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Real-Time Assessment of Black Carbon Pollution in Indian Households Due to Traditional and Improved Biomass Cookstoves

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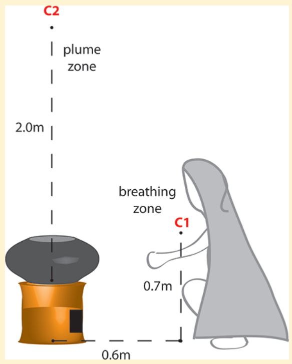
Supporting Information

ABSTRACT: Use of improved (biomass) cookstoves (ICs) has been widely proposed as a Black Carbon (BC) mitigation measure with significant climate and health benefits. ICs encompass a range of technologies, including natural draft (ND) stoves, which feature structural modifications to enhance air flow, and forced draft (FD) stoves, which additionally employ an external fan to force air into the combustion chamber. We present here, under Project Surya, the first real-time in situ Black Carbon (BC) concentration measurements from five commercial ICs and a traditional (mud) cookstove for comparison. These experiments reveal four significant findings about the tested stoves. First, FD stoves emerge as the superior IC technology, reducing plume zone BC concentration by a factor of 4 (compared to 1.5 for ND). Indoor cooking-time BC concentrations, which varied from 50 to 1000 $\mu g\ m^{-3}$ for the traditional mud cookstove, were reduced to 5−100 $\mu g\ m^{-3}$ by the top-performing FD stove. Second, BC reductions from IC models in the same technology category vary significantly: for example, some ND models occasionally emit more BC than a traditional cookstove. Within the ND class, only microgasification stoves were effective in reducing BC. Third, BC concentration varies significantly for repeated cooking cycles with same stove (standard deviation up to 50% of mean concentration) even in a standardized setup, highlighting inherent uncertainties in cookstove performance. Fourth, use of mixed fuel (reflective of local practices) increases plume zone BC concentration (compared to hardwood) by a factor of 2 to 3 across ICs.



■ INTRODUCTION

The introduction of clean cooking technologies in developing countries across South Asia, Africa, and South America—where use of the traditional mud stove and/or three stone fire is widespread—has recently gained momentum as a top-priority black carbon (BC) mitigation measure.[1−6] As BC aerosols–the second- or third-largest contributor to global warming[3,4]—have short atmospheric lifetimes (ranging from days to weeks), mitigation of BC emissions in the short term has been described by scientists as the "dark horse"/"low hanging fruit" in the fight against climate change.[3,5] Exposure to BC aerosols, a component of respirable particulate matter ($PM_{2.5}$), causes myriad health problems for stove users, primarily women and accompanying children.[7] Beyond BC mitigation, cleaner cooking technologies will reduce emissions of other products of incomplete biomass combustion, including total particulate matter and ozone precursers like carbon monoxide, which also have negative public health and climate effects.[7,8]

Previous assessments of stove-related BC emissions and concentration levels have relied on reported particle emission factors in inventory and review studies,[9−11] measurements from laboratory combustion of variety of biofuels,[12−17] real-time $PM_{2.5}$ measurements from which BC concentrations were estimated,[18,19] and BC concentrations from wood burned in laboratory conditions.[16,21] Two knowledge gaps with significant policy implications still exist. First, as stove performance in laboratory can differ dramatically from field measurements,[17,21] significant uncertainty remains in understanding how much reduction in BC concentration levels can be achieved by use of alternative cooking technologies during real cooking in actual field conditions. Second, the term "improved" is liberally used as a "catch-all" phrase for a range of cooking technologies with varying price points.[18,23] Although several wide-ranging cookstove technology intercomparisons have been made in the field setting where CO and $PM_{2.5}$ emission and concentration levels were measured,[17] identification of stove technologies that are truly improved in real field conditions from the point of view of BC concentration levels has not been reported. These two questions—of effective BC reduction technologies and true reduction potential—are critical for policy makers and those planning and budgeting stove dissemination programs. In an

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attempt to address these knowledge gaps, this paper presents findings from a series of real time, in situ BC concentration measurements from a suite of cooking experiments at a project site in northern India. These experiments used multiple commercially available improved cookstoves, as well as a typical traditional mud cookstove (used currently by most households in the region, as a baseline for comparison. It is important to note that this study focuses on BC concentrations and not on total BC emission measurements from improved cooking technologies. Both emissions and concentrations have a major role to play in the assessment of BC mitigation potential of improved stoves, and the results presented in our study should motivate complementary BC emission measurements.

