39)* and can also be measured continuously with small personal sampling devices (such as with newly developed micro-athelometers) .

Personal exposure measurements of CO have largely been conducted with technologies based on electrochemical cells or diffusion tubes. Electrochemical cell-based monitors are generally small, can log for long durations, and record continuous concentrations. Diffusion tubes, which change color as CO interacts with the chemical in the tube, have been used for some of the largest exposure studies, including for RESPIRE *(40)* and in The Gambia *(24)*. Diffusion tubes are small and require no power, which is why they are well-suited for personal monitoring, even for small children. Their precision is limited, however, as the demarcation of the color change is not distinct, and the cost of deployment can be considerable for large sample sizes as they are a one-time use instrument.

Due to the available monitoring technologies, measurement of personal CO exposure has been more feasible than for PM, especially for small children or infants, and thus has been used as a proxy for PM concentrations given the strong links with respiratory impacts. For example, simple linear models have been used to predict PM with CO by regressing PM measurements against co-located CO measurements in rural Guatemalan kitchens *(41-44)*. The key consideration for these models is that relationships between CO and PM change as a function of the source, and even across the different combustion phases during cooking *(45)*, so care must be taken to ensure that prediction of PM exposure takes into account relevant HAP sources and behavioral patterns.

Table 1: Common technologies for monitoring PM and CO exposure concentrations

Smoke Indicator	Technology	Considerations	Example studies
Particulate matter	Gravimetric system of filters, pumps and PM size cut device (cyclones, impactors) PM concentrations determined by dividing particulate mass deposited on filter by volume of sampled air	-Single integrated measurement for sample duration -Requires careful handling and transportation of filters for massing on sensitive balances -Generally bulky and cumbersome; not typically suitable for children or some sample populations -Battery life can limit sampling durations	*(8, 11, 13, 24, 46, 47)*
	Nephelometers Estimates PM concentrations by detecting light scattered by particles suspended in beam of light source (laser or light emitting diode)	- Sensitivity changes depending on optical properties of aerosol. Requires calibration in target aerosol. -Instruments require calibration and zeroing; zero level scan drift over time - Different nephelometers can be configured to sample actively or passively. Those with active sampling options can use a size-cut device. - Can provide continuous concentration estimates	*(8, 18, 48)*
Carbon Monoxide	Electrochemical sensors Chemical reaction with CO produces a small current, which is converted to a concentration.	- Many options which are relatively inexpensive, lightweight, and consume little power. -Other gases can interfere, and high concentrations of CO can poison cell. - Can provide semi-continuous concentration estimates - Resolution at lower concentrations can be poor.	*(47, 48)*
	Passive diffusion tubes Tube changes color as CO diffuses through chemical in tube.	- Light, small, and require no power. Well suited for infants and children. - Difficult to precisely determine extent of color change. - Single integrated measurement for sample duration	*(47, 49, 50)*

Exposure to other health damaging pollutants, such as PAHs *(51)*, VOCs *(52)*, dioxins *(53)*, and formaldehyde*(54)* have also been reported, but these are much less common, and methods and technologies for these are generally more complex and expensive. A comprehensive listing of methods used by HAP measurement studies may be found in the revised Global HAP database (Balakrishnan et al., "Global Household Air Pollution Database: Household concentrations and exposures from cooking fuels" Version 2.0, September 2012, Sri Ramachandra University, University of California Berkeley, World Health Organization.[3]

3.4 Summary of evidence for particulate matter (PM_{10} and $PM_{2.5}$)

A total of 46 PM studies and 27 CO studies that reported 24-hour averages for concentrations and/or exposures were included for the evidence review. Relatively few studies report measurement results for air toxics including metals, PAH, VOCs and other gases. Further, there are considerable variations in measurement methods and averaging times across the very small number of studies for each pollutant, making it difficult to draw a conclusion. Results from individual studies may be found in the revised Global HAP database cited above. Key findings from the PM and CO studies are summarized below in relation to WHO AQG levels for the respective pollutants.

3.4.1 Micro-environmental area concentrations of PM

The 24-hour kitchen concentrations for PM_{10} and $PM_{2.5}$ measured in households using solid fuels in traditional stoves are consistently (2 to often more than 10 fold) higher than the respective annual average WHO ITG-I levels of 70 μg/m^3 and 35 μg/m^3 (see Figures 7 and 8; and Table 2). The pooled mean and pooled SD for 24-hr kitchen concentrations are estimated to be 882 μg/m^3 (SD 971 μg/m^3) for PM_{10}; 972 μg/m^3 (SD 876 μg/m^3) for $PM_{2.5}$ and 548 μg/m^3 (SD549 μg/m^3) for PM_4.

Only a few studies have performed simultaneous measurements of concentrations in multiple microenvironments. The pooled mean and pooled SD for 24-hr living area concentrations are estimated to be 312 μg/m^3 (SD 521 μg/m^3) for PM_{10}; 228 μg/m^3 (SD 124 μg/m^3) for $PM_{2.5}$ and 395 μg/m^3 (SD 616 μg/m^3) for PM_4. The pooled mean and pooled SD for 24-hr outdoor (near household) area concentrations is estimated to be 111 μg/m^3 (SD 174 μg/m^3) for PM_{10}; 106μg/m^3 (SD79 μg/m^3) for $PM_{2.5}$ and 204 μg/m^3 (SD 246 μg/m^3) for PM_4.

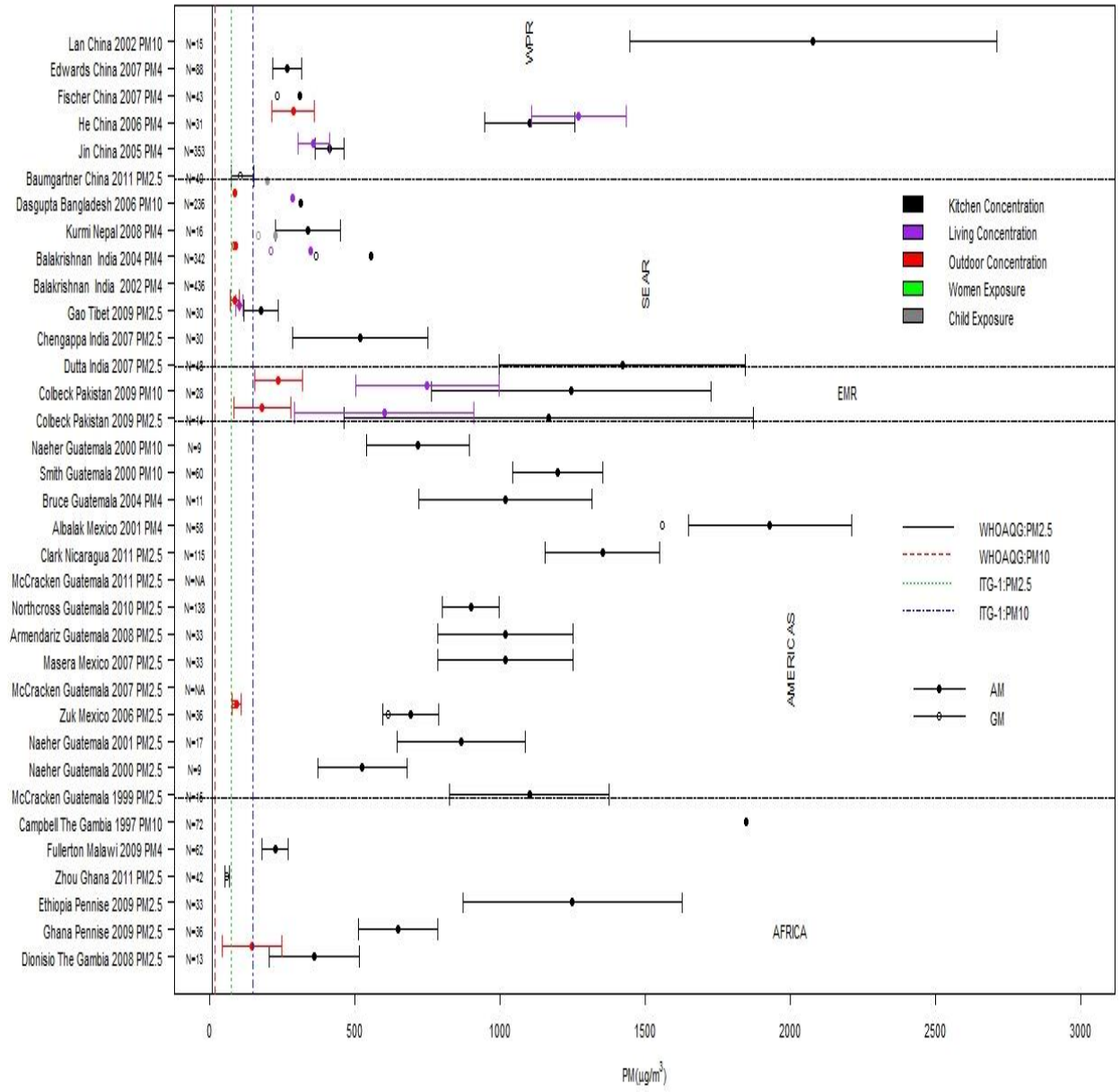
These estimates clearly indicate the substantial contributions of the solid fuel emissions to all household microenvironments including outdoor area concentrations. The ratio of kitchen to living concentrations range from 0.24 to 1.45 with household layout and use of solid fuels for heating playing an important role. The near household outdoor concentrations, although always lower than kitchen (or near the stove) concentrations, are still always higher than the AQGS. Consequently, the role of exchange between the outdoor and indoor microenvironments in influencing area concentrations becomes an important determinant of exposures for all household members. The high outdoor background also becomes a major contributor to HAP in households even in the absence of indoor sources (such as in gas or electricity using households within a community of solid fuel users).

