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Modeling emission rates and exposures from outdoor cooking

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HIGHLIGHTS

- Outdoor cooking is a significant fraction of global cookstove use, and is not addressed through health based emissions guidelines and models.
- Emissions guidelines should better represent the different cooking contexts in which stoves are being used.
- Inverse Gaussian dispersion combined with Monte Carlo simulation link emissions from outdoor cookstoves with health based exposure guidelines.

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ABSTRACT

Approximately 3 billion individuals rely on solid fuels for cooking globally. For a large portion of these – an estimated 533 million – cooking is outdoors, where emissions from cookstoves pose a health risk to both cooks and other household and village members. Models that estimate emissions rates from stoves in indoor environments that would meet WHO air quality guidelines (AQG), explicitly don't account for outdoor cooking. The objectives of this paper are to link health based exposure guidelines with emissions from outdoor cookstoves, using a Monte Carlo simulation of cooking times from Haryana India coupled with inverse Gaussian dispersion models. Mean emission rates for outdoor cooking that would result in incremental increases in personal exposure equivalent to the WHO AQG during a 24-h period were 126 ± 13 mg/min for cooking while squatting and 99 ± 10 mg/min while standing. Emission rates modeled for outdoor cooking are substantially higher than emission rates for indoor cooking to meet AQG, because the models estimate impact of emissions on personal exposure concentrations rather than microenvironment concentrations, and because the smoke disperses more readily outdoors compared to indoor environments. As a result, many more stoves including the best performing solid-fuel biomass stoves would meet AQG when cooking outdoors, but may also result in substantial localized neighborhood pollution depending on housing density. Inclusion of the neighborhood impact of pollution should be addressed more formally both in guidelines on emissions rates from stoves that would be protective of health, and also in wider health impact evaluation efforts and burden of disease estimates. Emissions guidelines should better represent the different contexts in which stoves are being used, especially because in these contexts the best performing solid fuel stoves have the potential to provide significant benefits.

1. Introduction

Health impacts of emissions from household fuel use are most closely linked to the exposures they cause. Models that link emissions from cookstoves with indoor concentrations of fine particulate matter ($PM_{2.5}$) (Johnson et al., 2011) have been useful in evaluating which stove types would meet WHO air quality guidelines in indoor environments (Johnson et al., 2014). These models revealed that even the most recent generation of unvented forced draft biomass cookstoves using non-pelletized fuels are still far from reaching emissions levels in controlled laboratory tests that would meet WHO guidelines or interim targets indoors (Johnson

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Nomenclature

C	concentration (g/m^3)
g	gravitational acceleration (m/s^2)
l_b	buoyancy length scale (m)
l_m	momentum length scale (m)
Q	pollutant emission rate (g/s)
r_0	stove radius (m)
U	near stove wind speed (m/s)
u_*	friction velocity (m/s)
w_0	smoke exit velocity (m/s)
x	axis in the Cartesian coordinate (m)
y	axis in the Cartesian coordinate (m)
z	axis in the Cartesian coordinate (m)
z_0	ground roughness height (m)
z_e	effective source height (m)
z_p	plume rise height (m)
z_s	physical source height (m)
Greek letters	
θ	potential temperature (K)
κ	Von Karman's constant $(=0.41)$
σ_y	plume spread in horizontal direction (m)
σ_z	plume spread in vertical direction (m)

et al., 2014). Since the focus was on emissions into indoor environments, outdoor cooking was not considered as part of the WHO indoor air quality guidelines. Based on these estimates standards for indoor emissions have been incorporated into the International Workshop Agreement (IWA) on tiers of performance[1] as part of the ISO framework as a precursor to International Standards.

In many areas of the world cooking occurs outdoors, especially in tropical regions. Although the number of houses using solid fuel has been estimated (Chafe et al., 2014) as a development indicator, and for global burden of disease estimates (Lim et al., 2013) the proportion of households cooking outside has not been disaggregated. This is important as the exposure and health implications of stoves operated outdoors are likely to be significantly different to those operated indoors in kitchens, both in the pollutant dispersal and in the amount of time spent in the near vicinity of the stove. Among solid fuel users in Andhra Pradesh in Southern India, kitchen and living room concentrations of PM_4 were higher for homes with enclosed indoor kitchens compared to homes with outdoor kitchens, which resulted in differences in exposure for both cooks and non-cooks (Balakrishnan et al.,). Outdoor concentrations of PM_{10} during cooking in Bangladesh were also substantially lower than those in kitchens and living areas (Dasgupta et al., 2006).

Outdoor cooking was not incorporated into WHO indoor air quality guidelines by definition. Although one of the tiers of performance as part of the ISO framework is currently for overall emissions from cookstoves, outdoor cooking is not addressed explicitly and overall emissions are not linked to health based air quality guidelines. The tiers for each performance indicator were developed by choosing values of performance for the upper and lower tier boundaries, and then selecting intermediate values. One end of the spectrum is emissions from a three stone fire, and the other is emissions from a forced draft stove during a water boiling test. To provide a consistent health based framework for standards relating to overall emissions from cookstoves, there is an urgent need to measure exposures and associated emissions from cooking outdoors. As an interim approach, and to guide future studies, a mechanistic model can outline the plausible health implications from cooking outdoors and other frequently encountered cooking and housing configurations.

In this paper we demonstrate the importance of outdoor cooking across the globe, and model the emission rates from outdoor cooking that would be required to reduce the personal exposure contributions from cookstoves to levels equivalent to the WHO AQG and interim targets, which are based on scientific evidence relating to air pollution and its health consequences. The modeling is performed using distributions of cooking times, and in field emissions rates from Haryana India as a growing body of evidence consistently indicates laboratory testing using the water boiling test does not reflect emissions during daily cooking activities both in emission rates and particle optical properties (Johnson et al., 2008, 2009a; Roden et al., 2009; Edwards et al., 2014; Johnson et al., 2010; Chen et al., 2012). In addition, emissions rates from forced draft Philips HD4012 stoves are modeled to demonstrate the degree to which current more advanced stoves achieve health based targets. Finally, since emissions from neighboring houses contribute to elevated ambient concentrations of PM, we model the distance where individual stove emissions will drop down to 1 $\mu g/m^3$, and the AQG of $10 \mu g/m^3$.

2. Methods

2.1. Prevalence of outdoor cooking

The prevalence of both outdoor cooking (as the most common location for daily use) and solid fuel as the primary cooking fuel in the home were separately plotted in ArcGIS, ArcMap 10.5 over the March 2017 “World Countries” layer package provided by the Environmental Systems Research Institute (ESRI). Both maps were color-coded according to the heat maps included in the legends.