This comparative evaluation of BC mitigation potential of ICs is part of a larger interdisciplinary study, *Project Surya* (www.projectsurya.org), which aims to quantify the climate and health impacts of large-scale adoption of cleaner cooking technologies in India and ultimately across the developing world. The field studies described in this paper were carried out in the *Project Surya* village, located in the Indo-Gangetic Plains (IGP) in India (see Figure S1 of the Supporting Information, left panel). As part of the overall Surya effort, a novel cell phone-based BC monitoring system was developed for measurements over large, heterogeneous spatial scales[24], the link between household-scale and village-level ambient BC concentrations in a village using traditional cookstoves was documented (see Figure S1 of the Supporting Information, right panel),[25] and local- and regional- scale radiative properties and forcing of BC across the IGP were explored.[26]

This study focuses on evaluating ICs for two reasons: First, the International Energy Agency (IEA) estimates that total biomass usage will continue to rise in near future, with 632 million expected to depend on solid unprocessed biomass for cooking and space heating needs in 2030 in India.[27] Second, because biomass is largely produced and consumed locally, it does not require establishment of elaborate and expensive supply chains (unlike, for example, LPG or kerosene). ICs are therefore the most affordable and accessible clean-cooking options for large-scale adoption by extremely poor populations.

Improved Biomass Cookstove Technologies. Only ICs that were (a) commercially available in India at the time of study (May and June 2010) and (b) were from reputed manufacturers with a track record/assurance of quality after-sales service were considered, as past studies[27,28] have indicated that poor after-sale service of ICs can result in high disadoption rates. Five portable single-burner IC models (with varying price points) met the above criteria and were included in this study. The selected ICs have been broadly segregated into two classes—three Natural Draft (ND) and two forced Draft (FD) stoves—based on the mechanism of air augmentation inside the combustion chamber. Although several other IC technologies exist—for example, mud stove models with chimneys,[28] thermoelectric stoves,[30] and biochar stoves[31]—they did not fulfill the selection criteria and were not included.

In general, IC developers attempt to create sufficient air draft inside the stove to reduce particulate emissions.[16] During combustion in a cookstove, the temperature and density differentials between the air inside and outside the stove result in airflow from the cooler ambient environment (~25 °C) into the chamber (~600 °C).[22,32] This natural convection draft is passively enhanced in ND ICs through structural design modifications; in FD models, an external fan (powered by battery pack) at the bottom of the combustion chamber additionally drives the airflow. Operation of the stove at near stoichiometric air to fuel ratio leads to peak combustion temperature, which in turn improves heat transfer efficiency (HTE).[22] HTE is not only dependent on stove geometry, but also on gas temperature and how much of the hot gas reaches the bottom and sides of the pot: For example, the use of a pot skirt helps maximize transfer of heat generated from the stove to the cooking pot.[16] All of the ICs tested feature metallic bodies and improved insulation around the fire for cleaner burning.[33] Basic features of the five ICs are presented in Table S1 of the Supporting Information. (For elaborate discussion on these stove technologies, please refer to Roth, 2011.[34])

In a traditional mud stove, combustion happens almost as soon as volatilization around the solid fuel zone; this can lead to significant emissions of products of incomplete combustion.[21,33] In contrast, both FD stoves and two of the ND stoves tested were designed on the basis of principles of microgasification[35] to improve combustion efficiency. In microgasification stoves, air supply [from either fans (FD) or free convection (ND)] is partially supplied into the combustion chamber from primary small openings located at the bottom of the stove. The remaining air supply is channeled to the top of the combustion chamber (and preheated) through secondary small openings.[35] Two distinct reactions take place during the pyrolysis of the solid biomass fuel: char and volatile gas are produced, and char gasification is initiated, leading to emission of CO. The combustible gases subsequently react with (secondary combustion) oxygen present in the air draft emanating from the secondary small openings. This mechanism of separating the generation of combustible gas and its subsequent combustion to create cooking heat leads to greater combustion efficiency (and therefore lower emission of products of incomplete combustion).[22,35] The remaining ND stove is a direct/in situ combustion stove (i.e., there is no temporal or spatial difference between the creation of combustible gases and actual combustion) where the stove developer has attempted to improve combustion efficiency through better geometry and materials.

