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New Approaches to Performance Testing of Improved Cookstoves

MICHAEL JOHNSON,[†] RUFUS EDWARDS,[*,†] VICTOR BERRUETA,[‡] AND OMAR MASERA[§]

Department of Epidemiology, School of Medicine, University of California at Irvine, Irvine, California 92697-3957, Interdisciplinary Group for Appropriate Rural Technology (GIRA), Pátzcuaro 61609, Mexico, and Center for Ecosystems Research, National Autonomous University of Mexico, Morelia 58190, Mexico

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Monitoring and evaluation of improved cookstove performance is a critical factor in program success; however, consistent evidence indicates water boiling tests and controlled cooking tests are not representative of stove performance during daily cooking activities, and there is no ability to link these tests to kitchen performance tests during normal daily cooking activities. Since emissions from cookstoves contribute heavily to regional estimates of carbonaceous aerosols and other short-lived greenhouse species and given the current importance of stove performance tests as a basis for global climate prediction models and IPCC inventories, improvements in performance testing are critical to derive more representative estimates. Here real-time combustion efficiencies and emissions rates from daily burn cycles of open fires and improved stoves in Mexico are used to propose a new approach to stove performance testing, using simple and economical measurement methods, based on replication of the distribution of emission rates and combustion efficiencies seen during daily cooking activities in homes. This approach provides more relevant information for global climate models and inventories, while also providing a means to recreate representative emissions profiles in a laboratory setting for technical analyses. On the basis of emission rates and combustion efficiencies during normal daily cooking, we suggest performance criteria that can be used as benchmarks for laboratory testing of improved stoves in the absence of site-specific information, although requiring confirmation by field testing during daily cooking activities.

Introduction

With limited development resources available and an increasing array of worthy actions to be taken to improve rural health, livelihoods, and global climate concerns, the need to compare the cost-effectiveness of alternatives is more pronounced than ever. For improved stove programs this includes a systematic monitoring and evaluation program of stove performance, in terms of combustion efficiencies, manufacturing quality, and stove usage, as this was among the most important factors explaining the differences in success between the Indian National Programme for Improved Chulhas and the Chinese National Improved Stove program (*1*). In addition to direct stove performance measures, systematic assessments using standardized methods should also be made of cobenefits to health, reductions in greenhouse species including black carbon and other short-lived species, and improved economic and social conditions to allow comprehensive evaluation and comparison of cost-effectiveness between alternatives.

In spite of well-documented problems associated with use of the three different stove performance tests developed in the 1980s—the water boiling test (WBT), the controlled cooking test (CCT), and the kitchen performance test (KPT)—little research has focused on improvements of stove testing methods. Critical has been the inability to link directly the results of the three tests in a consistent manner or to synthesize the results of the hot-start, cold-start and simmering phases of the water boiling test into a meaningful assessment of overall stove performance. Perhaps foremost, however, is that overall efficiencies during daily cooking activities in KPTs have been substantially misrepresented by water boiling tests (*2*–*4*). Recent studies using more sophisticated measurement methods have confirmed these earlier results demonstrating that WBTs of open fire stoves have underestimated emissions of productions of incomplete combustion by 77% (*5*) and particulate matter by 370% (*6*) relative to normal daily stove use. Conversely, WBTs were found to overestimate products of incomplete combustion (PICs) emissions from improved vented stoves by 40% relative to daily cooking activities (*5*), leading to substantial underestimation of reductions in PICs and carbon offsets as a result of installing improved stoves (*7*). Similarly, fuel saving estimates based on controlled tests have also proved misleading as consumption during daily cooking activities in KPTs was not represented by either WBTs or CCTs (*8, 9*), resulting in misplaced expectations of national programs (*10*). The nonrepresentative carbon emissions and efficiency estimates should not be surprising given that controlled burn cycles for specific tasks cannot encompass the variety of daily stove use activities, with up to 90% of stove tasks in some regions not involving boiling water (*11*). In addition, since efficiency varies significantly as a function of power output during the different phases of the burn cycle, a single efficiency is not a good performance indicator (*12*). Although it is well-acknowledged that laboratory results should not be expected to represent fuel economy in practice (*13*), technical and policy communities have frequently used these tests as a basis for wider ranging predictions, including as a basis for global climate prediction models and IPCC inventories (*14, 15*), which may result in considerable errors in regional greenhouse gas emissions estimates.