Data was derived from the most recent Multiple Indicator Cluster Surveys (MICS) and Demographic and Health Surveys (DHS) for each country other than China and Mexico. When a country had DHS and MICS surveys published after the year 2000 the latest available survey was preferentially utilized in plotting.-. Solid fuels were defined as charcoal, coconut parts, paraffin, wood, straw, shrubs, grass, saw-dust, dung, and agricultural crop residue. Chinese statistics were provided by Dr. Xiaoli Duan from the Ministry of Environmental Protection (MEP) of People's Republic of China (Duan et al., 2014). Statistics for Mexico were provided by the “Centro de Investigaciones en Ecosistemas (CIECO)” at the National Autonomous University of Mexico (Serrano-Medrano et al., 2014). Countries where outdoor cooking and solid fuel cooking were presumed to be very rare were included in the lowest range of both charts.

When data for solid fuel was unavailable in both the DHS and MICS survey, the latest estimates from the World Health Organization were utilized (Bonjour et al., 2013). The DHS and MICS survey were used preferentially because the WHO data utilized a multilevel model, rather than survey data, for all but five countries. The WHO data are 39% international multi-country surveys, 18% national census data, 20% from national surveys, “such as household, employment, living conditions, or expenditure surveys”, and the remaining 23% data points are from “other sources, including environmental and poverty assessments, MDG reports, and statistical figures provided on the websites of national statistics bureaus” (Bonjour et al., 2013). Population estimates are based on the latest World Bank estimates accessed on February 28, 2017.

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[1] http://cleancookstoves.org/technology-and-fuels/standards/iwa-tiers-of-performance.html.

2.2. Modeling emissions rates from outdoor cooking

For outdoor cooking a Gaussian based inverse dispersion model was nested in YASAIw, an Excel-based Monte Carlo simulation tool, to determine emission rates (mg/min) from outdoor cooking that would result in an incremental increase in exposures equivalent to WHO AQG or interim targets. Thus similar to the Box model for indoor emissions (Johnson et al., 2014), the annual mean WHO AQG (10 $\mu g/m^3$) or interim targets (IT1 35 $\mu g/m^3$; IT2 25 $\mu g/m^3$; and IT3 15 $\mu g/m^3$) are assumed to be the exposures for which the resultant emissions rates are estimated. Emissions rates that would result in these exposure increases for the cook were estimated based on cooking 2 meals during a 24 h period, which is typical of this region in India. Thus, exposure concentrations [E] for each emissions rate (mg/min) were calculated as:

$$[E] = AQG \bigg/ \left(\frac{cooking\ duration}{1440}\right)$$

Since exposures from outdoor cooking are a function of the times that cooks are in close proximity to the stoves during the day, a Monte Carlo approach was used to randomly select cooking times from a normal distribution of 51 measurements of cooking times for rice or chapatti meals for 4 adults in a village setting in Haryana India, where the time in minutes reflects the time the cook was next to the stove when lit. The total time next to the lit stove during the cooking of a meal was on average 69 ± 16.5 min. Thus the time spent cooking next to the lit stove to cook 2 daily meals was on average 138 min (~2.3 h), which is similar to the mean of 2.4 ± 1.1 h women cooks (16–60 years old) spent in the kitchen in Andra Pradesh while cooking ($n = 299$) (Balakrishnan et al.,).

Use of the Monte Carlo approach allows rapid, independent simulation of the duration of a morning and evening cooking event to generate a distribution of 20,000 simulations of emissions rates from outdoor cooking that would result in the incremental increase in exposure equivalent to the WHO AQG or interim target values during a 24 h period.

Since outdoor stoves in India are commonly placed on the ground and are about 30 cm high, while in other locations stoves may be placed on tables, or platforms and are waist-high, 2 scenarios were modeled to span the range of these cooking arrangements. The first scenario assumed the stove emission occurred 30 cm above the ground and the receptor (cook) squatting with the breathing zone approximately 1 m above the ground. In the second scenario the stove emission was at 0.9 m high and the receptor (cook) standing with the breathing zone approximately 1.5 m high. Although these scenarios do not represent a large difference between stove and receptor height, they were chosen to represent the most common cooking behaviors. Table 1 shows the other input parameters for the dispersion based model.

Wind speed in Table 1 corresponds to the wind speed in the breathing zone of the cook at a height of 1 m when squatting and 1.5 m when standing. Based on a logarithmic profile wind speed near the ground would be expected to be lower than wind speed in meteorological data usually measured at a height of 10 m. Thus, for wind speeds of 0.5 and 1.5 m/s in the breathing zone of the cook, the equivalent velocity at 10 m would be approximately 0.9 and 2.6 m/s, respectively.

Table 1
Input parameters for Gaussian-based inverse dispersion model.

Parameter	Value	Parameter	Value
Wind speed [m/s]	0.5	Exit velocity [m/s]	0.5
Receptor distance [m]	1	Smoke temp [K]	700
Stove diameter [m]	0.2	Ambient temp [K]	303

Exit velocities depend on the power and size of the stove and whether a flue is present. Exit velocities for small unvented stoves in outdoor environments are typically very low, and lower than typical stack velocities. Flue velocity of gases for small wood and coal heating stoves was reported to be 0.11 m/s (Butcher and Ellenbecker, 1982). Average flue gas velocity based on measured experiment values was reported to be 1.27 m/s for two plancha-type stoves with flues (Prapas et al., 2014). Sampling for PAH from cookstoves were conducted with an upward velocity of 0.7–1 m/s to capture all emissions from cookstoves in a thermally insulated hood (Kim Oanh and Dung, 1999). Since the objective of the analysis is to derive emission rates that would be protective of health we use a conservative value for exit velocity of 0.5 m/s, as higher velocities will result in reduced exposures. Thus the exit velocity selected in the current analysis is reflective of those reported, and also represents a conservative estimate to be more protective of health.

Smoke temperatures were assumed to be 700 K. Temperatures from 5 five configurations of natural-draft, top-lit up-draft (TLUD) semi-gasifier cookstoves tested with two biomass fuels generally all exceeded 500 °C at the top of the combustion chamber (Tryner et al., 2014). Similarly temperatures in the flue exceeded 650 °C in the flue of research furnaces simulating biomass cookstoves (Kirch et al., 2016). Temperatures of flue gas for rocket stoves can be considerably higher (760–1000 °C), as can other improved combustion stoves and stoves burning coal [2]. Sensitivity of dispersion results to this assumption is presented in the supplemental information.