METHODS

Experimental Setup. Cookstove emission is a function of many factors, including stove type and design, fuel type, lighting mechanism, fuel feeding style, burning rate, and combustion temperature.[11,18] In comparing BC concentration levels between stoves, it is therefore critical to standardize as many controllable factors as possible (like fuel type, cooking application, and cookstove user). The Controlled Cooking Test (CCT) is a standardized cookstove testing protocol commonly used to measure the fuel consumption associated with a specific cooking task.[36] The CCT was chosen as the basis of this study because it provides a standardized comparison of stove performance within the real-world parameters of local food and cooking practices.[35−37] Each cooking test consisted of boiling 400 g of rice and simmering 200 g of pulses—typical staples in the project area. The same locally sourced ingredients were used for the each test.

The experimental setup was designed to approximate average village cooking conditions. Cooking tests were carried out by volunteer cooks in the real kitchen space of a single household in the *Project Surya* village so that concentration levels from this experimental work would be more representative of routine usage by a village woman. The kitchen area measured 3 m × 2.5

m and was situated 1 m away from the exit door of the house: This geometry and ventilation are representative of average household conditions in the project area. Cooks were requested to perform the tasks as they would under normal conditions without any interference from the research team monitoring the cooking sessions. (Nevertheless, as the cooks were trained in stove handling, using each IC regularly for one week prior to cooking experiments, and they were likely more proficient in stove use than the average cook would be at the outset.) The cooking experiments were conducted during noncooking hours in the village (10:00−17:00 h) to avoid monopolizing the household's kitchen space and disturbing the family's daily cooking routine and to prevent measurement contamination by smoke from adjacent households. To minimize the impact of ventilation (due to varied wind and temperature conditions, which cannot be controlled in real village settings), the trials were spread out over a period of days and were repeated at different times of day (Table S2 of the Supporting Information).

Two distinct fuel types were used for the experiments. In order to standardize fuel as suggested by the CCT test protocol,[36] sun-dried hardwood (HW) of Acacia species with similar moisture content (ranging between 9.1% and 13.6% on wet basis) was used for HW experiments. Twigs (20−50 g, depending on the stove type) and kerosene (3−8 g) were used to ignite the test stoves. While critical for standardization, HW tests do not accurately reflect the every day cooking practices of most households in the region. Mixed fuel (MF) is more commonly used because of the cost and access constraints posed by hardwood. In order to utilize all accessible nonmonetized biomass, cooks across rural India generally use crop residues (as a the majority of families engage in agricultural activities) and cattle dung (if the family owns domestic cattle), along with fuel wood.[21] Hence, two additional experiments were carried out for each stove using a combination of wood, pigeon pea crop residues, and cattle dung in a 2:1:1 ratio. The volunteer cooks were instructed to use the fuel mix in a pattern that reflected their every day usage. It should be noted that cooks loaded fuel when they deemed the stove flame power needed to be boosted. Rigorous protocol for standardizing fuel loading (specific loading quantum and frequency) was not developed and executed for two reasons: First, protocol-based user behavior will not represent actual cooking,[22] and second, variations in design (e.g., direct combustion, gasification, etc.) and combustion chamber volume vary across the test stoves, precluding any uniform and standard protocol.

Instrumentation. Real-time indoor BC concentrations were measured using microaethalometers (model AE-51; Magee Scientific, Berkeley, CA) simultaneously at two points, C1 and C2 (Figure S2 of the Supporting Information). The AE-51 is a portable battery-operated instrument based on aethalometer technology.[40] The AE-51 draws ambient air onto a quartz filter and measures BC via attenuation of a single wavelength (880 nm) LED. During the cooking experiments, the flow rate was set at 50 mL/min with measurement frequency of 1 min. The filter strip of the microaethalometer was changed periodically to prevent the attenuation saturation level from exceeding 120. Our tests revealed that this level was reached at ∼30 min of operation at 50 mL/min during the cooking period.

