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Perspectives in Household Air Pollution Research: Who Will Benefit from Interventions?

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Abstract Household air pollution from solid fuel combustion in inefficient and poorly vented cookstoves is estimated to be responsible for 3.9 million premature deaths per year and 4.8 % of the global burden of disease, making it the third leading risk factor for morbidity and mortality worldwide. Despite increasing recognition surrounding this global environmental health problem, much remains to be elucidated regarding exposure response relationships, particularly among potentially susceptible population subgroups. Given that many of the communities most affected by household air pollution exposures also experience elevated exposures to poverty, psychosocial stressors, other environmental pollutants, and comorbid conditions, research needs to correctly specify risks due to these potentially interacting risk factors. Although suggestive evidence exists for differential improvements in health following reductions in ambient air pollution concentrations among specific subgroups, the question remains as to who will benefit and to what extent from efforts to reduce exposures to emissions from household solid fuel combustion. The ability to know what to expect from cookstove interventions and to accurately describe the presence of distinct subgroup responses is crucial to reduce uncertainty and to encourage policy makers to enact change.

Keywords Biomass · Cookstoves · Household air pollution · Health · Differential susceptibility · Interventions

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Introduction

In recent years there has been increasing recognition of the staggering public health and environmental impact of emissions from household solid fuel combustion utilized by nearly three billion people worldwide for cooking, heating, and lighting needs [1, 2, 3•]. This form of energy utilization, which consists of burning solid fuels (e.g., wood, crop residue, animal dung, coal, etc.) over an open fire or in a traditional cooking stove, is very inefficient, leading to the formation of toxic combustion by-products like carbon monoxide [CO] and particulate matter [PM], among many others [4]. These exposures are disproportionately experienced by women and children due to domestic roles typically encountered in least-developed or developing countries [2]. Average daily PM concentrations in homes burning solid fuels can range from 300 to 3,000 μg/m^3 [5, 6], substantially greater than the World Health Organization guidelines for ambient and indoor air quality intended to protect public health (e.g., the guidelines for daily mean $PM_{2.5}$ [PM with an aerodynamic diameter less than or equal to 2.5 microns] and PM_{10} are 25 μg/m^3 and 50 μg/m^3, respectively) [7].

Often characterized by large variability and uncertainty due to differences in factors such as stove use and time-activity patterns, household room configuration and ventilation, fuel type and moisture, weather, and instrument error [5], exposure to household air pollution has been linked to serious global health impacts, both acute and chronic [3]. Air pollution from household solid fuel combustion is the third leading risk factor for morbidity and mortality globally, responsible for an estimated 3.9 million premature deaths per year and approximately 4.8 % of disability-adjusted life years [3, 8]. The burden due to household air pollution far surpasses the burden of other environmental risk factors such as unsafe water and insufficient sanitation [8]. Despite increasing recognition, the attention and resources devoted to this problem do not match the severity of the issue. As a result, multiple knowledge gaps and critical research priorities for household air pollution and related health impacts have been identified. Here, we present a summary of recent health effects reviews (see Table 1) and discuss knowledge gaps not previously emphasized that are critical to characterizing the exposure-response relationship and answering the questions of who will benefit and to what extent from efforts to reduce exposures to emissions from household fuel combustion.

Table 1 Summary of the systematic reviews and meta-analyses included in the 2010 Comparative Risk Assessment on the health effects of household air pollution from solid fuel use [3]

Health Endpoint Evaluated*	First Author, year; type of study	Years covered: number of included studies	Estimate of relative risk** Pooled OR (95 % CI)	Conclusions
Acute lower respiratory infections in children under five years of age	Dherani M, 2008 [9]; systematic review and meta-analysis	1979-2008: 24 studies	Pooled OR=1.78 (1.45, 2.18)	Only three of 24 studies included direct measures of exposure; otherwise, use of proxies (e.g., stove/fuel type) of exposure likely lead to exposure misclassification Large variation in outcome definitions Evidence of publication bias may be explained by expected differences in magnitudes of risk for various severities of disease Preliminary results of the first RCT on pneumonia in children were available for inclusion in this systematic review [9]; due to the strength of the study design, final results of the RCT [26] were also included as part of the comparative risk assessment [3]. Intention-to-treat analyses conducted to evaluate the RCT supported conclusions drawn by Dherani et al [9]. Exposure-response analyses (conducted to augment the primary intention-to-treat analyses for the RCT) support causal inference; the shape of the exposure-response indicates greater predicted health benefits at the very low levels of exposure [26]
Chronic obstructive pulmonary disease	Stern-Nezer J, 2010 [10]; systematic review and meta-analysis	1979-2008: 24 studies	Pooled OR=1.94 (1.62, 2.33)	All observational studies; no studies with direct measure of exposure Strong evidence for publication bias and heterogeneity in reported risks Conclusions support three previous systematic reviews and meta-analyses [7, 11, 12]
Lung cancer	Hosgood HD, 2011 [13]; systematic review and meta-analysis for coal use	Through 2009: 25 studies	Pooled OR=1.81 (1.19, 2.76)	All observational studies (all case-control) with fuel type as the exposure of interest No evidence of publication bias Conclusions support one previous systematic review and meta-analysis [14]
	Smith KR, 2014 [3]; systematic review and meta-analysis for biomass use	Through 2012: 14 studies	Pooled OR=1.18 (1.03, 1.35)	All observational studies with fuel type as the exposure of interest No evidence of publication bias Conclusions support one previous systematic review and meta-analysis [14]
Cataracts	Smith KR, 2014 [3]; systematic review and meta-analysis	Through 2010: 7 studies	Pooled OR=2.46 (1.74, 3.50)	All observational studies (all in South Asia) No evidence of publication bias; substantial heterogeneity noted Adjustment for diabetes or exclusion of diabetics resulted in conflicting results

