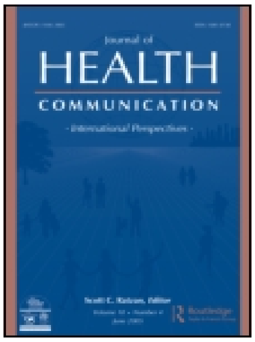

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Quantitative Stove Use and Ventilation Guidance for Behavior Change Strategies

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Achieving World Health Organization air quality targets and aspirational fuel savings targets through clean cooking solutions will require high usage rates of high-performing products and low usage rates of traditional stoves. Catalyzing this shift is challenging as fuel and stove use practices associated with new technologies generally differ from those used with traditional technologies. Accompanying this shift with ventilation improvements can help further reduce exposure to emissions of health damaging pollutants. Behavior change strategies will be central to these efforts to move users to new technologies and minimize exposure to emissions. In this article, the authors show how behavior change can be linked to quantitative guidance on stove usage, household ventilation rates, and performance. The guidance provided here can help behavior change efforts in the household energy sector set and achieve quantitative goals for usage and ventilation rates.

The majority of households in developing countries rely on solid fuels for their primary cooking energy (Bonjour et al., 2013) and exposure to pollutants from combusting these fuels are estimated to be responsible for four million premature deaths per year (Lim et al., 2012). Unsustainable use of wood and charcoal can also lead to deforestation and ecological degradation (Ghilardi, Mwampamba, & Dutt, 2013; Singh, Rawat, & Verma, 2010). There are a variety of promising technologies and fuels with strong fuel and emissions performance (Jetter et al., 2012; Smith et al., 2000) that can address the health and environment challenges of using solid fuels.

Laboratory-based evaluations, used to compare the performance and potential impacts of these different technologies, have been integrated into a standardized guidance frame work through the International Standardized Organization's International Workshop Agreement 11:2012: Guidelines for Evaluating Cookstove Performance (International Standardized Organization, 2012). These interim guidelines provide tiered levels of efficiency, emissions, and safety performance as quantitative and aspirational goals for technology developers and to help stakeholders make informed decisions related to stove and fuel performance. Previous evaluations and comparisons often relied on difficult to define terms such as *inefficient, clean*, and *improved*. The tiers provide more objective performance ranges for cooking technologies, starting from Tier 0 at the lower end. The boundary for Tier 0 range of performance is defined as equivalent to, or worse than the performance of traditional three-stone-fires. Tiers 1 to 3 represent interim performance ranges, and Tier 4 defines aspirational performance goals. The Tier 4 goal for indoor emissions is explicitly linked with emission performance required to meet World Health Organization (WHO) air quality targets for particulate matter and carbon monoxide. Formal standards of the International Standardized Organization, which have more regulatory weight than International Workshop Agreements, for cookstove performance are in development.

Similar quantitative guidance has not been provided for cookstove usage, which is equally critical for attaining health and environmental benefits sought through clean cooking solutions. Usage of the traditional stove in a household should be minimized, with the new stove usage maximized to attain the greatest benefits. The importance of promoting this transition was recently underscored by a study in India, which showed that even when a relatively high performing stove was adopted into homes, traditional stove usage was unchanged (Pillarisetti et al., 2014). Stove usage guidance would be an especially valuable tool for organizations using behavior change strategies to increase acquisition and to ensure correct and consistent usage of new stoves or fuels. Specifically, linking stove usage to impacts would help organizations set goals for their behavior change interventions, and measure progress toward those goals.

Behavior change strategies can also focus on other factors that influence the effectiveness of a given intervention. Kitchen ventilation and cooking location are of particular interest because they have a large effect on indoor air quality (Johnson, Lam, Brant, Gray, & Pennise, 2011; Rosa et al., 2014; Ruth et al., 2013), and can be improved through behavior change strategies (Barnes, 2014).