The accuracy of microaethalometers for the sort of high concentrations recorded here has been explored in detail in a companion Surya paper.[25] That study compared the microaeths against each other and against three other measurements systems: a standard rack-mounted aethalometer, a standard portable aethalometer, and one totally independent system that conducted chemical−optical mass balance-based determination of BC concentrations. All of these comparisons were conducted in the same Surya village as the present study. In all cases, the slope of microaethalometers against other instruments ranged from 0.8 to 0.85. The slope of different microaethalometers against each other ranged from 0.9 to 0.95. On the basis of these comparison studies, we estimate that the absolute accuracy of the BC measurements shown here are within 30%.

The measurement at C1 represents the concentration at the inhalation height of the stove user. As the cook is likely to have highest exposure level to cookstove smoke, C1 is therefore the more relevant data point for first-order health impacts that are caused by exposure to BC. Protocol developed by UC Berkeley[41] suggests that the "breathing zone" is 1 m away from the stove and 1.45 m above the ground, while Albalak et al. suggested 1.25 m above ground.[42] A survey of 30 randomly selected women from different households in the *Project Surya* village, however, revealed that most women preferred to sit in the squatting position in front of the stove, with an average breathing position of 0.6 m away from the stove and 0.7 m above the ground. We chose this representative location for C1.

Concentration C2 was measured at 2 m directly above the stove burner to maximize plume capture. The measurement at C2 (the "plume zone") is the more relevant metric (compared to C1) for climate considerations.[20] The choice of height for the plume zone measurements was partially determined by equipment constraints: The AE-51 requires periodic filter changes, and a lower measurement height would have necessitated multiple filter changes (and subsequent data loss) during cooking sessions. With C2 at 2 m, a single filter change (taking ∼2−4 min) was required during each test for some stoves, while no filter changes were required for the measurements at C1 during any cooking session.

Fuel wood was also measured both before and after cooking sessions using a digital scale (Make: Equal UNIQUE) of 0−15 kg range with 1 g resolution. Fuel savings is a critical performance indicator for ICs as it is perhaps the most compelling reason for economically disadvantaged users to adopt an alternative cooking technology.[43]

Data Correction. The raw microaethalometer data was processed for multiple scattering and loading corrections using standard methodologies.[25,43] It was also observed that the cooks had an uncanny ability, partway through the cooking task, to judge the amount of fuel they would require to complete the cooking. Hence, they did not end up with significant amount of charcoal leftover for reuse. Leftover charcoal was not measured and standard charcoal corrections for fuel usage[36] were therefore not carried out because our field observations indicated that charcoal is not generally saved for later use or sale. (MacCarty et al. corroborate this observation, noting that, for all practical purposes, charcoal from cookstoves is not reused in subsequent cooking sessions.[45]) In one experiment involving ND1, fuel data was not recorded because of instrumentation error. More information on data collection and correction can be found in the Supporting Information.

■ RESULTS AND DISCUSSION

Comparison of FD and ND Stoves. The two performance metrics used in this study to compare ICs with the traditional mud cookstove are (a) BC concentrations at C1 and C2 for both hardwood and mixed fuel, as an indicator of the BC mitigation potential of ICs in the breathing (health ramifications for cook) and plume zones and (b) the quantity of fuel required for each cooking session, giving a measure of fuel savings potential. The summary of experiments, showing mean results and confidence intervals (for 95% confidence level), is presented in Table 1. The mean indoor background BC concentration (at C1) in the kitchen space was recorded as 3.7 μg m^{-3} (±0.9, 95% C.I., n = 36 cooking experiments) in the absence of cooking activity (and during off-peak village cooking hours).

To illustrate the potential magnitude of BC mitigation from an IC, time-series plots for the cooking tests with FD1 and the traditional mud stove are shown in Figure 1. While BC concentrations from the mud stoves largely vary between 50 and 1000 μg m^{-3}, the concentrations for FD1 lie between 5 and 100 μg m^{-3}, or an order of magnitude lower. The time-series data underscore that the mean BC concentration values, and standard deviations reported in this paper are reflective of performance of various stoves for the entire cooking period and are not driven by sporadic concentration variations. (Summary data for all cooking sessions are presented in the Supporting Information.) The mud stove data shows a steady decrease in BC concentration over the last quarter of each cooking session. This stems from a common fuel-saving practice employed by cooks using mud stoves in the project area: toward the end of a cooking task, they often stop feeding the stove and slowly finish cooking using residual heat.