[3] See: http://www.who.int/indoorair/health_impacts/databases_iap/en/

3.4.2 Personal exposures for women, men and children in households using solid fuels in open fire or traditional stoves

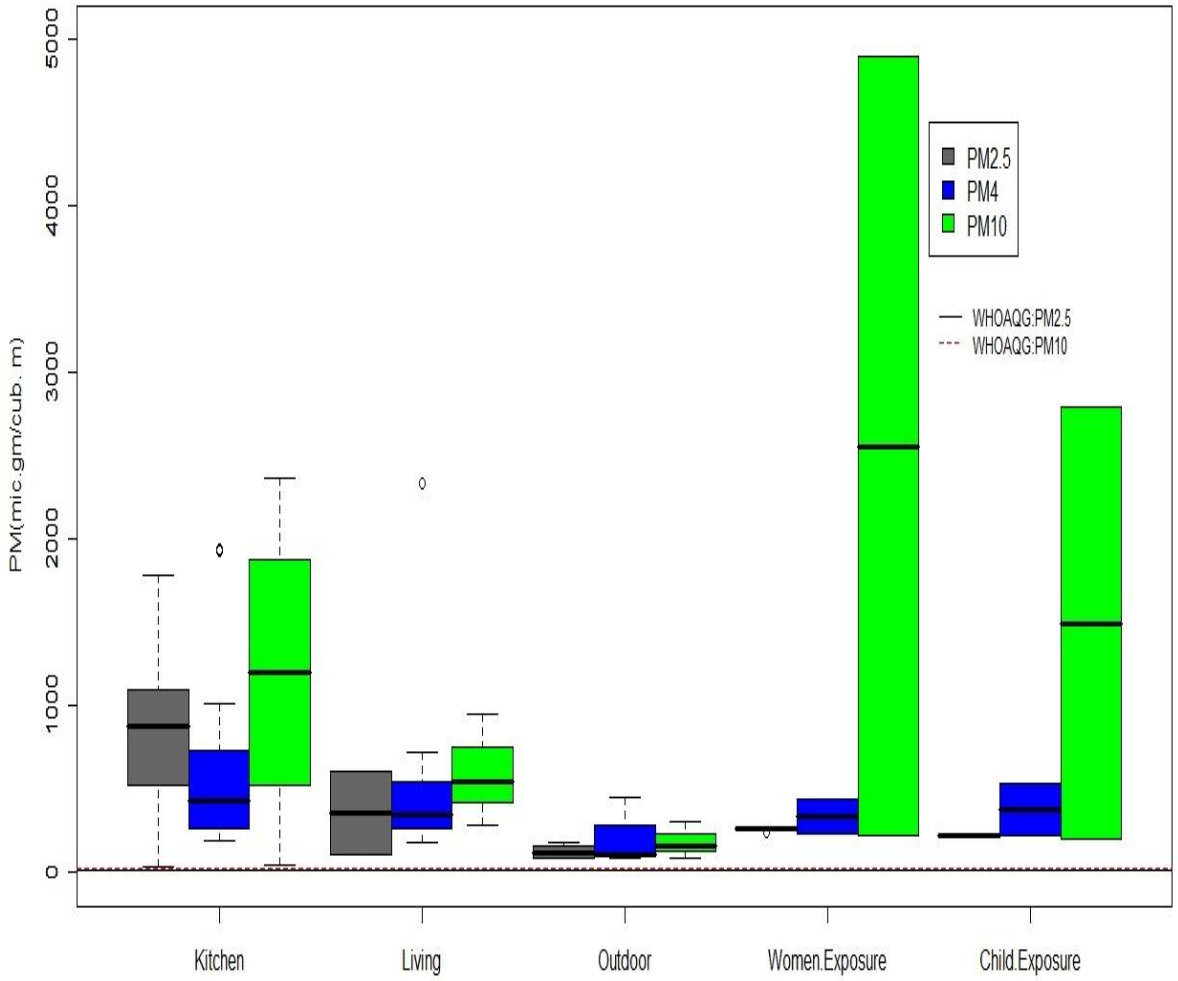
The personal exposures for women, men, infants and children are differently influenced by the complex interaction between multiple household level variables in addition to the respective time-activity profiles. Women and young children who spend a lot of time close to mothers receive some of the highest exposures. The pooled mean and pooled SD for 24-hr exposures for women are estimated to be 1231μg/m^3 (SD 3663 μg/m^3) for PM_{10}; 267μg/m^3 (SD 297 μg/m^3) for $PM_{2.5}$ and 331 μg/m^3 (SD 109 μg/m^3) for PM_4. The pooled mean and pooled SD for 24-hr exposures for children are estimated to be 199μg/m^3 for PM_{10}; 219μg/m^3 for $PM_{2.5}$ and 227μg/m^3 for PM_4. In the few studies that have addressed exposure for men [6,9] and infants [18] results indicate exposure levels to be higher than WHO AQGs (but lower than what has been reported for women in the same study). Ratio of personal exposure to kitchen area concentration for PM in studies that have measured both simultaneously, range from 0.24 to 1.02 for women, 0.39 to 0.84 for children and 0.27 to 0.85 for men. However, relatively little is known about the influence of individual household level determinants on personal exposures to PM over the long-term because of the logistic complexities in being able to perform direct PM exposure measurements.

Figure 7: Reported 24 or 48 hr means and standard deviations for area concentrations and personal exposures for PM amongst households using solid cookfuels in traditional stoves in relation to the annual WHO AQG and ITG levels for PM_{10} and $PM_{2.5}$



Note: PM expressed in µg/m^3. Values shown in figure adapted from: *(8, 9, 11, 13-15, 17, 42, 43, 47, 50, 55-76)*

Figure 8: Box plots showing the distribution of 24-48hr kitchen, living and outdoor area concentrations together with women and child exposure for PM amongst solid fuel using households in relation to the annual WHO AQG and ITG levels for PM_{10} and $PM_{2.5}$



Note: PM expressed in $\mu g/m^3$.The reported measurement results for $PM_{2.5}$, PM_{4} and PM_{10} are from different studies and hence cannot be used to judge the relationship between various size fractions.