In the current paper, we use real-time combustion efficiencies and emissions rates from daily burn cycles of open fires and improved stoves in Mexico to propose a new, criteria-based approach to stove performance testing based on replication of the distribution of emission rates and combustion efficiencies seen during daily cooking activities in homes. This approach links laboratory evaluations to burn cycles during daily cooking activities replicating burn cycles measured in the field, while using simple and economical measurement methods.

Methods

Patsari Stoves. Patsari stoves have been disseminated primarily in the Purépecha region of central Mexico by GIRA

* Corresponding author phone: (949) 824 4731; email: edwardsr@uci.edu.
† University of California at Irvine.
‡ Interdisciplinary Group for Appropriate Rural Technology (GIRA).
§ National Autonomous University of Mexico.

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A.C. The Patsaris have an insulated combustion chamber below a round metal cooking surface with tunnels that conduct the combustion gases to smaller secondary chambers for low-power cooking tasks and a flue to vent smoke outside the home. Patsaris have undergone several iterations as they were refined to meet the needs of the population and increase the overall energy efficiency. In this study, the original mud−cement Patsari and currently disseminated brick Patsari were assessed, as they are the most common stoves in use, and were compared to the traditional three-stone open fire or u-shaped cookstoves. Photographs and more details on stove design and dissemination strategy are presented in the Supporting Information.

Water Boiling Tests. The WBT was developed as a standard international method to compare the efficiencies of different stoves (*16*). Briefly, the test starts with a high-power boiling phase using a fixed amount of water followed by a low-power simmering phase, intended to simulate cooking rice or legumes. Fuel is added as needed during the high-power phase to achieve boiling temperature as quickly as possible, then the power is reduced to the minimum needed to maintain simmering for the low-power phase. WBTs were conducted in GIRA's simulated kitchen using protocols described in detail in Berrueta et al. (*9*). Fuel/stove combinations tested were pine/open fire, oak/open fire, pine/mud−cement Patsari, and oak/mud−cement Patsari. No differences in nominal combustion efficiency (NCE), defined as the fraction of fuel carbon emitted as CO_2, were observed between pine and oak during WBTs (*5*); thus, results for pine and oak are combined. More details on the WBT and fuel wood can be found in Supporting Information. For kitchen performance tests in homes, fuel use was not restricted since participants performed their normal daily activities with the stove. Pine and oak were the predominant fuel woods used in homes; however, at least six wood species were also employed, consisting of combinations of brushwood, carpenter scraps, and trunk wood, which are typically larger than the uniform 2−5 cm pieces recommended in the WBT. Wood moisture did not account for the differences in NCE between WBTs and daily cooking activities, as wood moisture content was very similar (8.1 ± 2.6% and 8.3 ± 2.1% on a wet basis for WBTs and in-homes, respectively).

Emissions Sampling. Emission sampling within homes was conducted from before breakfast to the completion of the main afternoon meal and was carried out with an identical sampling setup to that used for WBTs. Homes were selected with assistance from local community leaders and were located in San Juan Tumbio and Rancho de Álvarez, rural communities of less than 2000 people typical of the Purépecha region. Open fire CO and CO_2 emissions were sampled from the center of the flue exhaust section of a stainless steel portable hood, measuring 1 × 1 m at its base and placed directly over the center of the combustion zone. A small metal fan drew emissions through the hood exhaust, resulting in a face velocity of 0.11 m s^{-1} and flue velocity of 6.2 m s^{-1}. See Supporting Information for more details on the hood.

Patsari CO_2 and CO emission samples were collected via a sampling probe inserted into the center of the flue 70 cm above the stovetop. Although there may have been a small amount of fugitive emissions during sampling, in practice, the draw of the chimney captured the vast majority of emissions, and fugitive emissions were rarely observed. Zhang et al. (*17*) also reported no difference in emissions ratios when sampling directly from a vented stove flue or from a hood placed over the stove and flue.

Semicontinuous CO_2 and CO concentrations in the open fire hood exhaust and Patsari flue were measured and logged at 1 min intervals with a flue gas analyzer (Autologic), with simultaneous collection of gas samples for gas chromatography (*5*). The flue gas analyzer was calibrated with NIST-traceable CO_2 and CO reference gas (Scott Specialty Gases), and background concentrations were subtracted by zeroing the unit in room air for a minimum of 5 min before and after sampling. Samples were collected for six open fire WBTs, eight mud−cement Patsari WBTs, four open fires in homes, five mud−cement Patsaris in homes, and four brick Patsaris in homes.