The performance differences between the ICs and the traditional mud stove in terms of BC concentration are presented as box-plots in Figure 2. Both ND and FD stoves, as classes, (Figure 2, upper left) offer statistically significant reductions in BC concentrations in the plume zone (C2) compared to that of the mud stove. In the plume zone, the mean BC concentration of the mud stove is 335 ± 29 μg m^{-3}, while ND stoves (mean BC value of 224 ± 66 μg m^{-3}) and FD stoves (mean BC value of 78 ± 40 μg m^{-3}) reduce BC concentration by 33% and 77%, respectively. While both ND and FD stove technologies reduce indoor BC concentrations significantly (at 95% confidence level) over existing traditional stoves, the results indicate a significant performance difference, with FD outperforming ND stoves in BC mitigation. These findings support previous studies[17] that have reported superior performance of fan stoves in reduction of BC/PM concentration levels significantly. In the breathing zone, BC concentrations of the mud, ND, and FD stoves are 128 ± 65 μg m^{-3}, 78 ± 30 μg m^{-3}, and 38 ± 28 μg m^{-3}, respectively. While ND and FD technologies reduce mean BC concentrations in comparison to the mud stove by 39% and 70%, respectively, these findings are not statistically significant (at 95% confidence level) because of the high variance of results in each stove class (overlap of the boxes, Figure 2, upper left). This variance is discussed in greater detail in the next section.

When the data are broken down by individual stove, as opposed to stove class (Figure 2, upper right), both FD stoves FD1 and FD2 register significant reductions in mean BC concentrations in the plume zone (86% and 67%, respectively, compared to the mud stove). While ND2 and ND3 register

Table 1. Summary of Experimental Results[a]

stove and test				cooking time		fuel use			breathing zone			plume zone		
stove type	stove code	fuel type	# of trials	cook time (min)	±C.I. (95%)	total consumed fuel (kg) (95%)	±C.I. (95%)	% change compared to mud stove	mean BC concentration (μg/m3)	±C.I. (95%)	% change compared to mud stove	mean BC concentration (μg/m^3)	± C.I. (95%)	% change compared to mud stove
single pot mud stove	mud	HW	4	70.00	10.87	1.02	0.31	NA	127.55	103.51	NA	335.22	46.41	NA
		MF	2	65.00		1.37			89.69			430.72		
natural draft	ND1	HW	4	69.75	6.41	0.69	0.12	−0.32	75.46	59.40	−0.41	226.96	137.64	−0.32
		MF	2	73.50		0.68			78.59			448.16		
natural draft	ND2	HW	5	72.40	5.01	0.97	0.18	−0.05	99.66	21.42	−0.22	239.70	50.58	−0.28
		MF	2	67.50		1.21			220.70			478.80		
natural draft	ND3	HW	5	77.20	11.79	1.18	0.14	0.16	57.78	27.64	−0.55	205.83	98.65	−0.39
		MF	2	69.50		1.24			81.30			545.47		
forced draft	FD1	HW	3	67.33	6.25	0.65	0.10	−0.36	18.70	8.51	−0.85	45.85	10.87	−0.86
		MF	2	69.00		0.65			26.48			105.27		
forced draft	FD2	HW	3	71.00	11.38	0.56	0.11	−0.44	56.68	71.83	−0.56	110.08	77.35	−0.67
		MF	2	71.00		0.64			44.75			192.77		

[a]HW = hardwood, MF = mixed fuel, C.I. = confidence interval.