CI confidence interval, *OR* odds ratio, *RCT* randomized controlled trial

*Health endpoints included in this table represent those deemed by the Comparative Risk Assessment investigators as having multiple epidemiologic studies of good quality, with consistent results, and with supporting epidemiologic studies from particle exposures at higher and lower concentrations [3].

**A noted limitation of summarizing risk estimates in reviews and meta-analyses of household air pollution is the heterogeneous nature of the exposure measures used across individual studies; “exposed” versus “unexposed” categories are often based on factors related to the fuel type for cooking (e.g., biomass versus a “clean” fuel), stove type, rural-urban comparisons, outdoor versus indoor cooking, and time exposed to biomass fuel combustion [3].

The State of the Science: Household Air Pollution and Health Impacts

Our understanding of the disease burden from solid fuel combustion is still relatively limited; however, consistently and substantially elevated risks have been demonstrated for acute lower respiratory infections in children [9, 15], chronic obstructive pulmonary disease (COPD) [15–17], lung cancer [13, 15], and cataracts [18]. Although an exhaustive review of the health effects of household air pollution is beyond the scope of this manuscript, Table 1 provides a summary of recent systematic reviews on the primary health outcomes considered by the 2010 Comparative Risk Assessment for Household Air Pollution from the use of solid fuels for cooking [3, 8]. Detailed descriptions of the systemic reviews and meta-analyses for each health endpoint considered were provided by Smith et al [3]. Additionally, convincing evidence exists for adverse cardiovascular-related endpoints [19], and information on the exposure-response function determined from other sources of combustion-related air pollution exposure (e.g., ambient air pollution, secondhand smoke, and active tobacco smoke) was extrapolated when developing the Comparative Risk Assessment for household air pollution and hard cardiovascular disease endpoints [3]. Emerging evidence also suggests associations with adverse pregnancy outcomes [20], tuberculosis [21–23], and cognitive impairment [24]. Furthermore, recent publications have identified important gaps in knowledge focusing on the shape of the exposure-response curves [25], the need for improved exposure assessment, particularly challenging when long-term exposures are of interest [5], as well as the implications that solid fuel cookstove emissions have on climate-level impacts [26].

Ideally, the solution to household air pollution exposures is to transition households to cleaner fuels (e.g., liquid petroleum gas, electricity). The use of cleaner fuels tends to occur naturally with economic development and such efforts to encourage and promote modern energy access are underway in some parts of the world. However, the economic situation in many regions implies that a substantial proportion of the world's population, those unable to afford and/or access modern fuels, will continue to burn solid fuels for many decades. Therefore, it is critical to find economically feasible and culturally appropriate alternatives to the traditional solid fuel stove. Recent evidence suggests that the introduction of cleaner stoves is capable of improving health. For example, investigators evaluating the large-scale Chinese National Improved Stoves Program (NISP) reported improvements in several respiratory disease endpoints [27–29]. Additionally, the first randomized controlled trial evaluating the health impact of a chimney stove in Guatemala demonstrated a reduction in severe childhood pneumonia, although the effect was not statistically significant when all pneumonia types were considered [30••]. Beyond respiratory outcomes, the intervention in Guatemala also resulted in lower blood pressure levels among women [31]. Notwithstanding these encouraging results, many efforts to disseminate and sustain cleaner-burning cookstove technologies across the developing world have had limited success. Indeed, many of the stove intervention projects conducted have failed—some due to poor stove design and/or performance in the field (i.e., the exposure reduction achieved is still high compared to the WHO guidelines) and others due to cultural issues (i.e., lack of adoption of new stove technology). A recent review of studies measuring behavior change surrounding the dissemination of various cookstove technologies worldwide highlighted the need to characterize the most important factors (e.g., individual, household, and societal) necessary to promote the adoption and sustained proper use of clean fuels and/or cleaner-burning biomass cookstoves [32].

Who Benefits from Cleaner-burning Cookstove Interventions and To What Extent?