3.4.3 Area concentrations and personal exposures for PM in households using kerosene, gas or electricity as primary cooking fuels

In most HAP measurement studies households using kerosene, gas or electricity or some combination of these fuels have often been labeled as “clean fuel” households. Few studies specify the nature of use of these fuels. Some of these households also continue to rely on solid fuels for some of the cooking tasks, during some seasons or periods during a month/ year. Solid fuels may not have been used during the measurement period but the reported levels from such” clean” fuel using households may not be representative of usual exposures.

Despite these uncertainties area concentrations and personal exposures in gas-using households are consistently at or below the ITG-I levels for PM_{10} and usually around ITG-I levels for $PM_{2.5}$. None of the studies reported levels approaching guideline levels for $PM_{2.5}$. In

fact, the outdoor (near household) levels were often higher than indoor levels in gas/electricity using homes, due to high levels of background from neighbourhood emissions (Figure 9).

The pooled mean and pooled SD for 24-hr kitchen concentrations are estimated to be 148 $\mu g/m^3$ (SD 56 $\mu g/m^3$) for $PM_{10;}$ 66 $\mu g/m^3$ (SD37 $\mu g/m^3$) for $PM_{2.5}$ and 65 $\mu g/m^3$ (SD 29 $\mu g/m^3$) for PM_4. Mean 24-hr exposures for women were similar to kitchen area concentrations in gas/electricity using households, still well above the respective WHO air quality guideline levels.

HAP exposures in kerosene-using households are complex with many of these households having made incomplete transitions away from using solid fuels and using a range of kerosene grades with differential implications for PM and other toxicant exposures. The available evidence from a recent review [77] indicate the potential for some very high exposures (Table 2) and argues for careful considerations before kerosene may be labeled as a " clean" or " cleaner" fuel choice in comparison to solid fuels.

Table 2: HAP measurement results from kerosene using households

Location	Microenvironment	Stove Type	Sample Duration	N	PM		CO, mg m^{-3}	NO_2, µg m^{-3}	SO_2, µg m^{-3}	Study
					Size	µg m^{-3}				
Microenvironmental										
India	Center of house	Wick and press.	2–4 h*	20	TSP	520 (220)	157 (113)	184 (150)	121 (0.76)	Raiyani et al. 1993
India	Kitchen (indoor)	NS	12–24 h	61	PM_{10}	480 (336)	—	22 (6.6)	—	Smith et al. 1994
India	Kitchen (outdoor)	NS		61	PM_{10}	340 (204)	2.1 (4.4)	15 (3)	—	
India	Kitchen	NS	6–7 h*	3	TSP	154–1499[b]	—	—	—	Pandit et al. 2001
India	Most occupied room									
(High ambient)	(Indoor)	NS	24–48 h	19	PM_5	706 (465)^	5.3 (3.2)^[a]	—	—	Saksena et al. 2003
(Low ambient)	(Indoor)			19		662 (436)^	2.4 (2.7)^[a]	—	—	
(High ambient)	(Outdoor)			1		1280 (—)	10.3 (—)	—	—	
(Low ambient)	(Outdoor)			1		830 (—)	0 (—)	—	—	
India[b]	Living room	Wick	NS*	1	TSP	590 (—)	—	98 (—)	65 (—)	Kandpal et al. 1995
Personal										
India	NA	NS	12–24 h	30	PM_{10}	530 (318)	7.8 (11.7)	—	—	Smith et al. 1994
Mozambique	NA	NS	~1.5 h*	10	PM_7	760 (270)	—	—	—	Ellegard 1996
India										
(High ambient)	(Indoor)	NS	24 h	19	PM_5	793 (522)^	—	—	—	Saksena et al. 2003
(Low ambient)	(Indoor)			19		679 (474)^	—	—	—	
(High ambient)	(Outdoor)			1		1650 (—)	—	—	—	
(Low ambient)	(Outdoor)			1		450 (—)	—	—	—	
India										
(Crouching)[c]	NA	Wick	NS*	1	TSP	425 (—)	—	65 (—)	48 (—)	Kandpal et al. 1995
(Standing)[c]	NA			1	TSP	825 (—)	—	115 (—)	74 (—)	

Note. Values in table represent the arithmetic mean and standard deviation (in parentheses) during cooking. No study reported kerosene grade. NS, not specified. Symbols: ^Original values reported as geometric mean and geometric standard deviation. Presented are estimates of the arithmetic mean and standard deviation assuming a lognormal distribution of concentrations. *Testing was conducted only during meal preparations.

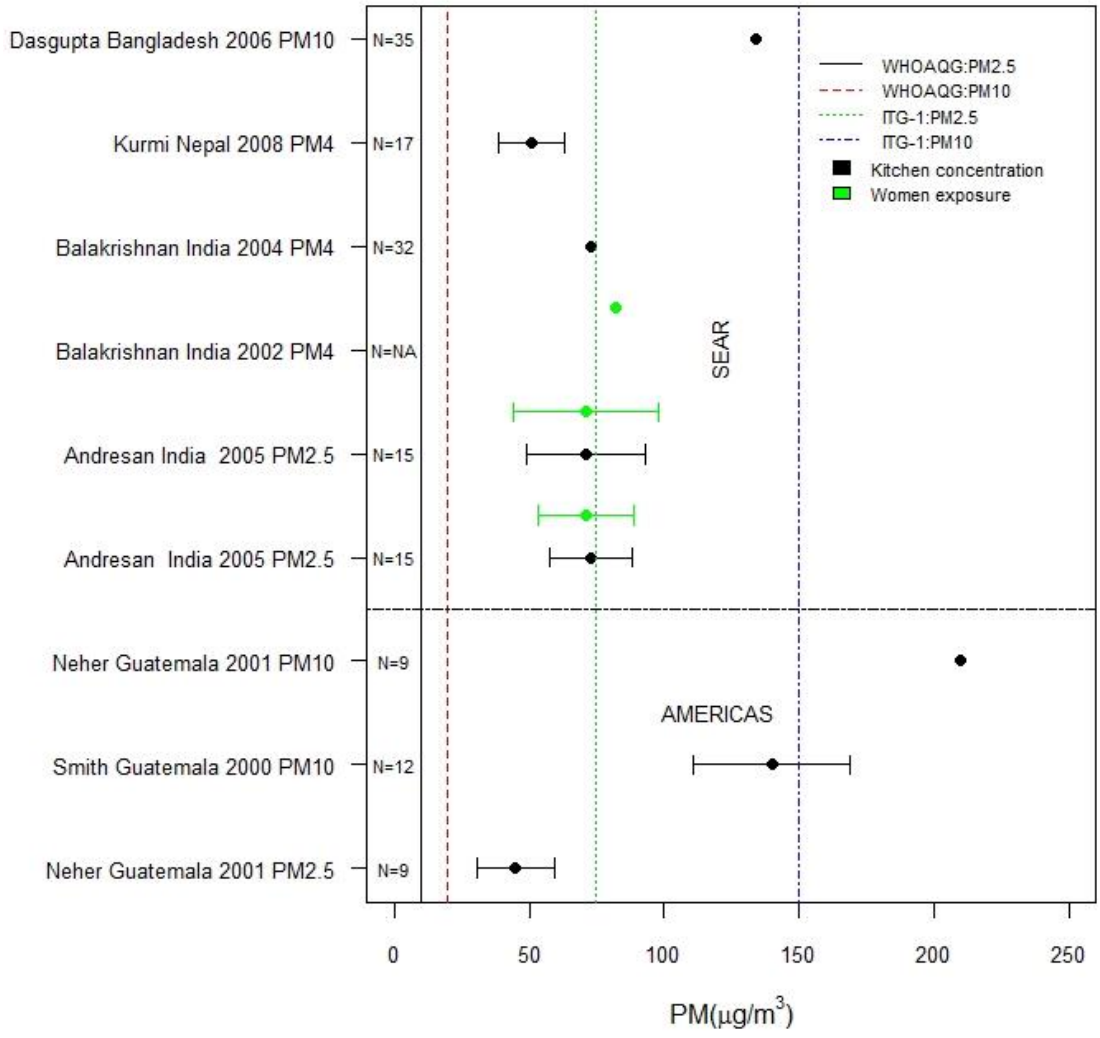
[a]Converted from ppm assuming 25°C, 1 atm pressure.