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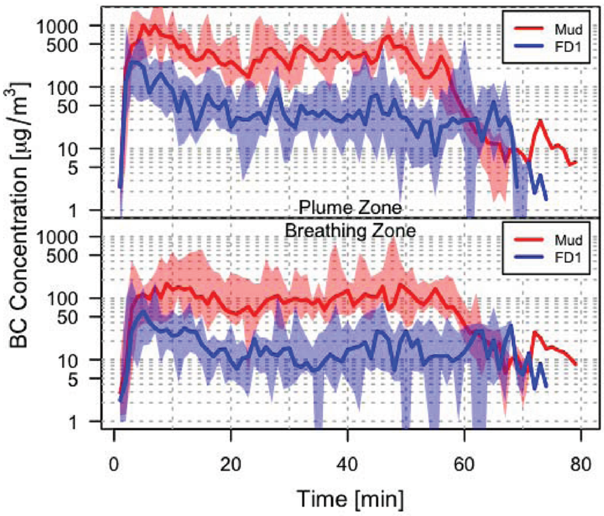

Figure 1. Time series data for (upper) plume zone and (lower) breathing zone BC concentrations during cooking. Dark lines show median values, with shaded regions indicating minimum and maximum values from repeated tests.

statistically significant mean plume zone BC reductions of 28% and 39%, respectively, the mean reduction of 32% for ND1 is not statistically significant (at 95% confidence level, represented by the overlapping of ND1 and mud box-plots). In the breathing zone, only FD1 showed a statistically significant reduction in BC concentration. In fact, mean BC concentrations at C1 of some ND cooking sessions were worse than better-performing mud cookstove sessions (represented by overlapping of mud and ND box-plots in Figure 2, upper right). Across all stoves and all tests, the BC concentrations in the plume zone are approximately three times higher than in the breathing zone because the radial diffusion of BC from the stove is expected to be lower than via the main vertical exhaust pathway. Beyond providing metrics relevant for health and climate impacts, the measurement in both breathing and plume zones provides a cross-check of the data. Consistency in interstove ranking of concentrations at C1 and C2 reduces the risk of experimental errors due to instrument, wind, or ventilation issues.

Using mean BC concentration values in either plume or breathing zone results in the same relative ranking of ICs in terms of BC reduction vis-à-vis the traditional mud stove (from