Although the evidence regarding the adverse health impacts of household air pollution is growing, uncertainty remains as to the health improvements expected as a result of interventions introducing cleaner burning stoves. Evidence that certain characteristics confer increased susceptibility to the adverse effects associated with exposures to air pollution is mounting, especially for ambient air pollution [33–41]. Here, we define susceptibility as individual- and population-level characteristics that increase the risk of air pollution-related health effects in a population. Susceptibility may, therefore, indicate the presence of different exposure-response relationships among different populations (i.e., given the same level of air pollution exposure, some populations will experience greater health effects than others), or it may also refer to a characteristic of a population that increases the likelihood or opportunity for greater exposure to certain pollutants (sometimes referred to as vulnerability) [33]. Factors that have been observed to increase susceptibility to air pollution exposures include age, sex, genetics, underlying health, obesity, diet, smoking status, socioeconomic status, and psychosocial stressors [33–41].

Much of the evidence regarding susceptibility is supported by the ambient air pollution literature, conducted primarily in urban areas of industrialized countries. However, this issue is gaining momentum within the household air pollution literature and evidence for effect modification now exists, particularly for cardiovascular-related effects. For example, the relationship between integrated 24-hour personal $PM_{2.5}$ concentrations and elevated systolic and diastolic blood pressure was stronger in women >50 years of age among a population of traditional stove users in China [42]. Similarly, a slight increase in the odds ratio for solid fuel use and hypertension was observed among those ≥40 years of age as compared to those

<40 years of age in a population-based study of over 14,000 Chinese men and women (p-value for interaction=0.34) [43]. The same investigators reported stronger evidence of effect modification by sex and smoking status when evaluating effects of solid fuel use on hypertension and coronary heart disease; elevated risks were observed among women (p-values for interaction=0.02 and 0.32, respectively) and among never-smokers (p-values for interaction=0.02 and 0.02, respectively) [43]. Finally, effects on systolic blood pressure were stronger among obese women in Nicaragua for both 48-hour indoor $PM_{2.5}$ and indoor CO (p-value for interaction=0.04 and 0.002, respectively) [44]. In addition to this compelling, initial evidence of differential susceptibility, further evaluation of other environmental, comorbid, social, and genetic factors will likely prove critical for determining an accurate picture of the magnitude of health effects due to household air pollution [19, 45, 46].

Several investigators have hypothesized that those individuals who are more susceptible to the adverse effects of air pollution exposure may also be the groups that benefit most from efforts to reduce air pollution levels (e.g., traffic reduction plans, industrial facility closings, indoor air filter interventions) [47, 48], yet this question has largely been ignored in the cookstove field. Valid assessments of the true exposure-response relationships among various subpopulations are necessary to inform a more accurate estimate of the global burden of disease attributed to cookstove smoke, an identified research gap needed to convince governments and policy makers to enact interventions [49]. Evidence regarding who benefits from improved air quality is limited and inconsistent. It is not known whether larger predicted benefits among certain subpopulations are due to differences in greater relative improvements associated with air pollution reductions (i.e., different exposure-response functions experienced by the subgroups) or differences in absolute improvements because of poorer baseline health status, which may be independent of air pollution [47].

Figure 1 is a simplistic example of the problem that may arise if investigators do not take into account that only a segment of their study population is able to experience a health benefit resulting from a cookstove intervention. Here, the "responders", or those benefiting most from the intervention, represent about a third of the total population, and both the responders and the non-responders have the same mean health measure at baseline (top panel). If the mean change in health response due to the intervention is calculated assuming the population is homogenous (i.e., ignoring that the subgroup of responders exists), then only a small, likely statistically non-significant improvement would be observed (a); however, the responders' improvement after the intervention may be meaningful (b) and should be described to inform public health officials as well as future studies. More complex scenarios likely exist in real-world settings. For example, the responders may start with poorer health status at baseline and also experience a greater response to the reduction in pollution concentrations.

Furthermore, although the scenario depicted in Figure 1 represents one study population that includes a proportion of responders, defining and identifying responders versus non-responders is also relevant for comparing results across study populations. This phenomenon might, in part, explain the heterogeneity in effects observed across studies evaluating distinct populations. For example, Clark et al. [51] did not observe a substantial mean reduction in systolic blood pressure among the entire population receiving a stove intervention in Nicaragua, which included women aged 11–80 years, with a mean age of 35 years; however, the mean reduction among those 40 years and older (-5.9 mmHg [95 % CI: -11.3, -0.4]) was comparable to the within-person average change (-3.1 mmHg [95 % CI: -5.3, -0.8]) observed among the entire Guatemalan study population with a mean age of 53 years after a similar stove intervention [31]. Furthermore, although reduced occurrence of ST-segment depression was associated with the same stove intervention in Guatemala, no evidence of effect modification by age or body mass index was observed [52]. It will be important to consider the restricted age range as well as the somewhat limited variability in body mass index (mean=24.3 $kg/m^2 \pm 3.0$ [standard deviation] at baseline) when comparing these results to future cookstove interventions. It is also important to note that the factors influencing the observed benefits of cookstove interventions are likely not the same for all health endpoints.