[b]Reports concentration ranges only.

[c]All experiments conducted in a single test house.

Note: Adapted from *(1, 19, 77-81)*

Figure 9: Reported 24-or 48 hr means and standard deviations for area concentrations and personal exposures for PM amongst gas or mixed (clean) fuel using households in relation to the annual WHO AQG and ITG levels for PM_{10} and $PM_{2.5}$



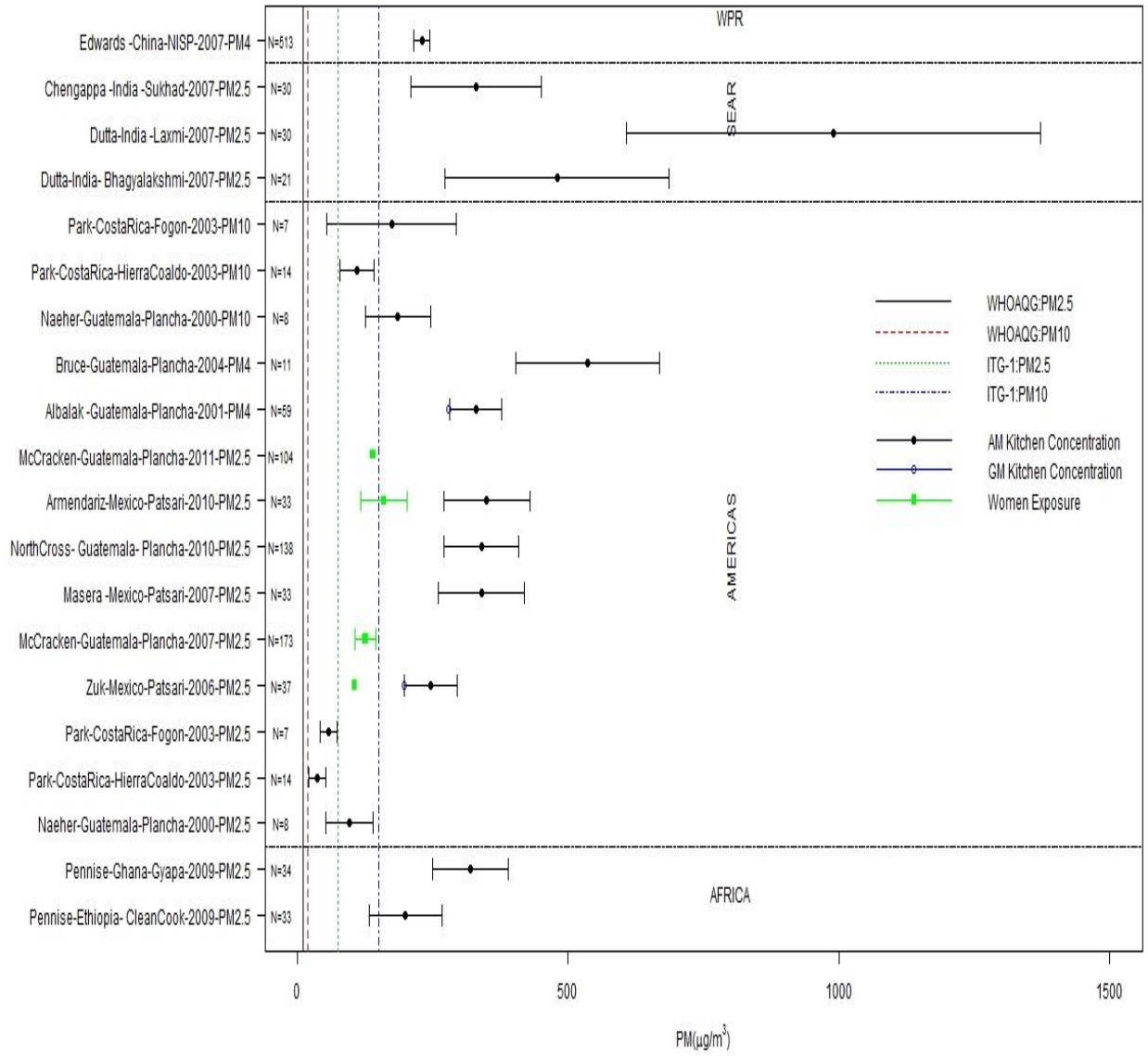
Note: PM expressed in µg/m^3 Values shown in figure adapted from : *(8, 9, 42, 56, 67, 75, 82)*

3.4.4 Area concentrations and personal exposures for PM in improved combustion cookstove using households

Households using improved combustion cookstoves reported kitchen area concentrations and exposures that were intermediate between households using solid fuels in traditional stoves and gas (or mixed clean) fuel using households with reported mean or median reductions ranging from 25 to 85% as compared to baseline solid fuel using conditions (Figure 10).

Figure 10: Reported 24-or 48 hr means and standard deviations for area concentrations and personal exposures for PM amongst improved combustion biomass cookstove

households in relation to the annual WHO AQG and ITG levels for PM_{10} and $PM_{2.5}$



Note: PM expressed in µg/m^3. Values in figure adapted from: *(11, 14, 43, 47, 50, 55, 57, 60, 69, 71, 72, 74, 76, 83, 84)*

A more detailed discussion of the improved combustion cookstove exposure evidence is provided in Review 6 along with exposure evidence from other studies reporting on impacts of interventions. The pooled mean and pooled SD for 24-hr kitchen concentrations are estimated to be 353 µg/m^3 (SD 406 µg/m^3) for PM_{10}; 146µg/m^3 (SD 94 µg/m^3) for $PM_{2.5}$ and 246 µg/m^3 (SD 234 µg/m^3) for PM_4. A complete summary of pooled estimates from all PM studies is provided in Tables 3 and 4.

Table 3: Pooled estimates for PM concentrations and exposures across all studies reporting measurement results from solid fuel using households (shown in Figure 7).

		24-hr Area PM Concentrations (Solid Fuel Users)												24-hr PM Exposures (Solid Fuel Users)							
		Kitchen				Living Room				Outdoor (Near Household)				SF Women Exposure				Children Exposure			
Pooled estimates from studies across all WHO regions	Pollutant	No of Studies	Total N	Mean	SD	No of Studies	Total N	Mean	SD	No of Studies	Total N	Mean	SD	No of Studies	Total N	Mean	SD	No of Studies	Total N	Mean	SD
	$PM_{2.5}$	18	682	972	876	2	28	228	124	4	91	106	79	8	751	267	297	1	13	219	
	PM_4	15	1440	548	549	8	721	395	616	4	56	204	246	2	564	331	109	2	372	227	
	PM_{10}	13	456	882	971	3	250	312	521	3	94	111	174	2	301	1231	3663	1	236	199	
Region - Wise Estimates																					
AFRICA	$PM_{2.5}$	4	124	846	783					1	13	147	205	1	13	275					
AFRICA	PM_4	1	62	226	206																
AFRICA	PM_{10}	7	108	1700	994									1	65	4898	3663				
AMERICAS	$PM_{2.5}$	8	396	1031	831					1	37	94	54	5	346	266	297				
AMERICAS	PM_4	2	69	1785	1171																
AMERICAS	PM_{10}	2	69	1137	668																
EMR	$PM_{2.5}$	1	14	1169	1489	1	7	603	421	1	7	182	132								
EMR	PM_4																				
EMR	PM_{10}	2	28	1247	1498	2	14	751	521	2	14	238	174								
SEAR	$PM_{2.5}$	4	108	826	1038	1	21	103	35	1	34	88	52								
SEAR	PM_4	4	794	547	256	2	338	349		2	24	91		2	564	331	109	2	372	227	
SEAR	PM_{10}	1	236	313		1	236	286		1	80	89		1	236	221		1	236	199	
WPR	$PM_{2.5}$	1	40											2	392						
WPR	PM_4	8	515	422	514	6	383	436	616	2	32	289	246								
WPR	PM_{10}	1	15	2080	1390																