Similar to the box model used to derive emission rates for stoves to meet indoor air quality guidelines and interim targets (Johnson et al., 2014), background ambient concentrations were not incorporated into the model as the objective was to determine emission rates that would result in an incremental increase in exposures equivalent to WHO AQG or interim targets. These concentrations can be readily incorporated based on the local context, however, since background ambient concentrations vary widely, they are not used to derive the emissions rates for stoves for more general application. Similarly, distributions for wind speed could be incorporated, but to be conservative in the estimates of emission rates, a constant wind speed of 0.5 m/s was used to reflect the low wind speeds present in densely built up village settings in India. Low wind speeds would decrease particulate dispersion and are thus conservative as they result in lower estimates of emissions rates that would increase exposures equivalent to the AQG. Exposures were also conservatively estimated based on the center of the plume, rather than what is typical where people try to avoid being directly downwind of the stove. While people tend to sit outside the plume, and wind speeds are frequently higher than 0.5 m/s, emissions rates were estimated to be protective of health by minimizing the dispersion of the plumes by wind, and represent a worst case scenario of poorly ventilated outdoor spaces.

2.3. Gaussian dispersion model

Gaussian dispersion models were used A) in an inverse mode to estimate emissions rates from outdoor cooking that would result in an incremental increase in exposures equivalent to WHO AQG or interim targets, and B) to estimate distance for the plume to disperse as an indicator of the impact on neighborhood pollution levels.

The Gaussian dispersion model was employed to estimate the

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[2] http://www.bioenergylists.org/stovesdoc/Ogle/DOStovetest.html.

concentration at the receptor located at (x, y, z):

$$C(x,y,z) = \frac{Q}{2\pi\sigma_z\sigma_y U}\left(\exp\left[-\frac{1}{2}\left(\frac{z-z_e}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+z_e}{\sigma_z}\right)^2\right]\right) \times \exp\left(-\frac{y^2}{2\sigma_y^2}\right)$$

Where Q is the pollutant emission rate, U is the near surface wind speed, z_e is the effective source height, σ_y and σ_z are a measure of plume spread in the horizontal and vertical directions, respectively (Venkatram et al., 2013). The plume parametrizations for σ_y and σ_z calculation were selected to be suitable for modeling near source concentration (Gorlé et al., 2009; Harrop, 2001).

The effective source height, z_e, is given by:

$$z_e = z_s + z_p$$

Where z_s is the physical source height and z_p is the plume rise due to the buoyancy and initial momentum associated with the smoke exit velocity computed as follows:

$$z_p = \left[8.3 l_m^2 x + 4.2 l_b x^2\right]^{\frac{1}{3}}$$

Where x is the distance downwind of the source, l_m and l_b are the momentum and buoyancy length scales, respectively:

$$l_m \approx \frac{w_o r_o}{U}$$

$$l_b \approx \frac{w_o r_o^2 g \Delta\theta}{U^3 \theta_a}$$

Where w_o is the smoke exit velocity, r_o is the stove radius where smoke exits, U is the ambient wind speed at stove top, g is the gravitational acceleration, $\Delta\theta$ is the temperature excess and θ_a is the ambient potential temperature (Stull, 2005). As the common cooking time in Haryana is early morning and early evening, the atmospheric stratification is neutral. Unstable stratification typically occurs in the middle of the day, when the heat flux on the ground is high and $dT/dz < 0$. Stable stratification occurs at night when the ground temperature is lower than atmosphere and $dT/dz > 0$. During sunset and sunrise the heat flux vector direction on the ground switches to a neutral condition approaching zero. Thus plume rise parameterization assumes that the plume rises in a neutral boundary layer, and a logarithmic wind velocity profile was used.

$$U(z) = \frac{u_*}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right)$$

Where U is the wind speed at height of z above the ground, u_* is the friction velocity calculated based on the reference velocity at the reference height, κ is the Von Karman's constant and z_0 is the ground roughness height. A roughness height of 0.03 m was applied based low vegetation or hard packed yards around village homes which is typical for village scenarios in Haryana India, based on Blocken 2015 (Blocken, 2015).

2.4. Emissions sampling

To estimate the distance for the plume to disperse as an indicator of the impact on neighborhood pollution levels, particulate emissions rates were measured during normal daily cooking tasks in homes in 3 villages within the SOMAARTH demographic site in Haryana India with 16 homes using Chulas, 7 using Angithi, and 13 using forced draft Philips stoves. Sampling consisted of two meals one in the morning and one in the evening. The chula is a traditional U-shaped mud stove covered with cow dung plaster with an open front where the fuel is loaded. The Philips forced draft advanced combustion stove was designed primarily to burn woody biomass and utilizes a battery-powered blower to maintain constant flow into the combustion chamber. The Angithi is a circular ring on which cow dung patties are placed and a coal lighted in the center. The stove smolders and is used for long term cooking of animal fodder in large vessels.

Emissions for each stove test were collected directly above the stove using a three-pronged aluminum sampling probe (Johnson et al., 2009b). A simultaneously collected background sample was used to correct emission factors for dilution with background concentrations. 37 mm Teflon filters were inserted in-line to determine PM emissions. Filters were equilibrated for 48 h at 45 ± 3% relative humidity and 20±2 °C before taking pre and post weights on an electro-microbalance (Cahn Model 29, Thermo Electron Corp., USA). No mass adjustments were necessary based on field blanks. Flows were evaluated via a Mesalabs Defender 530 before and after each cooking event. Pumps were turned on before cooking began so that entire cooking events were captured and turned off at completion of the burn cycle.

Emission factors were determined using the carbon balance method, which accounts for the fate of the fuel carbon in the emitted species (Crutzen et al., 1979), and has been used frequently for similar studies (Pennise et al., 2001; Zhang et al., 2000; Smith et al., 2000). Briefly, the ratios of each emission species (as carbon) in the sample to the total carbon in the sample are multiplied by the total emitted carbon to derive emission factors. Carbon content for PM was derived from analysis of elemental and organic carbon of particulate matter on quartz filters performed at the University of Illinois. Fuelwood weights were measured using a digital hanging scale with a 10 g resolution (American Weigh SR-20) over the course of the cooking event. Ash was weighed in a metal pan after taring on an Accuteck Digital Postal Scale (W-8580-110-Black) with 2.8 g resolution. Total fuel carbon was determined by weighing the fuelwood consumption and adjusting for water content and carbon diverted to ash. Water content was measured with a digital moisture meter (Model: 50270, SONIN Inc, China) and ash was measured after completion of cooking. Moisture measurements for dung patties were adjusted based on oven based drying methods (Gautam et al., 2016).