Since minute-by-minute monitoring of all emitted carbon species was not possible with gas chromatography, minute-by-minute $CO_2/(CO_2 + CO)$ ratios (as carbon) were used as a proxy for real-time NCE. Linear regression of $CO_2/(CO_2 + CO)$ ratios against NCE demonstrated excellent agreement with a Pearson r^2 of 0.98 ($p < 0.001$) for open fires and 0.94 ($p < 0.001$) for Patsari stoves (*7*) as CO_2 and CO account for almost all emitted carbon species by mass (*5*).

Emission rates, defined as emitted carbon per minute, were determined using the fraction of the total carbon emitted by weighting the instantaneous emission of CO and CO_2 by the total amount of CO and CO_2 emitted during the burn

$$\mathrm{ER} = C_T \times \frac{(CO_2 + CO)_P}{(CO_2 + CO)_T} \quad (1)$$

where ER is the emission rate [g[c] min^{-1}], C_T is the total emitted carbon determined by weighing the fuel wood before and after sampling and assuming 50% carbon on a dry basis (*18*), $(CO_2 + CO)_P$ is the $CO_2 + CO$ concentration as measured by the flue gas analyzer for that point in time, and $(CO_2 + CO)_T$ is the summed $CO_2 + CO$ concentrations as measured by the flue gas analyzer for the sample. Using the product of C_T and $(CO_2 + CO)_P/(CO_2 + CO)_T$ ratios controls for differences in emissions dilution between stoves since the C_T measurement is unaffected by dilution.

Monitoring without Emission Hoods. A critical issue in tests to evaluate stove performance in the laboratory and the field is a simple economical testing procedure. Stoves have typically been measured using constant flow sampling hoods to control for dilution effects of room air on gas concentrations in the plume. Although most of the data presented here were measured using a constant flow sampling hood, hoods are intrusive, cumbersome, and not suitable for widespread monitoring and testing in projects. To demonstrate that a simple probe hanging above an open fire or flueless stove could replace these sampling hoods, $CO_2/(CO_2 + CO)$ ratios monitored using a three-pronged probe that hung directly above an open fire were compared against $CO_2/(CO_2 + CO)$ ratios measured with a constant flow sampling hood. Samples were taken at 30 s intervals alternating between the hood and probe for three separate open fires. Table 1 shows that mean differences between percentage carbon emissions estimated by the probe and sampling hood for each $CO_2/(CO_2 + CO)$ range were less than 1%. Thus, combined with recent advances in economical instruments to measure CO and CO_2, a simple probe can be used to conduct stove performance tests both in the laboratory and during normal daily cooking activities.

Results

Figure 1 demonstrates typical differences in minute-by-minute emission rates and $CO_2/(CO_2 + CO)$ ratios across stove type during daily cooking activities in homes. Peak combustion events are associated with higher $CO_2/(CO_2 + CO)$ ratios, followed by decreasing $CO_2/(CO_2 + CO)$ ratios as the fire transitions to smoldering low-power phases. Brick and mud Patsaris maintain higher $CO_2/(CO_2 + CO)$ ratios for longer periods during each peak combustion event, resulting in increased overall combustion efficiency. Higher emission rates are also generally evident for the open fire, with peak events reaching 30−40 g min^{-1}, while Patsaris never exceed 25 g min^{-1}.

TABLE 1. Comparison of Mean Estimates of the Fraction of Carbon Emitted by Three Open Fires Using a Probe and a Constant Flow Sampling Hood for Ranges of $CO_2/(CO_2 + CO)$ Ratios

$CO_2/(CO_2 + CO)$[a]	sampling method	fraction of carbon emissions (%)	range of difference (%)
0.85−0.9	hood	1.0	
	probe	1.1	
	difference	−0.1	−0.53 to 0.24
0.9−0.95	hood	21.6	
	probe	21.5	
	difference	0.2	−0.03 to −0.57
0.95−1.0	hood	77.4	
	probe	77.5	
	difference	−0.1	−0.20 to −0

[a] No carbon was emitted at $CO_2/(CO_2 + CO)$ ratios below 0.85.