Table 4: Pooled estimates for PM concentrations and exposures across all studies reporting measurement results from clean fuel and improved combustion cookstove using households (shown in Figures 9 and 10)

		24-hr Area PM Concentrations (Improved Combustion Cookstove Users)				24-hr Area PM Concentrations (Clean Fuel Users)			
Pooled estimates from studies across all WHO regions	Pollutant	No of Studies	Total N	Mean	SD	No of Studies	Total N	Mean	SD
	PM_{10}	12	418	353	406	3	56	148	56
	$PM_{2.5}$	3	29	146	94	3	39	66	37
	PM_4	3	583	246	234	2	49	65	29
Region -Wise Estimates									
AFRICA	PM_{10}	2	67	261	235				
AFRICA	$PM_{2.5}$								
AFRICA	PM_4								
AMERICAS	PM_{10}	7	270	298	349	2	21	17	56
AMERICAS	$PM_{2.5}$	3	29	146	94	1	9	45	23
AMERICAS	PM_4	2	70	362	223				
EMR	PM_{10}								
EMR	$PM_{2.5}$								
EMR	PM_4								
SEAR	PM_{10}	3	81	613	743	1	35	134	
SEAR	$PM_{2.5}$					2	3	72	41
SEAR	PM_4					2	49	65	29
WPR	PM_{10}								
WPR	$PM_{2.5}$								
WPR	PM_4	1	513	230	236				

3.5 Exposure Models: A case study from India on modeling $PM_{2.5}$ exposures at a national scale

Previous global burden of disease (GBD) estimates for household air pollution (HAP) from solid cookfuel use were based on simple indicators of exposure such as type of cook fuel used, as few health studies performed quantitative measurements. Recent progress in GBD methodologies that use integrated–exposure–response (IER) curves for combustion particles required the development of models to estimate average HAP levels experienced by large populations. In a recent such exercise, a model to estimate state and national average household concentrations of $PM_{2.5}$ from solid cook fuel in India was developed *(85)*. For this, 24-hr kitchen and living area $PM_{2.5}$ concentrations were monitored across 617 rural households drawn from 48 villages across four Indian states. A log-linear multiple regression model related measured $PM_{2.5}$ concentrations to different cooking-related household level variables. Coefficients from these models were then used with information on the same variables from the Indian National Family Health Survey (NFHS-3) *(86)* to estimate household concentrations at state and national levels.

The measured mean 24-hr concentration of $PM_{2.5}$ in solid cook fuel using households ranged from 163 µg/m^3 (95% CI: 143,183; Median 106; IQR: 191) in the living area to 609 µg/m^3 (95% CI: 547,671; Median: 472; IQR: 734) in the kitchen area. Fuel type, kitchen type, ventilation, geographical location and cooking duration were found to be significant predictors of $PM_{2.5}$ concentrations in the household model. K-fold cross validation showed a fair degree of correlation (r=0.56) between modeled and measured values. Extrapolation of the household model to all solid cooking fuel using households in India, covered by NFHS-3, resulted in a modeled estimate of 450 µg/m^3 (95% CI: 318,640) and 113 µg/m^3 (95% CI: 102,127), for national average 24-hr $PM_{2.5}$ concentrations in the kitchen and living areas respectively.

Finally, median ratios between daily average personal exposures and kitchen concentration from available published studies (0.742 for women, 0.628 for young children, 0.450 for men) were applied to estimate exposures for different household members. Average national personal exposures were estimated to be 285 µg/m^3 (95% CI: 201, 405) for children, 337 µg/m^3 (95% CI: 238, 479) for women and 204 µg/m^3 (95% CI: 144, 290) for men *(87)*.

The model affords substantial improvement over commonly used exposure indicators such as “percent solid cookfuel use” in HAP disease burden assessments, by providing the first estimates of national and state HAP levels experienced in India while informing exposure estimates used in the GBD-2010 exercise.

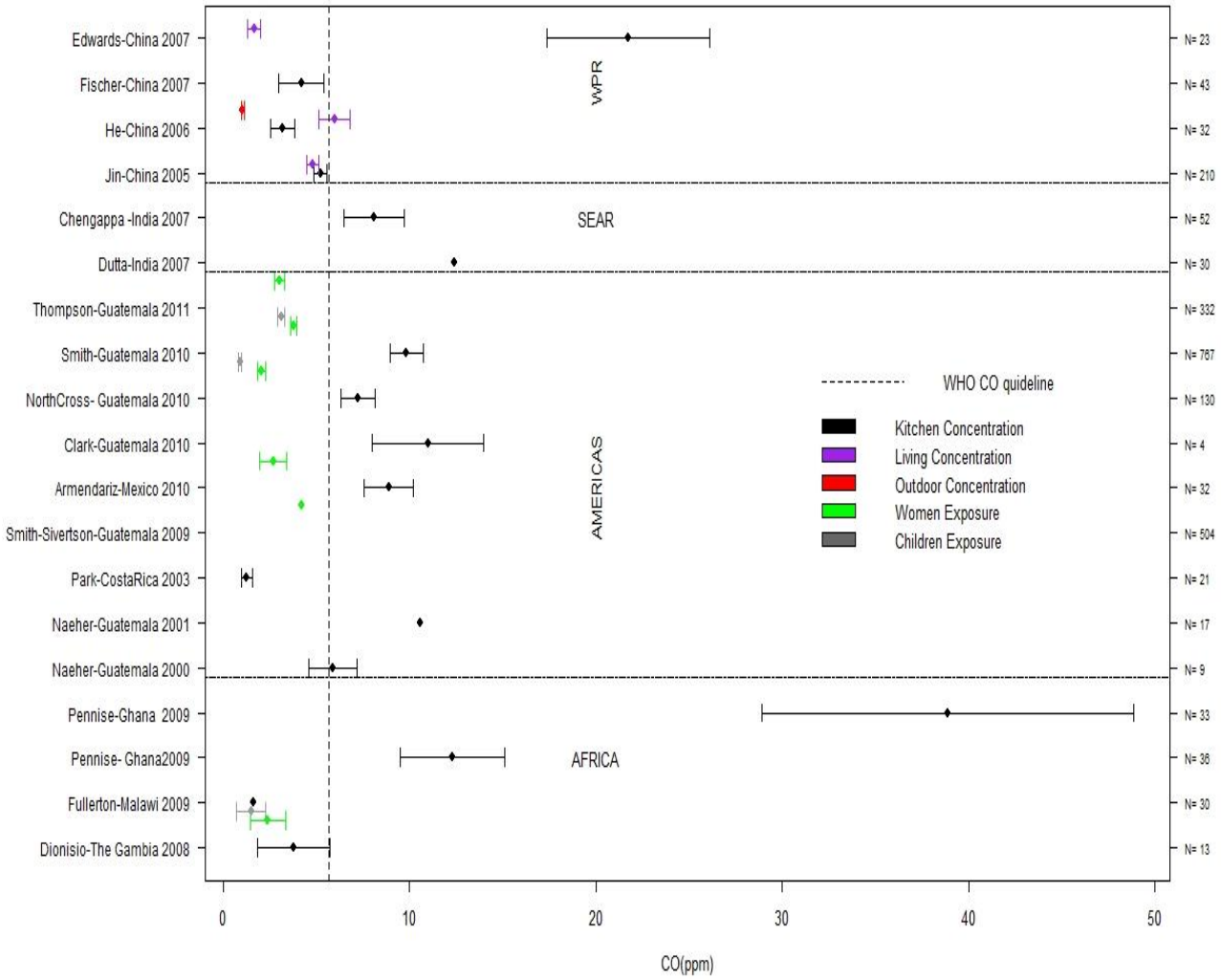
3.6 Summary of evidence for carbon monoxide