Evidence from the ambient air pollution literature supports the importance of investigating factors that may influence the observed benefits of interventions that reduce exposure to air pollution. The implementation of traffic-reduction policies in two large European city-centers resulted in observed health benefits for different socio-economic segments of the respective populations. In London, Tonne et al. reported greater life expectancy benefits among the low socio-economic group [53]. In contrast, Cesaroni et al. reported greater health benefits of traffic-related air pollution reductions among the higher socio-economic group in Rome [54]. The observed differences between the studies are due to differences in the residential make-up of the two cities; those with lower socio-economic status tend to reside in the most polluted, central areas of London, whereas those with higher socio-economic status are more likely to live near the city-center in Rome [53, 54]. Therefore, although differences in baseline health across socio-economic groups were considered, those benefiting most were those that experienced the greater reductions in traffic-related pollution following the policy changes. In other words, the scenarios described focused primarily on differences in exposure opportunity by the "susceptibility" factor (here, socio-economic status). Additionally, since Tonne et al. did not apply different exposure-response functions to the socio-economic groups, the authors stated that the resulting benefits to the lower socio-economic group in London may have been underestimated [53].

Challenges also arise when predicting health benefits for various subgroups of the population if the risk factor that defines the responder subpopulation has a nonlinear or threshold effect on the health endpoint of interest [48]. For example, improvements were not observed in symptoms following an allergen-reducing indoor air quality intervention in a public housing complex among asthmatic children reporting exposure to a psychosocial risk factor (e.g., fear of violence) [55]. Similarly, improved air quality was associated with a slower rate of decline in several lung function parameters among non-obese but not among obese participants in a study of Swiss adults [56]. Counter to initial hypotheses, those with factors typically thought to confer increased susceptibility to the adverse effects of air pollution exposures (e.g., psychosocial factors and obesity) did not experience greater benefits following reductions in air pollution exposures. These types of scenarios suggest that threshold or saturation effects occurring among those highly exposed to a secondary risk factor may overshadow or even negate any potential improvement resulting from a reduction in air pollution [48]. This phenomenon may be a particularly important consideration to discern when estimating benefits from cookstove interventions since the target populations are typically affected by several co-occurring risk factors (e.g., low socio-economic status, poor nutrition, exposures to pesticides), many of which are increasing rapidly in some developing countries (e.g., obesity, diabetes). Particular attention needs to be paid to the ranges of these co-occurring risk factors within and across study populations to obtain valid estimates of exposure-response (i.e., for cumulative and/or interacting risks) and to inform the interpretations of observed differences in results across studies.

Further Challenges

Another obstacle to the valid assessment of exposure-response relationships, and hence a more accurate estimate of predicted health benefits resulting from stove interventions and dissemination efforts, rests within our inability to identify enablers and barriers to cleaner-burning cookstove uptake and sustained use over time [32, 57, 58]. Behavior change is difficult to predict and measure in any public health scenario. The adoption of new cooking technologies may depend on a wide range of factors, including cultural, financial, geographical, familial, and individual factors [59, 60]; inconsistent acceptance of stoves within populations has been commonly observed [59, 61]. In the simplest scenario, these factors confer differences in the opportunity for exposure to air pollution emissions (e.g., older women may not adopt the cookstove as readily as younger women). In this situation, the exposure-response relationships may not be different for various age groups, but younger women will be more likely to experience health improvements than older women because their exposures have been reduced more.

In a more complex scenario, the factors that influence the degree to which a new cookstove is adopted and sustainably used may be the same factors that lead to heterogeneous exposure-response relationships. Although this phenomenon has not been evaluated thoroughly in cookstove research, lessons can be gleaned from other fields. For example, educational attainment is often associated with mortality. Level of education may also play a role in behaviors surrounding smoking, which may mediate the relationship with mortality while simultaneously acting as an effect modifier of the relationship between education and mortality [55]. In order to develop a complete picture it is critical to address both the differential opportunities for exposure to air pollution (and in the case of interventions, factors that may lead to greater behavior changes surrounding the adoption of new stoves) as well as factors that may confer increased responsiveness or different exposure-response curves across categories, as the two scenarios may not be mutually exclusive [62].