3. Results

3.1. Outdoor cooking prevalence

Fig. 1 shows the prevalence of solid fuel use and Fig. 2 the global prevalence of outdoor cooking. The percentage of the world population utilizing solid fuels as their main cooking fuel in 2010 was reported by the WHO as 41% (95% CI 37–44%). Utilizing the DHS and MICS data combined with WHO data suggests that 42% of the 2017 world population utilize solid fuels as their main cooking fuels. Outdoor cooking, as expected, appears to occur more frequently in equatorial and subtropical regions where ambient temperatures are higher. Although outdoor cooking is less frequent than indoor cooking it still remains an important fraction of global cooking supplying an estimated population of 533 million people.

The available data for outdoor cooking includes 85 countries and represents almost two-thirds of the world's population (4.8 billion individuals, 65.5%) of which approximately 11% (533 million individuals) live in homes where cooking is done primarily outdoors. MICS survey data, including surveys that were not utilized as a more-recent DHS survey was available, covers 939 million

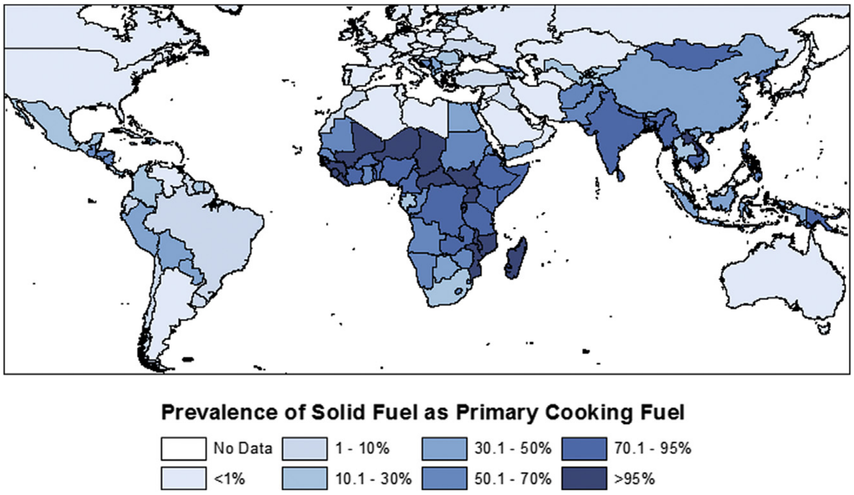


Fig. 1. Prevalence of solid fuel use for primary energy provision.

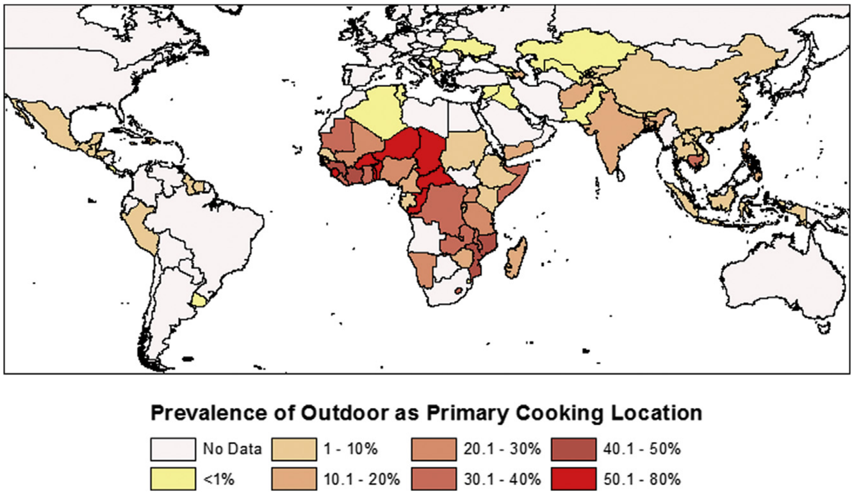


Fig. 2. Prevalence of outdoor cooking as a primary cooking location.

individuals (~13% of world population) of which approximately 14% live in homes where cooking is done primarily outdoors. The DHS survey data, including surveys that were not utilized as a more-recent MICS survey was available, covers 2.92 billion individuals (~40% of world population) of which approximately 18% live in homes where cooking is done primarily outdoors. Within the 21 countries where both DHS and MICS survey data was available (629 million individuals), DHS data indicates approximately 25% and MICS data indicates approximately 22% live in homes where cooking is done primarily outdoors. Although survey questions ask whether cooking is usually done in the house, in a separate building, or outdoors, seasonal changes in meteorology such as the monsoon rains may change the cooking locations for during periods of the year depending on the precipitation condition suited for outdoor cooking in a given geographic region, which is not captured in survey data.

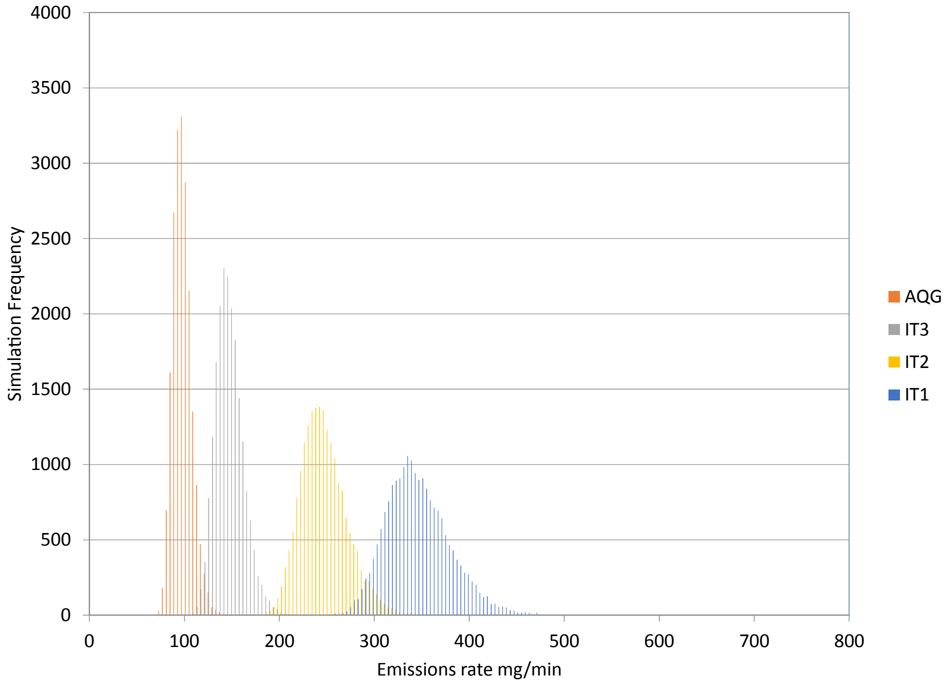
The available data for solid fuel cooking includes 154 countries and represents data for over 6 billion individuals (~82% the world's population), of which approximately 2.9 billion (49%) live in homes where they cook primarily with solid fuels. Including the 36 high income countries in which the WHO assumes solid fuel use to be negligible translates to a 42% global prevalence of solid fuel use estimated for 96% of the global population. Within the 28 countries where both DHS and MICS survey data was available for solid fuel use (821 million individuals), DHS data indicates approximately 62% and MICS data indicates approximately 73% live in homes live in homes using primarily solid fuels. The remaining 980 million individuals in 57 countries were covered by the WHO data, of which 150 million (15%) individuals live in homes using primarily solid fuels. Estimates for populations living in homes that cook primarily with solid fuels differ by 3% in countries that had both DHS and WHO data (66% and 62% respectively); 8% in countries that had both MICS and WHO data (65% and 57% respectively), and <1% between the combined MICS and DHS data set used for mapping in the current study and WHO data (49% vs 48% respectively).