As compared to PM measurements, 24 hour (24-hr) CO measurements are available from a far fewer number of studies. While recent advances in measurement technology using electrochemical sensors or diffusion tubes have made personal exposure measurements easier to perform, most earlier studies report cooking period or even shorter term exposures and could not be includes as part of the evidence review. The pooled mean and pooled SD for 24-hr kitchen concentrations are estimated to be 8.60 ppm and 6.21ppm respectively. While this is above WHO AQG level of 5.68 ppm, the exposures of women however have mostly been below this guideline value with a pooled mean of 3.63 ppm and pooled SD of 2.69 ppm. The concentrations in the living environment and outdoors are generally below guideline level

(Figure 11). Households using improved combustion cookstoves reported kitchen area CO concentrations and exposures that were substantially lower with a pooled mean of 3.98 ppm (SD 4.14) ppm for area concentrations and mean of 1.76 ppm (SD 2.28) ppm for exposures. The reported mean or median reductions as compared to the baseline while using traditional stoves ranged from 32 to 77%. However, unlike the high levels of baseline PM concentrations encountered in all households using solid fuels in traditional stoves, CO levels and exposures were often below the guideline values both before and after improved cookstove interventions (Figure 12).

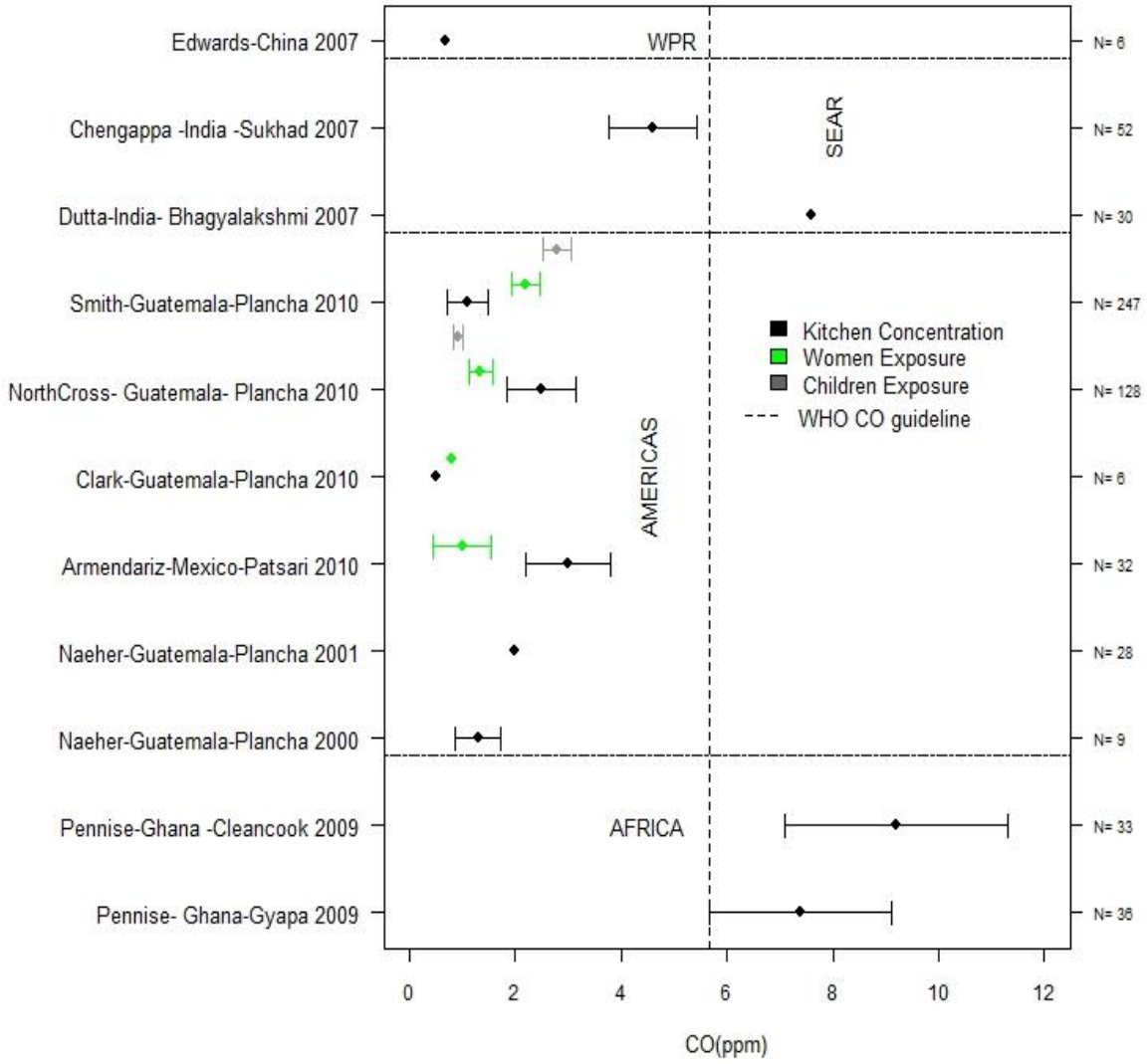
A complete summary of pooled estimates from CO studies is provided in Tables 5 and 6.

Figure 11: Reported Mean and SSDD of 24-hr area concentrations and /or 24 exposures to CO amongst households using solid cookfuels in traditional stoves, in relation to WHO AQG levels for CO.



Note: CO expressed in ppm Values in figure adapted from: *(15, 16, 42, 43, 50, 57, 60-62, 65, 66, 74, 76, 83, 84, 88-90)*

Figure 12: Reported Mean or Mean [95% CI] 24-hr kitchen area concentrations and /or 24 exposures to CO (expressed in ppm) in households using improved combustion cookstoves from developing countries across WHO regions



Note: Values in figure adapted from: *(16, 42, 43, 50, 57, 60, 74, 76, 83, 89)*

Table 5: Pooled estimates for CO concentrations and exposures across all studies reporting measurement results from solid fuel using households (shown in Figure 11)

		24-hr Area CO Concentrations (Solid Fuel Users)												24-hr CO Exposures (Solid Fuel Users)							
Pooled estimates from studies across all WHO regions	Pollutant	**Kitchen**				**Living Room**				**Outdoor (Near Household)**				**SF Women Exposure**				**Children Exposure**			
		No of Studies	Total N	Mean	SD	No of Studies	Total N	Mean	SD	No of Studies	Total N	Mean	SD	No of Studies	Total N	Mean	SD	No of Studies	Total N	Mean	SD
	CO	27	818	8.60	6.21	9	262	4.67	2.76	2	32	1.05	0.25	10	1770	3.63	2.69	5	661	2.66	2.19
Region - Wise Estimates																					
Africa	CO	4	112	16.29	18.67									1	13	2.40	1.90	1	13	1.50	1.60
Americas	CO	10	318	8.06	5.25									9	1757	3.64	2.70	4	648	2.69	2.20
EMR	CO																				
SEAR	CO	3	82	9.68	7.01																
WPR	CO	10	306	6.06	3.71	9	262	4.67	2.76	2	32	1.05	0.25								