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To illustrate how behavior change strategies can be informed by quantitative guidance frameworks, here we use the approach in Johnson and Chiang (provisionally accepted), which integrated stove performance and usage by using the Tiers of Performance framework in the International Workshop Agreement 11:2012 to provide quantitative guidance on likely impacts with different performance-usage scenarios. The objective of this article is to show how key findings from this study can be applied to household energy activities with behavior change components. We also extend the model and results from Johnson and Chiang (provisionally accepted) to provide quantitative guidance on ventilation, another important target for behavior change interventions.

Relating Stove Usage, Ventilation, and Impacts

A key finding from Johnson and Chiang (provisionally accepted) was that meeting the WHO Interim 1 target for PM2.5 (particulate matter less than 2.5 microns in aerodynamic diameter) require near complete displacement of three-stone-fires with stoves that perform at the cleanest International Workshop Agreement 11:2012 indoor emissions performance levels. The authors show that mean 24-hour PM2.5 concentrations in the kitchen are estimated to rise above WHO guidance levels after just 1 hour of three-stone-fire use, or after 3 hours of traditional charcoal use. The modeled three-stone-fire's effect on household air quality implies that near exclusive use of stoves with indoor emissions Tier 4 performance would be required to meet the WHO PM2.5 target in kitchens. More modest air quality targets and health benefits could be achieved with intermediate performance-usage scenarios. For example, an estimated 75% reduction in PM2.5 relative to exclusive three-stone-fire use could be achieved with at least 77% displacement of the three-stone-fire with an indoor emissions Tier 4 stove, or 86% displacement of the three-stone-fire with a Tier 3 stove (Johnson & Chiang, provisionally accepted).

These scenarios, however, only considered a single ventilation rate (15 air changes per hour), consistent with the International Workshop Agreement 11:2012.[1] Recent systematic laboratory studies have shown that increased ventilation achieved through opening doors, windows, or venting holes can reduce indoor concentrations of PM2.5 by 60% to 98% (Grabow, Still, & Bentson, 2013; Ruth et al., 2013). In Rwanda, Rosa and colleagues (2014) reported median PM2.5 concentrations in the kitchen were half as much for those cooking outdoors compared to indoors (Rosa et al., 2014). Using a similar version of the air quality model as presented here, Johnson and colleagues (2011) reported that ventilation rate was responsible for 34% to 42% of the variability in modeled kitchen concentrations of PM2.5 and CO in Southern India.[2] Figure 1 shows empirical data on the effect of ventilation on carbon monoxide concentrations from that study. The strong inverse relationship between ventilation rate and carbon monoxide concentrations shows the considerable effect of ventilation on indoor air quality.

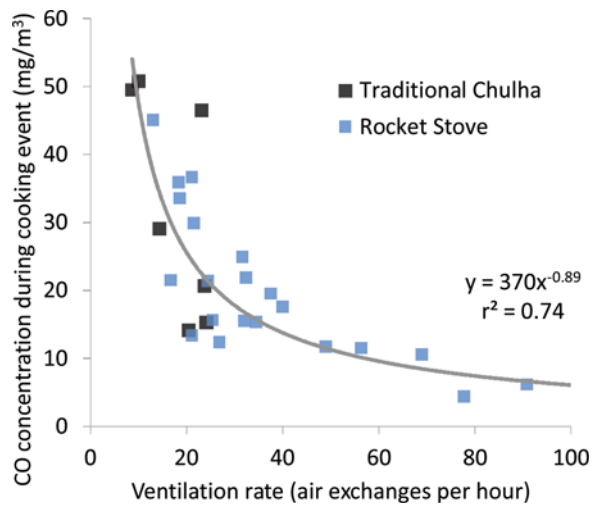

Fig. 1. Kitchen concentration of carbon monoxide versus ventilation rate for homes in Southern India.