Emission profiles in Figure 2 show carbon emission rates on the *x*-axis (5 g min^{-1} increments) and corresponding $CO_2/(CO_2 + CO)$ ratios on the *y*-axis, with the size of each bubble representing the respective fraction of carbon emitted. Figure 2a demonstrates that open fire emission profiles produced during the WBT's boiling and simmering phases overestimated $CO_2/(CO_2 + CO)$ ratios and emission rates relative to normal daily stove use in homes. $CO_2/(CO_2 + CO)$ ratios were higher for all emission rates during WBTs relative to in-home samples, the lowest rate (0−5 g min^{-1}) being the only exception. Emissions rates greater than 20 g min^{-1} were not evident during the different WBTs, though they accounted for 49% of all carbon emissions for in-home samples, indicating that WBTs did not replicate the high emission rates found during normal stove use. Thus, higher $CO_2/(CO_2 + CO)$ ratios were achieved at lower emissions rates in the WBT phases, but in-home cooking showed a much larger range of emissions rates. Simmering phases of WBTs with open fires had lower $CO_2/(CO_2 + CO)$ ratios than boiling phases, especially at lower emission rates, though they still were not indicative of in-home $CO_2/(CO_2 + CO)$ ratios.

Similarly, Figure 2b shows the WBT misrepresented Patsari emission profiles. Although the ranges of emissions rates between the WBT and the in home testing overlap to a greater extent, a larger fraction of total carbon emissions in homes was at lower emissions rates, and higher $CO_2/(CO_2 + CO)$ ratios were maintained at emission rates greater than 15 g min^{-1}, indicating that Patsaris were less oxygen limited during in-home cooking. The boiling and simmering phases of WBTs had $CO_2/(CO_2 + CO)$ ratios more than 10% lower than in-home samples at emission rates higher than 15 g min^{-1}. Comparing in-home emission profiles, the Patsari and open fire are fundamentally different, as open fires with unrestricted airflow have approximately linearly increasing $CO_2/(CO_2 + CO)$ ratios with emissions rate while Patsaris reach peak $CO_2/(CO_2 + CO)$ ratios at 15−20 g min^{-1} and then decrease at higher emission rates as the airflow through the small aperture to the combustion chamber is increasingly restricted by greater fuel loading. Comparison of Patsaris and open fires during normal daily cooking activities is presented in Figure S3 of Supporting Information.

Figure 3 shows the fraction of carbon emitted across $CO_2/(CO_2 + CO)$ ratios (increments of 0.05) for open fire and mud−cement Patsaris during WBTs and normal stove use in homes. The majority of carbon emitted during the WBT with an open fire was emitted at $CO_2/(CO_2 + CO)$ ratios greater than 0.95, which was over 2.5 times that in homes, where 68% of carbon emissions were emitted at $CO_2/(CO_2 + CO)$ ratios less than 0.95. In contrast, 1.75 times more carbon was emitted at $CO_2/(CO_2 + CO)$ ratios greater than 0.95 by the mud−cement Patsari during daily cooking activities in homes compared to the WBT.

Discussion

Stove performance tests in laboratories or simulated kitchens are based on the assumption that performing a standard task such as boiling water or cooking a staple food produces representative estimates of efficiency and emissions that can be used to evaluate technology options during stove development or for global climate models and inventories. The critical issue, however, is not that the task or cooking activity is representative but that the burn cycle is representative of that which occurs during daily cooking activities in homes. The cooking activity itself does not matter (*12*). Perhaps more fundamentally, daily cooking encompasses such a wide range of tasks, resulting in a high degree of variation in fuel economy between meals (*2*), that use of a simulated cooking task is unlikely to reflect actual performance in the field (*13*). Thus, even when a simulation test procedure reflects local cooking practices, differences in fuel economy between simulation and cooking tests can result (*2*).

Figure 1 illustrates the complexities of typical daily cooking cycles for the open fire, improved mud−cement Patsari, and brick Patsari stoves. The daily burn cycle of the open fire is characterized by numerous discrete burn events with different combustion efficiencies and emissions rates. The open fire stove shown in Figure 1, for example, had early and midmorning (before 11:30) burn events with $CO_2/(CO_2 + CO)$ ratios exceeding 0.95 only 14% of the time and a mean emission rate of 20 g min^{-1}. During the late morning and early afternoon (11:30−14:00), however, peaks were characterized by higher combustion efficiency, with $CO_2/(CO_2 + CO)$ ratios exceeding 0.95 24% of the time and a mean emission rate of 18 g min^{-1}. Midafternoon (14:00−16:15), which was characterized by a high combustion efficiency, high emission rate burn event followed by tailing off of the fire during the later afternoon with only limited use of the stove in the early evening typical of heating of cooked dishes, had $CO_2/(CO_2 + CO)$ ratios exceeding 0.95 only 15% of the time and the lowest mean emission rate of 10 g min^{-1}. Using these real-time emission rates and combustion efficiencies, the effects of improved stoves on improving the combustion efficiencies during discrete burn events are clear. Almost all the discrete burn events have a larger proportion of the event at higher combustion efficiencies, with the brick Patsari showing dramatic improvements, an expected transition for improved stoves with well-designed combustion chambers. With both the open fire and the Patsari stoves, however, it is clear that individual burn events over the course of a day show varying relative distributions of combustion efficiencies and emissions rates, making it difficult to identify what would be a representative cooking task for simulated tests. When summarized over the course of a day into a daily burn cycle, Figure 2 shows how both the open fire and the Patsari are misrepresented by both simmering and boiling phases of the water boiling test, yet in opposite directions. Figure 2a shows that $CO_2/(CO_2 + CO)$ ratios of the open fire were overestimated across emissions rates by WBT compared to daily cooking, with the sole exception for the lowest emissions range (0−5 g min^{-1}), which accounted for only 1% and 8% of in-home and WBT carbon emissions, respectively. Overestimation across the range of emissions rates suggests that the combustion was characteristically different between the WBT and normal cooking activities. Figure 2b shows that neither boiling nor simmering phases of the WBT replicated $CO_2/(CO_2 + CO)$ ratios across emission rates for the Patsari improved stoves, and combustion efficiencies were underestimated by the WBT compared to normal daily cooking.