Table 6: Pooled estimates for PM concentrations and exposures across all studies reporting measurement results from clean fuel and improved combustion cookstove using households (shown in Figure 12)

		24-hr Area CO Concentrations (Improved Combustion Cookstove Users)				24-hr Area CO Concentrations (Clean Fuel Users)			
Pooled estimates from studies across all WHO regions	Pollutant	No of Studies	Total N	Mean	SD	No of Studies	Total N	Mean	SD
	CO	12	391	3.98	4.14	1	9	1.30	0.60
Region -Wise Estimates									
Africa	CO	2	69	8.26	6.58				
Americas	CO	6	234	2.19	3.45	1	9	1.3	0.6
EMR	CO								
SEAR	CO	3	82	5.70	3.58				
WPR	CO	1	6	0.70					

3.7. HAP measurement results from developed-country studies

The high emissions from wood combustion relative to other heating fuels has led to large contributions of wood smoke to ambient pollution levels even in developed countries using a mixture of woodstove technologies. This source of ambient air pollution is especially of concern during the heating season in locations (especially rural areas) with high space heating requirements and where residential wood combustion is more prevalent or where a combination of meteorology and topography reduce dispersion of emitted pollutants. The chemical composition of woodsmoke and contributions of residential wood combustion to ambient air quality have been described in detail in a several recent reviews *(91, 92)*.

Most studies have measured emissions or ambient concentrations of $PM_{2.5}$. In terms of total $PM_{2.5}$ mass emitted over time (grams per hour), woodstoves meeting current U.S. EPA certification limits emit over 85 times more $PM_{2.5}$ than oil or gas furnaces, while conventional woodstoves emit over 250 times more $PM_{2.5.}$ In North America the prevalence of outdoor wood boilers (OWBs), used to provide residential and commercial space and water heating, has increased in recent years. Based on $PM_{2.5}$ emissions testing, unregulated OWBs emit almost 4 times more $PM_{2.5}$ than conventional wood stoves, 12 times more than EPA-certified wood stoves, 1,000 times more than oil furnaces, and 1,800 times more than natural gas furnaces *(93)*.

Emissions contributions from residential wood combustion (RWC) vary across North America and are known to be higher in northern U.S. states (especially the Northeast) and in Canada *(94)*. In the U.S. RWC is responsible for 6.9% of the national primary $PM_{2.5}$ emissions, which is greater than the contribution of on-road (2.5%) and similar to that for off-road (7.3%) mobile sources *(95)*. Across Canadian provinces, RWC is responsible for 10-70% of annual $PM_{2.5}$ emissions *(91)*, while in Denmark and Norway RWC is estimated to contribute 47 and 64%, respectively, of all $PM_{2.5}$ emissions *(91)*.

Source apportionment studies generally indicate 20-30% contributions from wood combustion to heating season ambient $PM_{2.5}$ levels, although this estimate varies greatly by location (Table 7). For example, RWC is the largest single contributor to $PM_{2.5}$ in rural areas of Montana, New York State and cities in Tasmania, New Zealand and in Seattle, but also is an important factor in cities not traditionally associated with wood burning such as Prague, San Jose and Portland. Given the seasonal nature of wood combustion and its prominence in non-urban areas, RWC is usually not well-characterized by regulatory monitoring networks; most information on exposure is derived from targeted monitoring campaigns and epidemiologic studies and therefore may be over-represented by areas with high woodsmoke contributions. Ambient $PM_{2.5}$ concentrations attributable to woodsmoke vary greatly depending on the prevalence of sources, the specific technologies that are employed as well as local meteorology and topology. However, in general the RWC contribution rarely exceeds 25 $\mu g/m^3$ on a seasonal basis, although short-term concentrations of 100 $\mu g/m^3$ may be experienced.

Table 7: Results from select developed country studies concerned with household use of solid fuels (primarily wood, for heating)

Location	Estimated % contribution to ambient PM	Estimated ambient woodsmoke $PM_{2.5}$[4] (µg/m3)	Remarks	Reference
Canada	10 – 70% annual $PM_{2.5}^{EI}$			*(91)*
Denmark	47% annual $PM_{2.5}^{EI}$			*(91)*
Launceston, AUS	85% annual PM_{10}^{EI}			*(91)*
Christchurch, NZ	90% heating season $PM_{2.5}^{SA}$			*(96)*
Tasmania, AUS			90th percentile PM_{10} concentration was 46 µg/m^3 in Launceston and 22.5 µg/m^3 in Hobart during study period (cross-sectional analysis, comparing two cities).	*(97)*
Armitage, AUS		200	Night time (2-week) winter mean	*(98)*
Temuco, CHILE	87% winter PM_{10}^{EI}			*(99)*
San Jose, USA	42% heating season PM_{10}^{SA}			
Atlanta, USA	11% of annual $PM_{2.5}$			*(100)*
Vermont, USA	10 – 18% of $PM_{2.5}$			*(100)*
Montana (5 communities), USA	55 – 77% heating season $PM_{2.5}^{SA}$	7.0 – 10.9		*(101)*
Rural New York, USA		4 – 22	Nighttime, heating season, inversion conditions. Short-term peak concentrations from mobile monitoring as high as 100 µg/m^3.	*(102)*
Rochester, NY	17%^{SA}	3.2	Woodsmoke contribution to $PM_{2.5}$increased to 27.2% when the corresponding hourly $PM_{2.5}$ concentrations were greater than 15 µg/m^3	*(103)*
Seattle, USA			Mean heating season concentrations on $PM_{2.5}$in a woodsmoke-impacted area of Seattle (measured during panel study of 19 subjects): Mean =11.23 (SD=6.48). Ambient-source $PM_{2.5}$ exposure: Mean:6.26 SD:3.93	*(104)*
Seattle, USA	7 – 31% annual $PM_{2.5}^{SA}$			*(105)*
Seattle, USA	~30% heating season)^{SA}	4		*(106)*
Seattle, USA	33% annual PM_{10}^{SA}			*(107)*
Seattle, USA	42% annual $PM_{2.5}^{SA}$			*(108)*
Portland, USA	27% (annual)^{SA}	7	Percent contribution to $PM_{2.5}$may also include influence of wildfires	*(105)*
Rural British Columbia, CANADA			10.8 (SD 5) µg/m^3 7-day average concentrations during heating season in small communities in northern British Columbia where air quality is heavily impacted by wood combustion. Estimates of outdoor-generated $PM_{2.5}$ measured indoors of 3.5 (SD 2.3) µg/m^3.	*(102)*
Austria	10 – 20% of winter PM_{10}^{SA}			*(109)*
Southern GER	59% (winter) PM_{10}^{SA}			
Duisberg, GER	13% (fall)^{SA}	14.7 (range: 6.3 – 28.7)		*(110)*
Prague, CZ	37% (heating season)^{SA}	29.6 (range: 9.5 – 53.4)		*(110)*
Amsterdam, NL	11% (heating season)^{SA}	25.4 (range: 6.6 – 53.9)	Including contribution from long-range transport of biomass aerosol	*(110)*
Helsinki, FI	17% heating season)^{SA}	11.9 (range: 6.9 -18.3)		*(110)*
Northern SWEDEN	36 -81% of winter PM_{10}^{SA}			*(111)*
Kurimaki, FI		8	Small community (Kurimaki, 164 single family homes) in central Finland. 8 µg/m^3 $PM_{2.5}$ over full sampling campaign, with daily values of 5 – 40 µg/m^3 and hourly averages as high as 50	*(112)*

[4] Where PM_{10}, but not $PM_{2.5}$ measurements were made, we estimated the level of woodsmoke $PM_{2.5}$ based on the contribution to PM_{10} and assuming a typical PM_{10}:$PM_{2.5}$ ratio of 0.65 for combustion-dominated aerosol.

			µg/m^3.	