3.2. Modeling emission rates from outdoor cooking

The models for outdoor cooking while squatting and while standing were the product of random selection from the distribution of cooking times for a morning and evening cooking event over 24 h with 20,000 simulated runs. The model then calculated the emission rate from the stove (mg/min) for each of the simulated runs that would result in an incremental increase in personal exposure equivalent to the WHO AQG or interim targets during a 24 h period. The output distributions in Fig. 3 and Fig. 4 therefore represent the distribution of emissions rates from a stove that would result in incremental increases in personal exposure equivalent to the WHO AQG or interim targets during a 24 h period. Table 2 shows summary statistics of the output distributions of emissions rates that are relevant to standards and guidelines for stoves that emit pollutants outdoors.

4. Discussion

In households cooking with solid fuels the location where the cooking occurs significantly impacts the exposures to the cook and to other family members, and thus the potential for adverse health impacts from exposure to the smoke. Cooking outdoors results in significantly different exposures to the cook and to family members compared to indoor cooking largely because the smoke disperses



b) Cumulative frequency

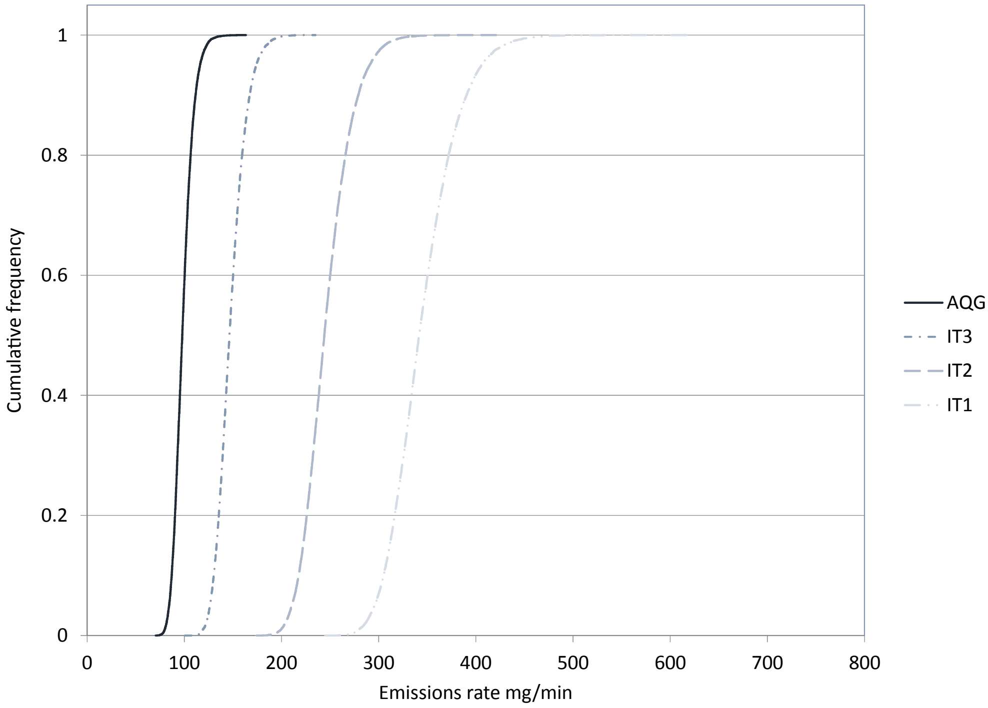
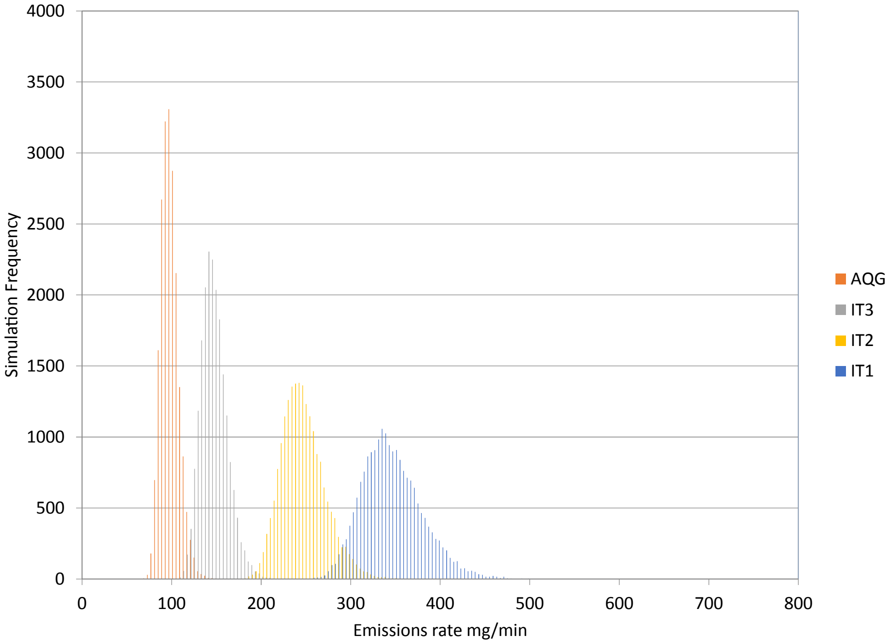