Conclusion

Although a limited amount of work has been conducted to characterize those who benefit most from interventions intended to improve air quality (e.g., traffic reduction schemes, indoor air filtration), much remains to be elucidated regarding this question for cookstove interventions. Accurate identification of factors that modify the relationships between reductions in cookstove-related air pollution exposures and improved health endpoints, including the correct identification of the shape of the responses and potential for threshold effects, is not just an academic exercise but information critical to making progress on this global health problem. The global disease burden estimates assume homogeneous exposure-response relationships, yet many of the communities affected by household air pollution exposures also experience a multitude of additional chronic disease risk factors. Many of these co-occurring risk factors are already known or hypothesized to modify the effects of air pollution exposures from various combustion-related sources. The ability to know what to expect from cookstove interventions (i.e., to accurately describe the presence of the subgroup response, as simplified in Figure 1, as being a meaningful shift in health improvement) is crucial to reducing scientific uncertainty and to encourage policy makers to enact change. In order to gain the biggest advances in health improvements, or what may be considered sufficient health improvements in cost-benefit scenarios, answers to these questions may demonstrate the

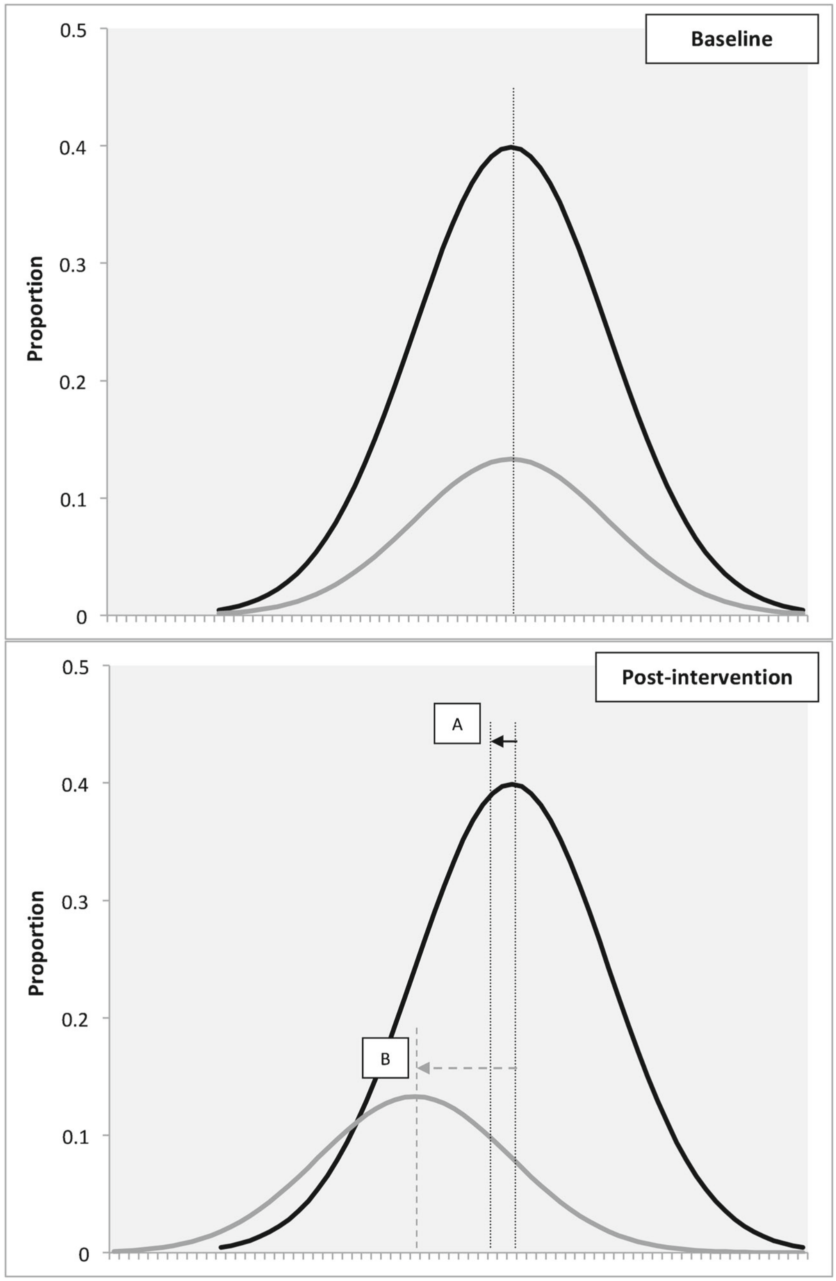

Figure 1 Hypothetical population distribution of a health endpoint measured at baseline and following a cookstove intervention. The *black line* represents the entire target population (mean change in health represented by [A]) and the *gray line* represents the proportion of the population that responds to the reduction in household air pollution (mean change in health represented by [B]). (Adapted from: Weiss B and Bellinger DC. 2006. Social ecology of children's vulnerability to environmental pollutants. Environmental Health Perspectives 114: 1479-1485) [63]

importance of developing co-interventions aimed at reducing more than one risk factor. Despite the challenges and knowledge gaps discussed here and elsewhere, large-scale and ambitious initiatives for the dissemination of cleaner-burning stoves are underway or planned [1, 49, 63]. These international efforts are proving to be a critical impetus for the scientific research sector to provide credible evidence on the exposure-response relationships among potentially susceptible population subgroups. If the relationships between these additional risk factors and household air pollution are correctly specified, we will gain a much better understanding of the health patterns observed in these vulnerable communities—those often experiencing elevated exposures to poverty, psychosocial stressors, other environmental pollutants, and comorbid conditions, all of which have been implicated within the multifactorial nature of the health conditions commonly associated with household air pollution.