To provide more relevant guidance for ventilation interventions, including for location-specific scenarios, the model used in Johnson and Chiang (provisionally accepted) was applied to relate indoor air quality and ventilation for various performance-usage scenarios. Figure 2 shows these scenarios for 100% and 75% three-stone-fire displacement with the WHO Interim 1 PM2.5 target for context. The best scenarios again require 100% displacement of the three-stone-fire, although at high ventilation rates (>35 air exchanges per hour), stoves with indoor emissions Tier 3 performance are also estimated to achieve the WHO target. At 75% three-stone-fire displacement, no combination of stove performance and ventilation rate is estimated to meet the WHO target, although all but Tier 1 indoor emissions stoves could reduce the mean indoor $PM_{2.5}$ concentrations to 100 $\mu g/m^3$ depending on the ventilation. The nonlinear relationships in Figures 1 and 2 also show that ventilation has its largest relative impact at low ventilation rates, with the curves generally leveling off after approximately 20 to 25 air exchanges per hour.

Johnson and Chiang (provisionally accepted) also provided guidance on how stove usage relates to household fuel consumption. While the highest fuel savings (~70%) are clearly achieved with exclusive use of the highest performing stove, there are other performance-usage scenarios that may be more realistic. For example, the authors estimated that 50% fuel savings could be achieved by entirely displacing the three-stone-fire with a thermal efficiency Tier 2 stove, or ~80% three-stone-fire displacement with a Tier 3 stove, or ~70% three-stone-fire

[1]For context, rural kitchens in developing countries generally have high ventilation rates (~10–40 air exchanges per hour (Bhangar, 2006; Cowlin, 2005; Park & Lee, 2003; Saksena, Thompson, & Smith, 2003) in comparison with those in developed regions. Guidance from the American Society of Heating, Refrigerating and Air Conditioning Engineers, for example, recommend that use of kitchen fans in the United States should result in five air changes per hour (ASHRAE, 2010).

[2]More technical details on the air quality model's performance can be found in Johnson and colleagues (2011).

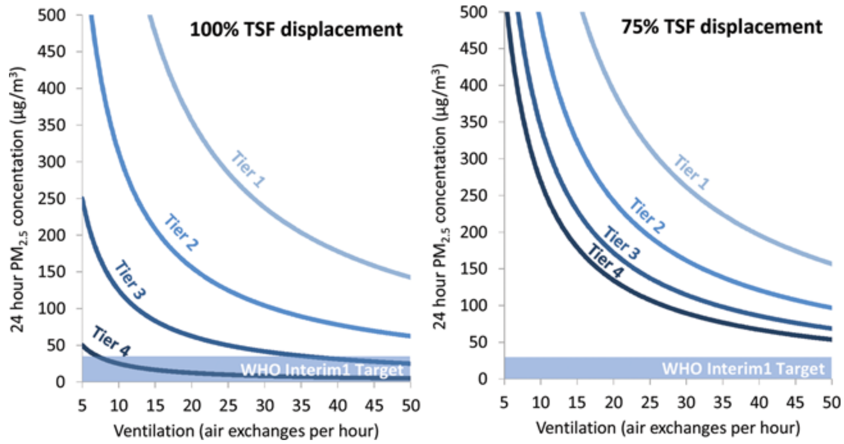

Fig. 2. Twenty-four-hour mean kitchen concentrations versus ventilation rate for different indoor emission performance levels.

displacement with a Tier 4 stoves. These multiple pathways illustrate how balancing usage and stove performance may be used to meet specific fuel consumption goals.

Implications

Stove and fuel performance are fundamental to a technology's potential to achieve WHO indoor air quality targets within kitchens and reduce fuel consumption. Additional levers are also important for realizing these benefits, including usage of the new stove, displacement of the traditional stove, and ventilation. By modeling these parameters together, we have identified specific combinations of factors that are needed to achieve specific targets for indoor air pollution and reduced fuel use. Broader implications of this guidance are discussed in Johnson and Chiang (provisionally accepted). Similar to the quantitative goals set for stove performance in the International Standardized Organization's International Workshop Agreement, the guidance provided here sets quantitative goals to guide the behavior change efforts that are critical to maximizing the benefits of new technologies.