Fig. 3. Monte Carlo simulation of emissions rates from outdoor cooking while standing that would result in incremental increases in personal exposure equivalent to the WHO AQG or interim targets during a 24 h period.



a) Cumulative frequency

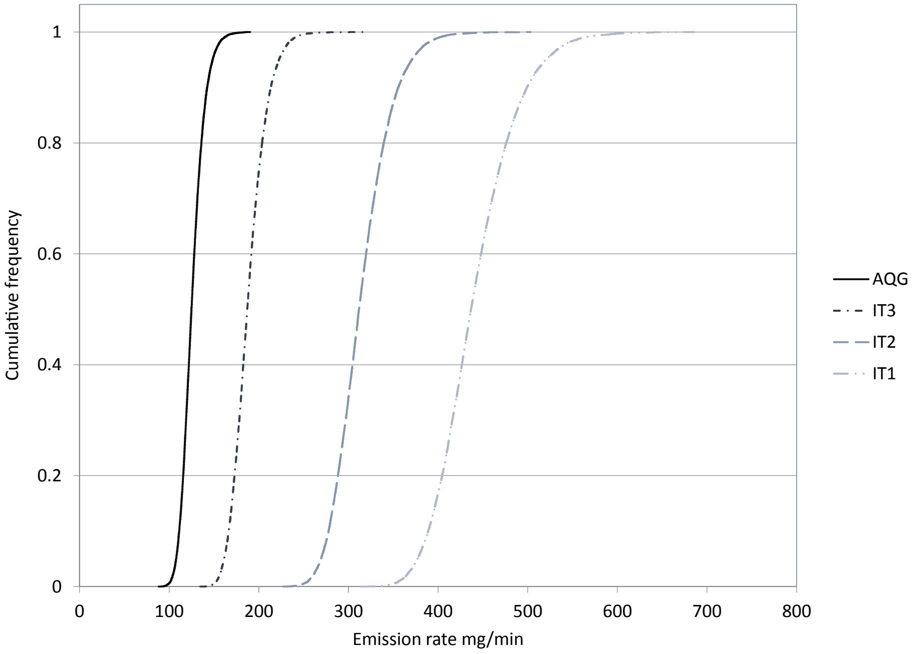


Fig. 4. Monte Carlo simulations of emissions rates from outdoor cooking while squatting that would result in incremental increases in personal exposure equivalent to the WHO AQG or interim targets during a 24 h period.

more readily outdoors compared to unvented indoor cooking (Balakrishnan et al.,). Exposures for family members that are not actively cooking are also reduced since smoke does not transfer within the household as is seen when kitchens are connected to other rooms in the household (Balakrishnan et al.,). The location where cooking occurs therefore impacts which emissions rates are likely to pose a health issue. Of current IWA performance guidelines for stoves, only the indoor emission tier derived using a box model for indoor kitchens is based on health endpoints (Johnson et al., 2011, 2014). While there are tier guidelines for overall emissions from a stove, these are not related to health. The analysis presented here is a first step in modeling emission rates relevant to health endpoints for one of the more common cooking arrangements found globally. Globally outdoor cooking with biomass fuels in cookstoves is a significant fraction of the total solid fuel use in cookstoves supplying an estimated population of 533 million people, or approximately 18% of the 2.9 billion individuals who cook primarily with solid fuels. Understanding the exposure patterns of these individuals is therefore important in understanding the overall impacts of the use of solid fuels for cooking globally. In

Table 2
Emissions rates from outdoor cooking to increase exposures equivalent to air quality guidelines and interim targets.

Exposure	stove/cook	Emission rate(mg/min)								
Concentration	height (m)	Mean	St Dev	5%	10%	25%	50%	75%	90%	95%
AQG	0.3,1	126	13	108	111	117	125	134	142	148
IT3	0.3,1	189	19	161	166	176	187	200	213	222
IT2	0.3,1	315	31	269	278	293	312	334	355	371
IT1	0.3,1	441	44	377	389	411	437	468	499	520
AQG	0.9,1.5	99	10	84	87	92	98	105	112	116
IT3	0.9,1.5	148	15	126	130	138	146	157	167	174
IT2	0.9,1.5	247	24	211	218	229	244	261	279	291
IT1	0.9,1.5	345	34	296	305	321	342	366	390	406

addition modeling emissions rates should be expanded from a single room house to cover some of the more common housing configurations and kitchens.

Emission rates modeled for outdoor cooking (Table 2.) are substantially higher than IWA emission rates for indoor cooking because the models estimate impact of emissions on personal exposure concentrations rather than microenvironment concentrations, and because the smoke disperses more readily outdoors compared to indoor environments. In contrast emissions remain in indoor environment for longer periods until ventilation rates reduce concentrations back to ambient levels. Emission rates for WHO indoor air quality guidelines use a Monte Carlo probability analysis of the number of homes that meet guidelines and interim targets, and focus explicitly on cookstove emissions and the resulting indoor air pollutant concentrations in kitchens or single room houses (Johnson et al., 2014). IWA emissions rates rely on a more simplified assumption of 30 m^3 room and a rate of 15 air exchanges per hour. WHO guidance allows for small single room homes where fires are lit most of the day and cooks and infants are exposed for extended periods. Typically however personal exposure concentrations are lower indoor kitchen concentrations due to the time spent away from the proximity of the stove (Armendáriz Arnez et al., 2008). Use of personal exposure concentrations as a basis for estimating emissions rates to meet AQG or interim targets would allow for substantially higher emissions rates from stoves. In smaller homes where the stove is not separated from the main living areas, the contribution of the cookstove to exposures will be substantial as mothers with young infants frequently spend a large fraction of their day inside at home. For kitchens separated from the living area by a wall or partition the contribution to exposure reflects the time spent in proximity to the stove during cooking and while preparing food. In contrast the dynamics for outdoor cooking tend to be somewhat different, and exposure contributions reflect the time in close proximity to the stove. In this case a focus on the contribution of time near the stove to personal exposures, rather than ambient concentrations is more relevant, as pollutant concentrations change quite rapidly with distance from the stove even at low wind speed. Guidance for the WHO AQG notes that to be related to health, air pollutant concentrations should be representative of exposures (WHO, 2005), and thus this approach is taken for outdoor cooking.