[SA]Source apportionment, [EI]Emissions Inventory

A recent analysis for Vancouver, Canada indicated a high intake fraction for wood smoke *(113)*, meaning that a large fraction of wood smoke emissions result in exposure, comparable to the "intake fraction" resulting from motor vehicle exhaust. This is due to the conditions under which wood is burned – in neighborhoods where people reside, at times of day when people are at home, and often during meteorological conditions of stagnant air. Indoor levels as high as 100 µg/m^3 PM_{10} in homes using wood exclusively for heating, have been measured *(114)*. Mean levels in homes in Libby, Montana were 51 µg/m^3, but were dramatically reduced (mean concentration of 15 µg/m^3) when replaced with new, lower emission stoves *(115)*. A similar study conducted in Canada, however, reported no change in pre and post exchange indoor concentrations and generally lower indoor concentrations (median indoor concentrations ~ 12 µg/m^3)*(116)*, although ambient concentrations were lower in this community compared to Libby. Evidence from a study in northern British Columbia, Canada indicates that portable HEPA-filter air cleaners can effectively reduce indoor concentrations and exposures for those living in areas with high levels of outdoor woodsmoke. HEPA filters reduced indoor concentrations by 60%*(102)*. In another study in a woodsmoke-impacted community in Canada, portable HEPA filters reduced indoor $PM_{2.5}$ concentrations by an average of 55% *(117)*.

A study of an extensive stove exchange in Libby Montana USA indicated that residential woodstoves were the major source of pollution, contributing approximately 80% of the ambient $PM_{2.5}$ throughout the winter months prior to the initiation of the exchange program. Average winter $PM_{2.5}$ mass was reduced by 20%, and woodsmoke-related $PM_{2.5}$ (as identified through source apportionment) was reduced by 28% when compared with the pre-change-out winter (Pre (SD)-exchange: 27.3 (7.5) - Post-exchange: 21.8 (4.9) *(115)*. In a stove exchange on a Native American reservation in Idaho, US, homes had improved indoor air quality post-exchange (39.2 +/- 45.7 µg/m^3 median pre-exchange to 19 +/- 47.5 µg/m^3 post-exchange) with a 52% reduction in median indoor PM and a 60% reduction in short-term spikes *(115)*. A study in Australia reported that a combination of community education, enforcement of environmental regulations, and a woodstove replacement (with electric heating) reduced mean wintertime PM_{10} by 39% (from 44 to 27 µg/m^3 *(118)*).

Collectively, the available evidence suggests that efforts to reduce wood smoke emissions, through fuel switching, use of lower emission appliances or a combination of approaches can be highly effective in reducing population exposure. Table 7 provides a summary of study results on HAP exposure from developed countries.

4. Overall assessment of strength of evidence

The evidence compiled in this systematic review was intended to provide comprehensive descriptive information on average levels of HAP and exposure for population groups using traditional solid fuels, improved solid fuel stoves, and clean fuels. The impacts of interventions as reported from intervention-based studies (or observational studies of intervention projects and programmes) are reviewed separately (see Review 6: Intervention Impacts). Meta-analysis was not carried out, although pooled values for pollutant concentrations were calculated using weighted averages. GRADE domains have been used as a guide to assess the quality of the overall body of evidence.

Study designs

All of the studies included were cross-sectional, and were subject to inclusion criteria covering: provision of adequate details of sampling criteria, sampling methods (including specification of sampling devices, flow rates, calibration procedures etc.), analytical methods (including specification of analytical instrumentation, sensitivity and wherever applicable specificity of method), calibration standards and corrections for measurement errors (such as co-locating or calibrating against gravimetric samplers for nephelometric or light-scattering devices used in measuring PM).

Risk of bias

As the inclusion criteria covered all main aspects of study design and conduct that may bias results, the risk of bias is judged to be low. In order to provide comparable average levels of PM and CO, only those reporting 24-hr or 48-hr measurements were included. As studies have variously measured $PM_{2.5}$, PM_4 and PM_{10}, results for these different particle size cut-offs have been reported (and averaged) separately.

Indirectness

Since the questions for this review concerned average concentrations and exposures of air pollutants, indirectness is not a concern.

Heterogeneity

No formal assessment of statistical heterogeneity was made. A large degree of variability in household and personal exposure levels was expected due to highly variable conditions in respect of household energy use, housing type, seasonal factors, etc. The pattern of variability was, however, generally not suggestive of unreliable results. Thus, values for homes using traditional stoves and solid fuels reported high (albeit variable) levels of PM and CO, and did not have unusually low values. Some of the studies of homes using clean fuels found levels higher than might be expected on the basis of emission rates, but these could be explained by multiple stove/fuel use in the study homes, and emissions from neighbours and other external sources of combustion.

Precision

The precision of estimates varied by type of stove and fuel, by outcome (pollutant) measure, and level of aggregation. Precision of global results are considered here, and will be lower for the regionally-stratified results also reported in the review. For area kitchen levels for traditional solid fuel stoves, there were almost 20 studies with more than 600 subjects for $PM_{2.5}$ and larger numbers for CO. Adequate precision was also available for improved solid fuel stove users, and for personal exposure measurements of both PM and CO with solid-fuel users for both women and children, although similar numbers were not available for all the particle sizes. Rather less precision was available for kitchen area concentrations with use of clean fuels, with 3 studies (56 subjects) for PM and only one study (9 subjects) for CO. No personal PM or CO exposure data were available for clean fuels. All of the weighted average pooled estimates are provided with standard deviations.

Publication bias

This was not formally assessed due to the large variability expected between studies from different regions. It is possible that some unpublished studies have not been included.

Summary

This assessment found that the evidence for the majority of area and personal results for PM and CO was of **moderate** quality, but much more limited (principally by small numbers of studies and subjects) for homes using clean fuels.

5. Conclusions

This review provides a comprehensive description of the nature and magnitude of HAP exposures across all WHO regions. There is considerable variability in methods used by studies to measure area concentrations and/or exposures. Despite the uncertainty introduced while pooling across studies, **the evidence for high or extreme exposures in solid fuel using households in developing countries is unequivocal,** where people are exposed indoors and outdoors. The levels of exposure associated with solid fuel use in developed counties are much lower, although the use of solid fuels for heating can be a major source of ambient air pollution. It may thus be challenging to reach extremely low levels of HAP exposure whenever large portions of the population are burning solid fuels, even when extremely ‘clean’ technologies are being employed.

There are important gaps in the existing exposure evidence base. Considerable additional information is needed for example, to understand the drivers of the variability within solid fuel using households. Factors to be carefully addressed include the influence of household characteristics (ventilation, housing material), cooking practices and behaviour (short term, seasonal, long term changes in meal preferences, fuel quantity, cooking location, stove use and stove maintenance) and fuel characteristics (dry vs. moist, processed vs. unprocessed). At present, insufficient information is available to characterize impact of ‘improved’ and ‘advanced’ combustion cookstoves on exposures, as well as information to explain the distribution of exposures associated with each major stove/fuel combination. Exposure assessment approaches relevant for monitoring and evaluation of intervention programs also remain to be developed fully.

Although PM and CO assessments have been the focus for most exposure or health studies, there is also a need to assess exposures for a range of air toxics including black carbon, PAHs, VOCs and metals. This will especially augment the evidence base for health effects (such as cancer, cataracts and asthma) shown to be associated with HAP but lack exposure measures to assess the strength of association. The relative paucity high quality exposure studies for kerosene and coal cookstove use and for solid-fuel space heating, also make it difficult to judge the magnitude of exposure contributions from these sources in household settings.

Finally, the available exposure evidence argues for imminent need to frame interventions. Review 6 uses the exposure evidence provided in this review to evaluate and recommend intervention options. By quantifying the extent to which different cookstove and fuel interventions impact exposures, the available health –based pollutant specific AQGs may thus be used as a benchmark to develop technology or practice based guidelines that can reduce or minimize associated risks to public health.

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