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Compliance with Ethics Guidelines

Conflict of Interest Maggie L. Clark and Jennifer L. Peel declare that they have no conflicts of interest.

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References

Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

1. Anenberg SC, Balakrishnan K, Jetter J, Masera O, Mehta S, Moss J, et al. Cleaner cooking solutions to achieve health, climate, and economic cobenefits. Environ Sci Technol. 2013;47:3944–52.
2. Martin II WJ, Glass RI, Araj H, Balbus J, Collins FS, Curtis S, et al. Household air pollution in low-and middle-income countries: health risks and research priorities. PLoS Med. 2013;10(6):e1001455.
3.• Smith KR, Bruce N, Balakrishnan K, Adair-Rohani H, Balmes J, Chafe Z, et al. Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. Annu Rev Public Health. 2014;35:185–206. *This paper provides an explanation of the methods used to quantify the comparative risk of household air pollution as part of the Global Burden of Disease project*.
4. Naeher LP, Brauer M, Lipsett M, Zelikoff JT, Simpson CD, Koenig JQ, et al. Woodsmoke health effects: a review. Inhal Toxicol. 2007;19(1):67–106.
5. Clark ML, Peel JL, Balakrishnan K, Breysse P, Chillrud SN, Naeher LP, et al. Household air pollution related to solid fuel use and health: the need for improved exposure assessment. Environ Health Perspect. 2013;121(10):1120–8.
6. Saksena S, Thompson L, Smith KR. 2003. The Indoor Air Pollution and Exposure Database: Household Pollution Levels in Developing Countries. Version 1.1. Geneva:World Health Organization. Available: http://ehs.sph.berkeley.edu/hem/content/iapi.pdf.
7. World Health Organization. 2006. WHO Air Quality Guidelines for Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide. Global Update. Summary of risk assessment. Geneva: WHO; 2005. Available: http://apps.who.int/iris/bitstream/10665/69477/1/WHO_SDE_PHE_OEH_06.02_eng.pdf?ua=1.; Accessed April 7, 2014.
8. Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet. 2012;380:2224–60.
9. Dherani M, Pope D, Mascarenhas M, Smith KR, Weber M, Bruce N. Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis. Bull World Health Organ. 2008;86(5):390–8.
10. Stern-Nezer J. 2010. Chronic obstructive pulmonary disease and biomass fuel combustion: systematic review and meta-analysis. Stanford University.
11. Hu G, Zhou Y, Tian J, Yao W, Li J, Li B, et al. Risk of COPD from exposure to biomass smoke: a meta-analysis. Chest J. 2010;138(1):20–31.
12. Po JY, FitzGerald JM, Carlsten C. Respiratory disease associated with solid biomass fuel exposure in rural women and children: systematic review and meta-analysis. Thorax. 2011;66(3):232–9.
13. Hosgood HD, Wei H, Sapkota A, Choudhury I, Bruce N, Smith KR, et al. Household coal use and lung cancer: systematic review and meta-analysis of case–control studies, with an emphasis on geographic variation. Int J Epidemiol. 2011;40(3):719–28.
14. Kurmi OP, Arya PH, Lam KBH, Sorahan T, Ayres JG. Lung cancer risk and solid fuel smoke exposure: a systematic review and meta-analysis. Eur Respir J. 2012;40(5):1228–37.
15. Torres-Duque C, Maldonado D, Pérez-Padilla R, Ezzati M, Viegi G. Biomass fuels and respiratory diseases: a review of the evidence. Proc Am Thorac Soc. 2008;5(5):577–90.