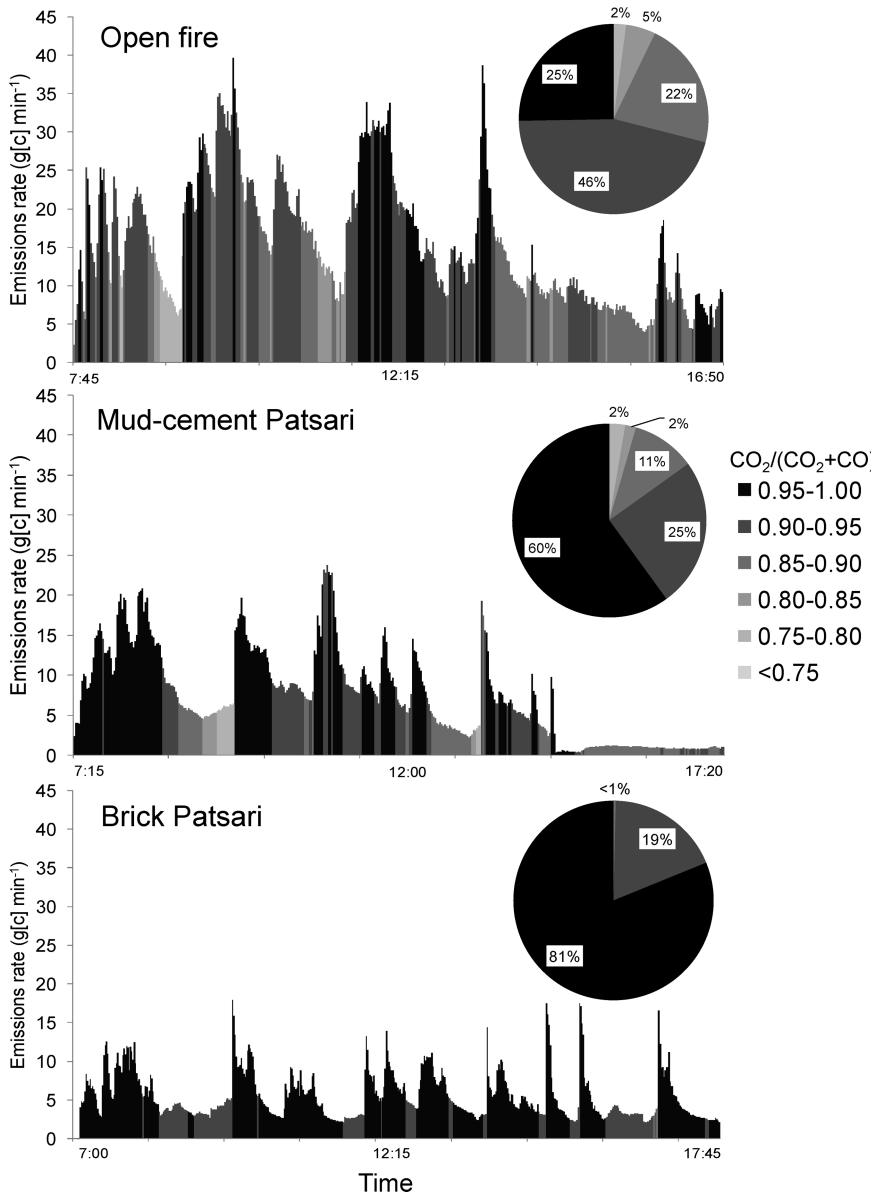

FIGURE 1. Minute-by-minute emissions rates and $CO_2/(CO_2 + CO)$ ratios (represented by shading) during a typical day of in-home stove use. Pie charts show the fraction of carbon emitted across $CO_2/(CO_2 + CO)$ ratios for the sample.