Another key consideration for linking emissions sources with exposures and air quality guidelines is that exposures reflect emissions from a variety of sources needed to meet daily cooking and lighting needs, including other household sources such as tobacco smoke, mosquito coils and incense, and exposures in other indoor and outdoor environments, such as during transportation. The models presented here therefore represent the contribution of stoves to personal exposures rather than the total exposure. While the supralinear nature of the dose response curves implies that the health implications of a given emission rate depend on the other sources that contribute to personal exposures, in practice ambient concentrations vary substantially by region (Brauer et al., 2016) and contributions from other sources are too numerous and varied to be practical for modeling guidance in emissions rates from outdoor cooking. Thus in a manner similar to box models to evaluate emissions rates for indoor cooking (Johnson et al., 2014), the models presented here focus on the contributions of outdoor cooking to personal exposures and to neighborhood pollution levels. Exposure contributions of the stove will also depend on the precise position of the cook relative to the emissions and shifts and changes in wind speed and direction. Exposure contributions are modeled in the center of the plume, although in practice people are likely to avoid standing or sitting in smoke where possible. Thus estimates of emissions rates in Table 2 are likely conservative, and more protective of health.

In indoor environments for stoves to meet WHO AQG guidelines, emissions rates are lower than the best performing solid-fuel biomass stoves, which make use of fans and/or gasify the solid fuel before combusting the resulting gases (Johnson et al., 2014). Since emissions performance from daily cooking is often worse than that observed in controlled water boiling tests, the fraction of stoves in indoor environments that meet AQG is likely even lower. In contrast, many more stoves would meet AQG when cooking outdoors. Since outdoor cooking represents a significant fraction of global cooking, emissions guidelines should better represent the different indoor and outdoor contexts in which stoves are being used, especially given that in these contexts the best performing solid fuel stoves have the potential to provide significant benefits.

That many more stoves would meet AQG when cooking outdoors also highlights the significant benefits of venting of stoves outdoors, or separating the cooking areas from the living areas as a separate room or with physical boundaries or partitions to reduce exposures to cooks and family members (Balakrishnan et al., ; Amendariz Arnez et al., 2008). Although ambient concentrations are elevated by the number of other homes in close proximity, contributing to a localized neighborhood pollution effect, the reductions in exposures to the cook and family members are substantial. To better quantify the impacts of outdoor cooking emissions rates on neighborhood pollution levels Fig. 5 shows outdoor cooking emissions rates and Gaussian dispersion modeling of the distance from the stove when emissions are diluted to an air concentration of 1$\mu g/m^3$ for 4 different wind speeds 0.5 m/s, 1.0 m/s, 1.5 m/s and 2 m/s. The relationship between emission rate and distance is close to linear consistent with neutral stratification.

Table 3 shows in field emissions rates and modified combustion efficiencies during normal cooking activities in village homes in Haryana India for traditional Chula stoves, Angithi stoves used principally for animal fodder, and the Philips forced draft stove using wood and dung fuels. In addition, Table 3 shows Gaussian modeling of the distance for the plume to reach 1 $\mu g/m$ (Chafe et al., 2014) as an indicator of the impact on neighborhood pollution

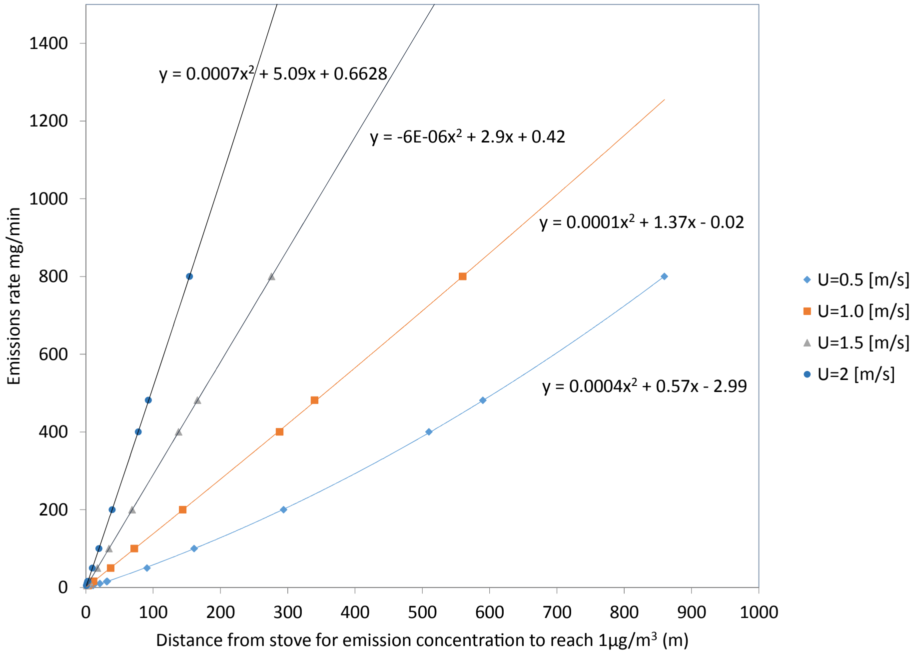


Fig. 5. Gaussian dispersion modeling of distance from the stove before outdoor cooking emissions are diluted to $PM_{2.5}$ concentration of 1µg/m^3.

levels. Angithi stoves outdoors would have to be 104 m apart and traditional Chula 37 m apart for the stove not to appreciably increase background concentrations creating a localized neighborhood pollution effect with a wind speed of 1.5 m/s. This distance is much greater than the typical distance between village homes in Haryana, with the result that significant neighborhood pollution impacts are seen. In contrast the Philips stove using wood only would only have to be 7 m apart for the stove not to appreciably increase neighborhood pollution levels with a wind speed of 1.5 m/s, and impacts on neighborhood pollution would be minimal.

Emissions rates from outdoor cooking that would increase exposures equivalent to air quality guidelines and interim targets would generally result in a neighborhood pollution impact in villages in Haryana, which are densely populated. In the more rural conditions prevalent in many parts of Central America and Africa this would not be the case due to the housing density. Thus prioritization of emissions rates to reduce personal exposure impacts or neighborhood impacts will be a function of local conditions, and both models should be evaluated simultaneously. These models however highlight the importance of looking at personal exposures and the impacts of neighborhood pollution. Inclusion of the neighborhood impact of pollution should be addressed more formally both in guidelines on emissions rates from stoves that would be protective of health, and also in wider health impact evaluation efforts and burden of disease estimates. This is especially true as the burden of disease from household air pollution is likely underestimated since the impacts of neighborhood pollution are not captured by satellite models that estimate global burdens of ambient pollution (Brauer et al., 2016) as the resolution is much larger than that of neighborhood pollution.