16. Diette GB, Accinelli RA, Balmes JR, Buist AS, Checkley W, Garbe P, et al. Obstructive lung disease and exposure to burning biomass fuel in the indoor environment. Global heart. 2012;7(3):265–70.
17. Kurmi OP, Semple S, Simkhada P, Smith WC, Ayres JC. COPD and chronic bronchitis risk of indoor air pollution from solid fuel: a systematic review and meta-analysis. Thorax. 2010;65(3):221–8.
18. Pokhrel AK, Smith KR, Khalakdina A, Deuja A, Bates MN. Case-control study of indoor cooking smoke exposure and cataract in Nepal and India. Int J Epidemiol. 2005;34(3):702–8.
19. McCracken JP, Wellenius GA, Bloomfield GS, Brook RD, Tolunay HE, Dockery DW, et al. Household air pollution from solid fuel use: evidence for links to CVD. Global Heart. 2012;7(3):223–34.
20. Pope DP, Mishra V, Thompson L, Siddiqui AR, Rehfuess EA, Weber M, et al. Risk of low birth weight and stillbirth associated with indoor air pollution from solid fuel use in developing countries. Epidemiol Rev. 2010;32(1):70–81.
21. Mishra P, Hansen EH, Sabroe S, Kafle KK. Socio-economic status and adherence to tuberculosis treatment: a case-control study in a district of Nepal. Int Jo Tuberc Lung Dis : Off J Int Union Against Tubercu Lung Dis. 2005;9(10):1134–9.
22. Behera D, Aggarwal G. Domestic cooking fuel exposure and tuberculosis in Indian women. Indian Chest Dis Allied Sci. 2010;52(3):139–43.
23. Pokhrel AK, Bates MN, Verma SC, Joshi HS, Sreeramareddy CT, Smith KR. Tuberculosis and indoor biomass and kerosene use in Nepal: a case-control study. Environ Health Perspect. 2010;118(4):558–64.
24. Dix-Cooper L, Eskenazi B, Romero C, Balmes J, Smith KR. Neurodevelopmental performance among school age children in rural Guatemala is associated with prenatal and postnatal exposure to carbon monoxide, a marker for exposure to woodsmoke. Neurotoxicology. 2012;33(2):246–54.
25. Smith KR, Peel JL. Mind the gap. Environ Health Perspect. 2010;118(12):1643–5.
26. Smith KR, Uma R, Kishore VVN, Zhang JF, .Joshi V, Khalil MAK. Greenhouse implications of household stoves: an analysis for India. Annu Rev Energy Environ. 2000; 25: p. 741.
27. Chapman RS, He X, Blair AE, Lan Q. Improvement in household stoves and risk of chronic obstructive pulmonary disease in Xuanwei, China: retrospective cohort study. BMJ. 2005;331(7524):1050.
28. Shen M, Chapman RS, Vermeulen R, Tian L, Zheng T, Chen BE, et al. Coal use, stove improvement, and adult pneumonia mortality in Xuanwei, China: a retrospective cohort study. Environ Health Perspect. 2009;117:261–6.
29. Sinton JE, Smith KR, Peabody JW, Yaping L, Xiliang Z, Edwards R, et al. An assessment of programs to promote improved household stoves in China. Energy Sustain Dev. 2004;8(3):33–52.
30.•• Smith KR, McCracken JP, Weber MW, Hubbard A, Jenny A, Thompson LM, et al. Effect of reduction in household air pollution on childhood pneumonia in Guatemala (RESPIRE): a randomised controlled trial. Lancet. 2011;378(9804):1717–26. *This article, describing the first randomized controlled trial evaluating the impact of a cleaner burning stove on childhood pneumonia, reported an exposure-response curve that suggests greater predicted health benefits at lower levels of exposure*.
31. McCracken JP, Smith KR, Diaz A, Mittleman MA, Schwartz J. Chimney stove intervention to reduce long-term wood smoke