The fraction of carbon emitted by mud−cement Patsaris at $CO_2/(CO_2 + CO)$ ratios less than 0.95 was 68% during WBTs but only 44% during in-home use. The drop in combustion efficiency at higher emission rates for the Patsari was the result of overloading the combustion chamber with fuel wood, which restricts airflow, in agreement with the idealized curves of Prasad et al. (*12*).

Further evidence of the increased variability as a result of varied cooking tasks is shown by 9% and 29% increases in coefficients of variation between daily cooking tasks and WBTs, for CO_2 and CO emission rates, respectively. Roden et al. (*6*) also found 43% and 34% increases in coefficients of variation for CO_2 and CO emission rates, respectively, between in-home and WBT samples. Perhaps most important is that the bias of the WBT in estimating combustion efficiencies during daily cooking activities is in opposite directions for the open fire and the Patsari. Since combustion efficiencies of other stove types are probably also under- or overestimated to differing extents by the WBT, systematic adjustment for the bias is not possible between stove types. Further, simple alteration of testing protocols of the WBT would be unlikely to produce representative emissions for both stove types, much less the extensive variety of fuel/stove combinations in use throughout the developing world.

Implications of Nonrepresentative Stove Emission Estimates. Certified methods to compute CO_2-equivalent savings from a transition from traditional to improved stoves allow for use of a single default fuel-based emission factor for both the open fire and the improved stove, estimating the CO_2-equivalent savings from reductions in fuel consumption. Figures 2 and 3 clearly show that this simplification is inappropriate, given that emissions are directly related to combustion conditions, which vary in response to stove design factors such as combustion chamber dimensions and lining, body material, and venting mechanisms. Emission factors for methane used in deriving IPCC defaults for wood stoves, for example, varied by ~10 fold across 32 stoves types (*15*). Each stove type, therefore, should be treated as an independent technology with corresponding emission factors in determination of carbon savings by an improved stove program.

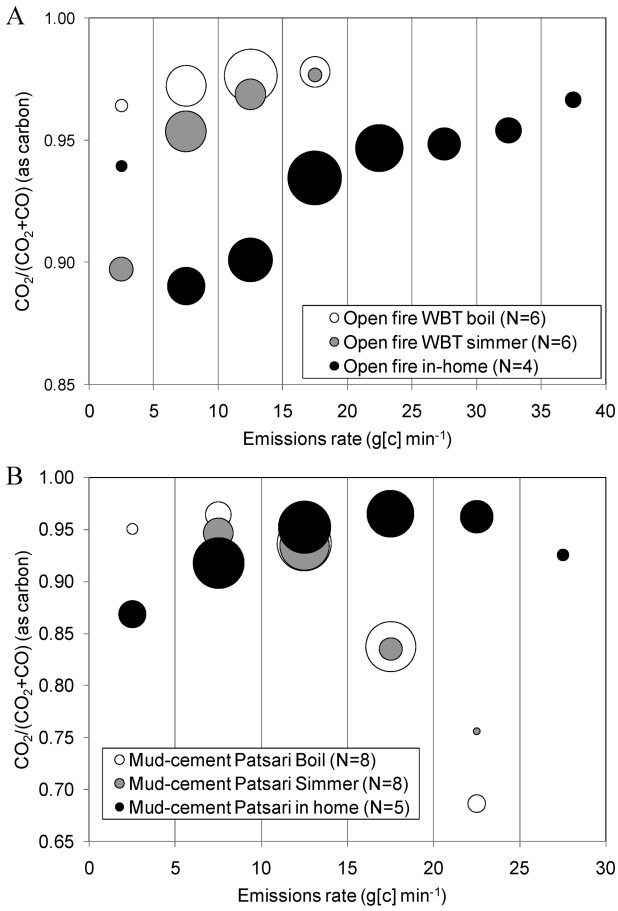

FIGURE 2. Emission profiles of open fires (A) and mud−cement Patsaris (B) during WBTs and normal stove use in homes. Note: the size of the bubble represents the fraction of total carbon emitted during in-home or WBT emissions sampling. Total carbon for the WBT was determined as the combined carbon for both boiling and simmering phases.