Although outdoor cooking thus contributes to both neighborhood concentrations and ambient background concentrations, from an individual stove perspective it is useful to evaluate what emissions rates cause direct impacts to neighbors. Fig. 6 shows a comparison of emission rates from outdoor cooking for exposures to increase equivalent to AQG, with distance required for emissions plume concentrations to reach 10 µg/m (Chafe et al., 2014). For emissions rates that would reduce exposures of the cook equivalent to the AQG (126 mg/min) and IT 3 (189 mg/min), the plume concentration would reduce to lower than the AQG before the plume reached neighbors downwind in these Haryana villages at wind speeds greater than 1 m/s (10 m and 14 m respectively). In contrast emission rates that would reduce exposures of the cook equivalent to IT 2 and IT 1 would result in emissions concentrations that were significantly above the AQG by the time the plume reached neighbors downwind (23 m and 32 m respectively), and thus would be expected to have a direct health implication. Clearly, however, the extent of impacts would again be dependent on housing density.

While these examples serve to illustrate the impacts on

Table 3
Emissions rates, modified combustion efficiency, and distance before plume reaches 1 µg/m (Chafe et al., 2014) for stoves in Haryana India (Edwards et al., 2017).

Stove Type	Fuel	n	Time (min)	MCE	$PM_{2.5}$ (mg/min)	U=0.5 [m/s]	U=1 [m/s]	U=1.5 [m/s]	U=2 [m/s]
Angithi/Haro	Dung	5	143 (±52)	0.87 (± 0.02)	302 424 (±395)	407	217	104	59
Chula	Dung + wood	12	169 (± 52)	0.91 (± 0.02)	108 182 (±192)	163	78	37	21
Philips	Dung + wood	5	238 (± 139)	0.93 (± 0.02%)	27 59 (±56)	50	20	9	5
Philips	Wood only	7	211 (± 101)	0.95 (± 0.03%)	21 27 (±22)	42	15	7	4

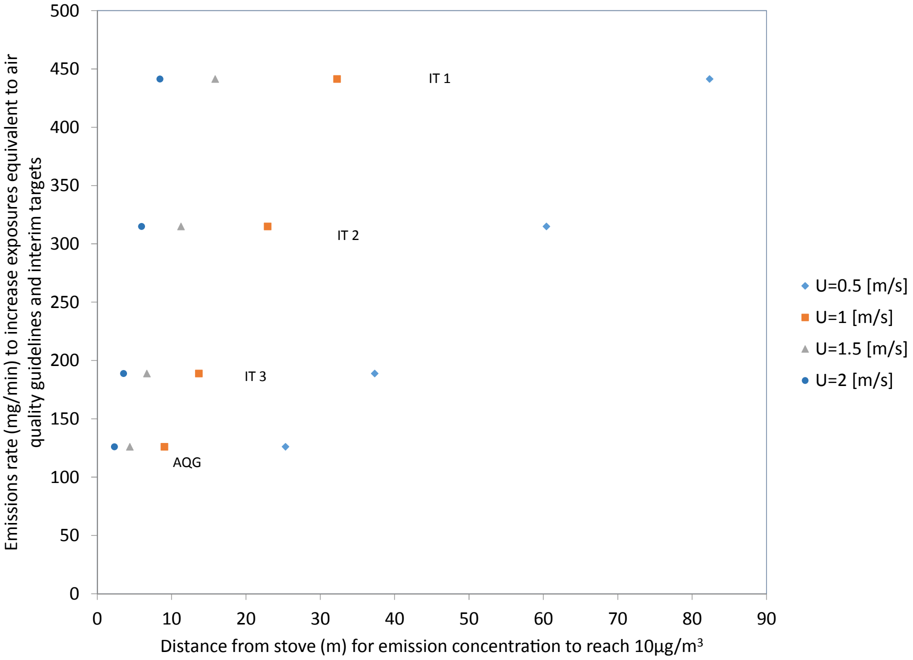


Fig. 6. Emission rates from outdoor cooking for exposures to increase equivalent to AQG in comparison to distance required for emissions concentrations to reach 10 µg/m (Chafe et al., 2014).

neighborhood pollution of different emissions rates, there are many other factors in the real world that impact pollution dispersion such as building orientation, barrier walls, variable wind speeds etc. The dispersion models here do not incorporate this variability, but rather use a set of relatively conservative assumptions to be more protective of health. Most critically these models use a set of measurements of emissions rates from real village homes during normal daily cooking activities and are not the result of controlled water boiling tests, as controlled water boiling tests are not representative of in field emissions and generally tend to underestimate emissions from open fire type stoves (Johnson et al., 2008; Edwards et al., 2014). In addition, these measurements use a set of cooking times from real cooking of rice and chapatti meals in a village kitchen. Clearly, however the meals cooked do not represent the wide range of dishes cooked in village households in India, or seasonal changes in dishes, but rather represent the two basic meal types typical for that area for an average household size. Field measurements of exposures during cooking would improve modeled estimates of emissions rates and are a priority. Wind speeds used to estimate emissions rates and pollution dispersion are low to represent the dense building in Haryana villages. Pollution concentrations are estimated in the center of the plume representing the most elevated concentrations, although that is unlikely as people avoid standing directly in the smoke plume. Further, these models assume use of one stove at a time in a household, but it is possible that cooking animal fodder and cooking meals may occur simultaneously. However, these models are a first step in integrating neighborhood pollution impacts into emissions rates from outdoor cooking that are protective of health.

5. Conclusions

Globally outdoor cooking with biomass fuels in cookstoves is a significant fraction of the total solid fuel use in cookstoves supplying an estimated population of 533 million people. Emission rates modeled for outdoor cooking are substantially higher than emission rates for indoor cooking to meet AQG, because the models estimate impact of emissions on personal exposure concentrations rather than microenvironment concentrations, and because the smoke is able to disperse more readily outdoors compared to indoor environments. As a result, the best performing solid-fuel biomass stoves would meet AQG when cooking outdoors. Since outdoor cooking represents a significant fraction of global cooking, emissions guidelines should better represent the different contexts in which stoves are being used, especially given that in these contexts the best performing solid fuel stoves have the potential to provide significant benefits.

Emissions rates from outdoor cooking that would increase exposures equivalent to air quality guidelines and interim targets may also result in neighborhood pollution impacts depending on housing density. Thus prioritization of emissions rates to reduce personal exposure impacts or neighborhood impacts should be evaluated based on local conditions. Inclusion of the neighborhood impact of pollution should be addressed more formally both in guidelines on emissions rates from stoves that would be protective of health, and also in wider health impact evaluation efforts and burden of disease estimates.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2017.05.029.

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