Behavior change strategies can have large impacts in places where cooking takes place indoors with limited ventilation by focusing on changing cooking locations (e.g., indoors/outdoors), keeping windows and doors open, elevating stoves to placements closer to ventilation openings, and adding ventilation openings to kitchens. It is also important to note that these behavior change strategies may require complimentary structural changes such as the addition of a raised platform for the stove and/or venting openings in a kitchen. Figure 2 provides specific guidance to help determine whether the ventilation strategies are meeting their targets. For example, based on the nonlinear relations between ventilation and indoor concentrations, ventilation rates of 25 to 30 air changes per hour appear to provide a reasonable balance of benefit and feasible ventilation targets.

Behavior change efforts may be most effective for reducing exposures when applied to address communitywide adoption and usage of clean technologies. Emissions from cookstoves contribute substantially to ambient air quality in addition to household air pollution. In some regions, cookstove contributions to ambient particulate matter are estimated at 37% (Chafe et al., 2014), and certainly much higher on the small spatial scales of communities where solid fuel is the primary household energy source for cooking and heating. Reducing emissions at the community level through widespread adoption of clean technologies is therefore critical for overall air pollutant concentrations within and outside the household, and in turn increasing the likelihood of lowering exposures to levels that meet WHO air quality targets.

To maximize benefits of stoves, behavior change strategies should focus on transitioning users from traditional to new technologies, while helping users address their range of cooking needs with the cleanest, most efficient, and feasible set of solutions. Therefore, behavior change strategies should start with understanding consumer segmentation on cooking needs and willingness to adopt new technologies. Based on this consumer information, technologies should be matched to user needs, with additional targeted training, education, and incentives to help displace use of the traditional stove. The strategy subsequently outlined is designed to help organizations optimize these behavior change strategies based on the target consumer segments, available technology, and goals for air quality and fuel use.

On the basis of the quantitative guidance, specific behavior change strategies can be selected and combined to achieve goals for usage and ventilation (see Figure 3). This framework can also be used to identify when behavior change strategies are not enough or when a higher performing stove is needed before behavior change strategies will make a difference. This framework does not provide guidance on which specific behavior change strategies should be selected. However, based on studies such as those in this special issue, the quantitative guidance could be expanded in the future to provide estimates of the likely benefits that are achievable with specific behavior change strategies. Thus, when planning future activities, clean cooking sector organizations can use this quantitative guidance to develop goals and then select the combination of specific strategies that are likely to achieve these goals.

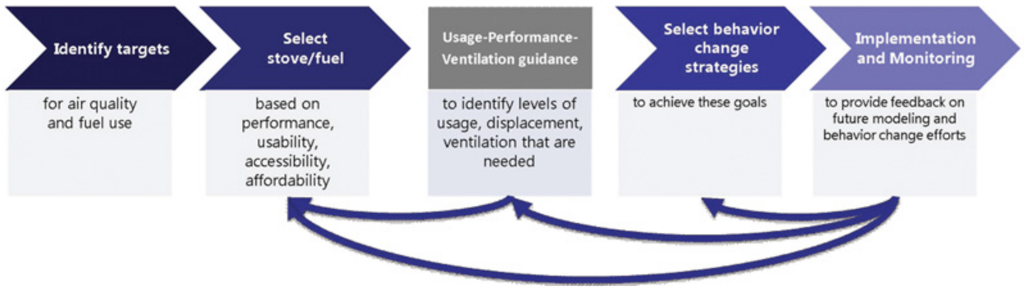

Fig. 3. Framework for applying usage-performance-ventilation guidance. The first step for behavior intervention activities is to identify targets for improving air quality and fuel use and selecting the stove/fuel combination that addresses the context-specific needs, based on performance, usability, accessibility, and affordability. The usage-performance-ventilation guidance provided in this article can be used to identify the levels of usage, displacement, and ventilation needed to reach the selected targets with the selected technology. A set of behavior change strategies can then be selected that can meet these goals of usage, displacement, and ventilation. If the original targets cannot be achieved through any feasible combination of usage, displacement, and ventilation, the stove/fuel should be reconsidered. Other levers for improving air quality may also be considered. If these options are not possible, this framework still provides a realistic understanding of what targets can or cannot be reached. The results of behavior change activities can then be used to provide feedback for improving the computational model and developing more specific guidance on the likely effects of specific strategies.

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