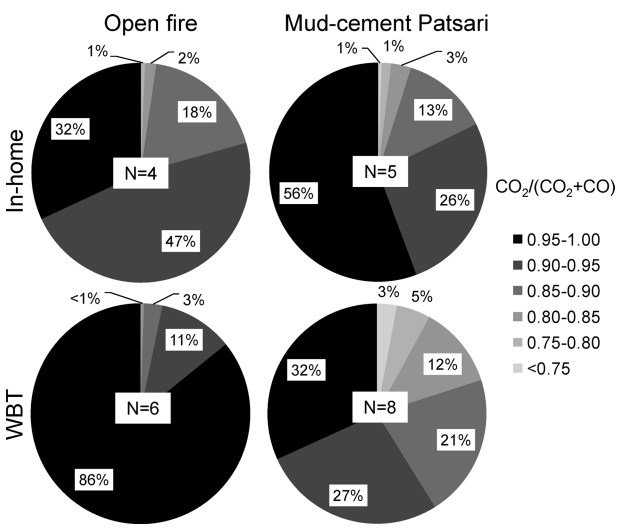

FIGURE 3. Distribution of carbon emissions across $CO_2/(CO_2 + CO)$ ratios during WBTs and normal stove use in homes. Note: The brick Patsari was not tested with the WBT in a simulated kitchen.

Criteria-Based Stove Evaluation. With recent advances in emissions measurement methodologies in homes that demonstrate that simple emissions probes measure equivalent emission ratios as those in complex emissions hoods (*7*), combined with economical monitors to measure real-time CO and CO_2 ratios, significant advances can be made in stove performance testing that provide more relevant data for inventories and climate models, in addition to providing real-time feedback on stove design during the different stages of a burn event. Here we build on the ideas of Prasad to propose a stove performance test whereby the distributions of carbon emissions across combustion efficiencies can be used to develop a set of criteria to characterize the performance of an improved stove.

Prasad theorized that cookstove performance can be better characterized by a graph of efficiency versus power, validated with field measurements rather than a single efficiency value, as stoves are not steady-state but a batch process system involving sequential burn cycles (*12*). Prasad et al. (*12*) proposed an alternative test whereby the overall efficiency, defined as the fraction of energy in the fuel that is transferred to the pot, is measured with varying power output under a batch operating system to assess the range of burn cycles produced during diverse cooking activities in homes (*12*). In these tests, 1 kg of wood was split into five or six equal parts, the stove was charged at intervals determined by the desired output, and a pan of water was used to measure the heat transfer. Measured stove efficiencies across batch sizes agreed with theoretical power vs efficiency curves (*12*).

Here we propose a modification to this strategy in first measuring $CO_2/(CO_2 + CO)$ ratios to derive burn cycles typical of daily cooking for the specific location in a subset of five homes with traditional open fire stoves during routine initial assessments of fuel consumption at the outset of the project. A sample size of five homes would result in a 95% confidence interval of ±1.75% for NCE of open fires and ±1.14% for NCE of Patsari improved stoves during daily cooking activities (*9*). Subsequently, during laboratory tests using similar fuel type and composition, 1 kg of wood would be split into five or six equal parts and fed into an open fire to reproduce the distribution of emissions rates and combustion efficiencies seen during the daily burn cycle. Using this as a basis, laboratory tests of the improved stove could be conducted during the design phase. Once more detailed distributions had been generated of carbon emissions across combustion efficiencies during improved stove usage during daily cooking activities in homes, design modification could be directly compared in the laboratory to previous iterations of the improved stove.

The advantages of this approach would be (1) laboratory tests would be clearly linked to performance in the field, as burn cycles produced in homes are replicated in laboratory settings; (2) stove performance would be based on a distributional comparison of carbon emissions across combustion efficiencies rather than a single efficiency value; (3) for stoves that increase heat transfer efficiency, the use of combustion efficiency profiles in characterizing stove performance assists in promoting development of stoves that maintain combustion efficiencies and produce fewer products of incomplete combustion; (4) stove designers would be guided toward engineering stoves that produce high combustion efficiencies during burn cycles typical of local cooking practices, while also enabling preliminary estimates of greenhouse species emissions through prediction models using $CO_2/(CO_2 + CO)$ ratios. Since CO_2-equivalent emissions are linearly related to nominal combustion efficiency, of which $CO_2/(CO_2 + CO)$ ratios are a good predictor, the distribution of $CO_2/(CO_2 + CO)$ ratios can be used to estimate CO_2-equivalent emissions. Linear regression models using $CO_2/(CO_2 + CO)$ predicted CO_2-equivalent stove emissions (including CO_2, CO, CH_4, and TNMHC) with a Pearson r^2 of 0.91−0.98 for wood-burning stoves (*7*) and 0.78 across multiple fuel types (including CO_2, CO, CH_4, NO_x, TNMHC)