exposure lowers blood pressure among Guatemalan women. Environ Health Perspect. 2007;115(7):996–1001.
32. Rehfuess EA, PuzzoloE SD, Pope D, Bruce NG. Enablers and barriers to large-scale uptake of improved solid fuel stoves: a systematic review. Environ Health Perspect. 2014;122(2):120–30.
33. Sacks JD, Stanek LW, Luben TJ, Johns DO, Buckley BJ, Brown JS, et al. Particulate matter-induced health effects: who is susceptible? Environ Health Perspect. 2011;119:446–54.
34. Baccarelli A, Cassano PA, Litonjua A, Park SK, Suh H, Sparrow D, et al. Cardiac autonomic dysfunction effects from particulate air pollution and protection by dietary methyl nutrients and metabolic polymorphisms. Circulation. 2008;117(14):1802–9.
35. Bell ML, Ebisu K. Environmental inequality in exposures to airborne particulate matter components in the United States. Environ Health Perspect. 2012;120:1699–704.
36. Chen E, Schreier HMC, Strunk RC, Brauer M. Chronic traffic-related air pollution and stress interact to predict biologic and clinical outcomes in asthma. Environ Health Perspect. 2008;116: 970–5.
37. Kannan S, Dvonch JT, Schulz AJ, Israel BA, Mentz G, House J, et al. Exposure to fine particulate matter and acute effects on blood pressure: effect modification by measures of obesity and location. J Epidemiol Community Health. 2010;64(01):68–74.
38. Lu KD, Breysse PN, Diette GB, Curtin-Brosnan J, Aloe C, Williams D, et al. Being overweight increases susceptibility to indoor pollutants among urban children with asthma. J Allergy Clin Immunol. 2013;131:1017–23.
39. O'Neill MS, Jerrett M, Kawachi I, Levy JI, Cohen AJ, Gouveia N, et al. Health, wealth, and air pollution: advancing theory and methods. Environ Health Perspect. 2003;111:1861–70.
40. Romieu I, Téllez-Rojo MM, Lazo M, Manzano-Patiño A, Cortez-Lugo M, Julien P, et al. Omega-3 fatty acid prevents heart rate variability reductions associated with particulate matter. Am J Respir Crit Care Med. 2005;172(12):1534–40.
41. Zanobetti A, Schwartz J. Race, gender, and social status as modifiers of the effects of PM10 on mortality. J Occup Environ Med. 2000;42:469–74.
42. Baumgartner J, Schauer JJ, Ezzati M, Lu L, Cheng C, Patz JA, et al. Indoor air pollution and blood pressure in adult women living in rural China. Environ Health Perspect. 2011;119(10): 1390–5.
43. Lee MS, Hang JQ, Zhang FY, Dai JL, Su L, Christiani DC. In-home solid fuel use and cardiovascular disease: a cross-sectional analysis of the Shanghai Putuo study. Environ Heal. 2012;11:18.
44. Clark ML, Bazemore H, Reynolds SJ, Heiderscheidt JM, Conway S, Bachand AM, et al. A baseline evaluation of traditional cook stove smoke exposures and indicators of cardiovascular and respiratory health among Nicaraguan women. Int J Occup Environ Health. 2011;17(2):113–21.
45. Rajagopalan S, Brook RD. The indoor-outdoor air-pollution continuum and the burden of cardiovascular disease: an opportunity for improving global health. Global Heart. 2012;7(3):207–13.
46. Bloomfield GS, Lagat DK, Akwanalo OC, Carter EJ, Lugogo N, Vedanthan R, et al. Conditions that predispose to pulmonary hypertension and right heart failure in persons exposed to household air pollution in LMIC. Global Heart. 2012;7(3):249–59.
47. Levy JI, Greco SL, Spengler JD. The importance of population susceptibility for air pollution risk assessment: a case study of power plants near Washington, DC. Environ Health Perspect. 2002;110:1253–60.
48. Clougherty JE, Kubzansky LD. A framework for examining social stress and susceptibility to air pollution in respiratory health. Environ Health Perspect. 2009;117:1351–8.
49. Martin 2nd WJ, Glass RI, Balbus JM, Collins FS. Public health. A major environmental cause of death. Science. 2011;334(6053): 180–1.
50. Weiss B, Bellinger DC. Social ecology of children's vulnerability to environmental pollutants. Environ Health Perspect. 2006;114: 1479–85.
51. Clark ML, Bachand AM, Heiderscheidt JM, Yoder SA, Luna BR, Volckens J, et al. Impact of an improved biomass stove intervention on blood pressure in Nicaraguan women. Indoor Air. 2013;23(2): 105–14.
52. McCracken J, Smith KR, Stone P, Diaz A, Arana B, Schwartz J. Intervention to lower household wood smoke exposure in Guatemala reduces ST-segment depression on electrocardiograms. Environ Health Perspect. 2011;119:1562–8.
53. Tonne C, Beevers S, Armstrong B, Kelly F, Wilkinson P. Air pollution and mortality benefits of the London Congestion Charge: spatial and socioeconomic inequalities. Occup Environ Med. 2008;65:620–7.
54. Cesaroni G, Boogaard H, Jonkers S, Porta D, Badaloni C, Cattani G, et al. Health benefits of traffic-related air pollution reduction in different socioeconomic groups: the effect of low-emission zoning in Rome. Occup Environ Med. 2012;69:133–9.
55. Clougherty JE, Levy JI, Hynes HP, Spengler JD. A longitudinal analysis of the efficacy of environmental interventions on asthma-related quality of life and symptoms among children in urban public housing. J Asthma. 2006;43(5):335–43.
56. Schikowski T, Schaffner E, Meier F, Phuleria HC, Vierkötter A, Schindler C, et al. Improved air quality and attenuated lung function decline: modification by obesity in the SAPALDIA cohort. Environ Health Perspect. 2013;121(9):1034–9.
57. Pine K, Edwards R, Masera O, Schilmann A, Marron-Mares A, Riojas-Rodriguez H. Adoption and use of improved biomass stoves in Rural Mexico. Energ Sustain Dev. 2011;15(2):176–83.
58. Ruiz-Mercado I, Masera O, Zamora H, Smith KR. Adoption and sustained use of improved cookstoves. Energy Policy. 2011;39: 7557–66.
59. Perez-Padilla R, Schilmann A, Riojas-Rodriguez H. Respiratory health effects of indoor air pollution. Int J Tuberc Lung Dis. 2010;14(9):1079–86.
60. Naeher LP. Biomass-fueled intervention stoves in the developing world: potential and challenges. Am J Respir Crit Care Med. 2009;180(7):586–7.
61. Troncoso K, Castillo A, Masera O, Merino L. Social perceptions about a technological innovation for fuelwood cooking: case study in rural Mexico. Energy Policy. 2007;35(5):2799–810.
62. Helene N, Theis L, Merete O, Finn D, Ingelise A, Eva P, et al. Education and cause-specific. Mortality: The Mediating Role of Differential Exposure and Vulnerability to Behavioral Risk Factors. Epidemiology published ahead of print; 2014. doi:10.1097/EDE.0000000000000080.
63. Global Alliance for Clean Cookstoves. 2013. Global Alliance for Clean Cookstoves Website. Available from: http://www.cleancookstoves.org/.