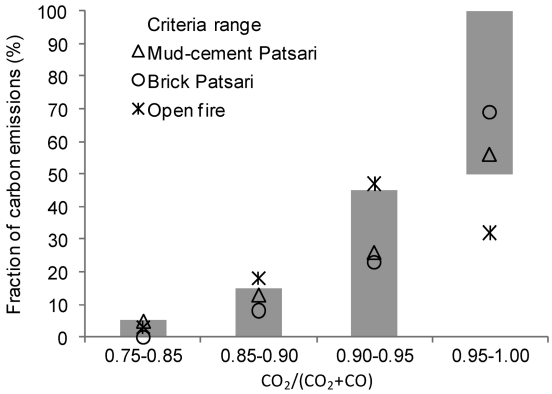

FIGURE 4. Criteria for stove performance evaluation using the fraction of carbon emitted across $CO_2/(CO_2 + CO)$ ratio intervals.

(*19*). Edwards et al. (*19*) also used nominal combustion efficiency in linear regression models to predict TSP (Pearson $r^2 = 0.59$) and products of incomplete combustion (Pearson $r^2 = 0.79$). Similar models can also be employed to predict indoor air concentrations such as those recently developed by Berkeley Air Monitoring Group (Berkeley, CA). Perhaps more interestingly, the distribution-based approach for stove performance testing may also allow estimation of a stove's CO_2-equivalent and PIC emissions associated with different parts of its burn cycle, ideally targeting for improvement those parts that produce the most CO_2-equivalent and PICs.

As a starting point for the development of stove performance benchmarks, Figure 4 provides suggested ranges for the fraction of carbon that may be emitted across $CO_2/(CO_2 + CO)$ ratio intervals in order that a stove model be considered "improved," provided that the stove also meets the requirements of reducing indoor air pollution and other associated socioeconomical needs. The ranges of carbon fractions in Figure 4 are based on the mud−cement Patsari's distribution of carbon emissions during normal daily stove use (Figure 3), which suggest that over 50% of carbon be emitted above $CO_2/(CO_2 + CO)$ ratios of 0.95, while those from 0.90 to 0.95, 0.85 to 0.9, and 0.75 to 0.85, 0 to 0.75 should be limited to a maximum of 45, 15, 5, and 0%, respectively. These benchmarks are designed such that a stove meeting these criteria would have to have a minimum mean $CO_2/(CO_2 + CO)$ ratio of 0.93, which is greater than the mean of the $CO_2/(CO_2 + CO)$ ratio of 0.92 for open fire stoves during normal cooking in the current literature (*12, 15, 16*) and the mean of 0.90 for 25 homes in five communities in the Purépecha region of Mexico measured by our group. The distributions of carbon emissions for open fires and Patsaris during normal daily stove use are shown in Figure 4 for reference, demonstrating that Patsaris meet all criteria for improved stoves while the open fire exceeds the criteria at lower $CO_2/(CO_2 + CO)$ ratios and does not attain the criteria at the highest $CO_2/(CO_2 + CO)$ ratio. The many stove/fuel combinations across developing regions may also require further development of emissions criteria, although most well-designed improved stoves will likely result in similar transitions toward emission profiles with broadened periods of high combustion efficiencies. Clearly, however, use of these benchmarks cannot replace representative sampling in homes during daily cooking activities.

Finally, use of the $CO_2/(CO_2 + CO)$ ratio as a proxy for combustion efficiency involves simple to use economical instrumentation, making it accessible to many stakeholders from NGOs directly developing stoves to expert groups assessing stove performance in the field. Emission profile criteria would also be useful for technical emissions analysis not suited for field application in rural homes, such as those involving large particulate dilution chambers, gas cylinders, or instrumentation requiring substantial electrical power, as burn cycles during cooking activities in homes can be replicated in the laboratory, ensuring the validity of the test.

Acknowledgments

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Supporting Information Available

Additional information regarding the Patsari stove, water boiling tests, emissions hood, in-home emission profiles, and pot selection for performance testing. This information is available free of charge via the Internet at http://pubs.acs.org.

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