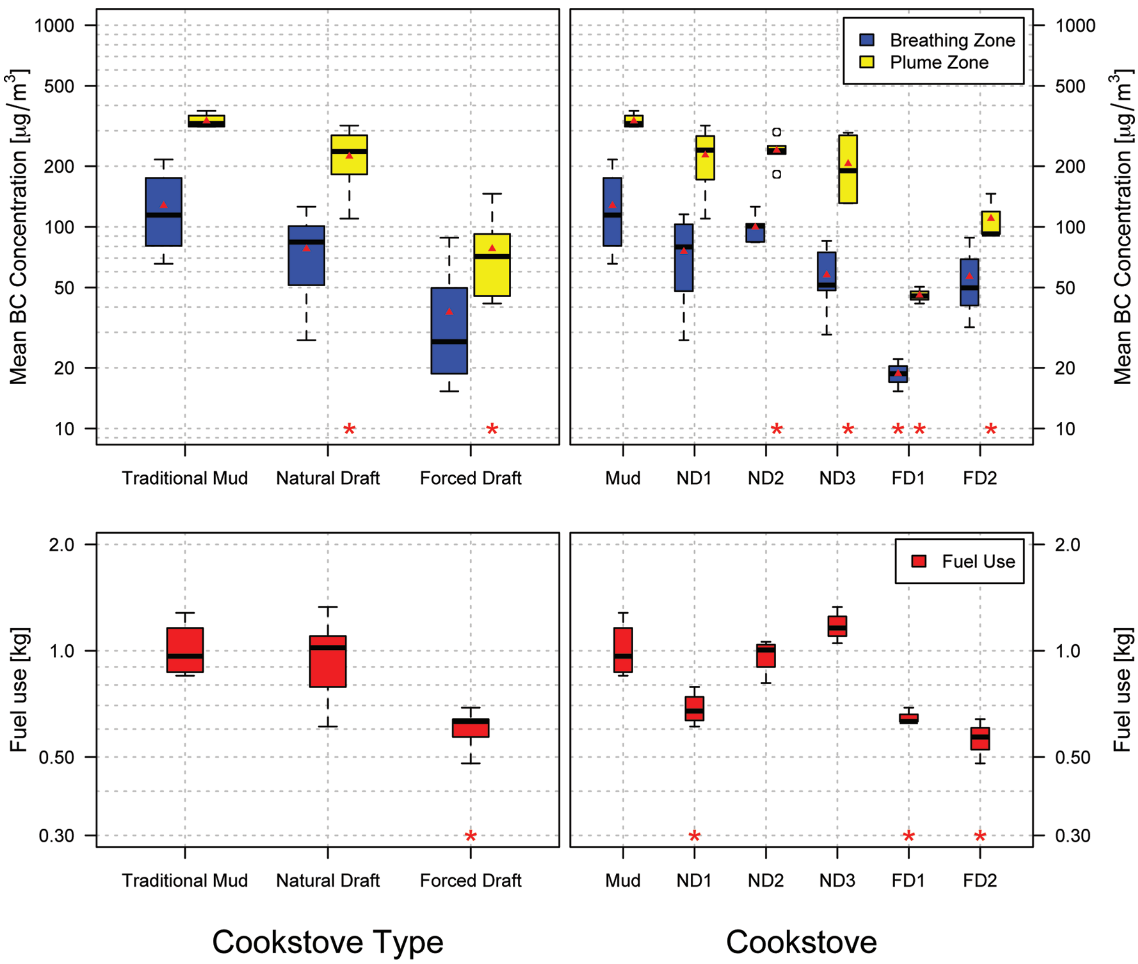

Figure 2. (upper panels) BC emissions of different cookstoves in breathing and plume zones (left) grouped by stove class and (right) displayed individually. (lower panels) Fuel use for different stoves (left) grouped by stove class and (right) displayed individually. In each box-plot, the dark line represents the median value, with the colored box showing the interquartile (25th−75th percentile) range (IQR). The whiskers extend to 1.5xIQR, with outliers denoted by circles. Mean values for each set of measurements are plotted as red triangles. A red star under the box means that the mean value for that stove is statistically different than the mean value for the traditional mud stove (at the 95% confidence level, $p < 0.05$). Data shown are for hardwood fuel tests only.

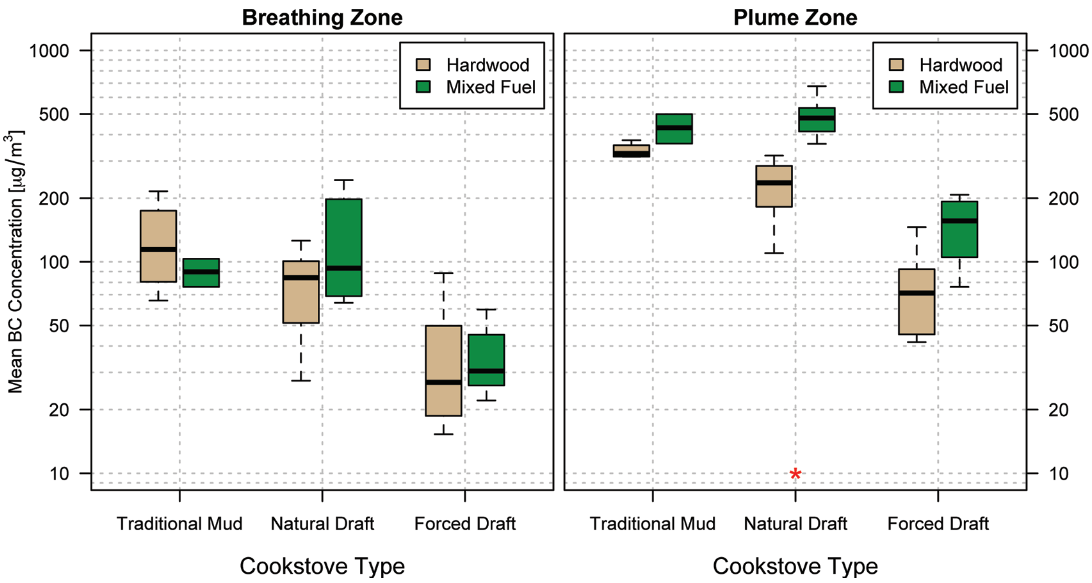

Figure 3. Comparison of BC concentrations for hardwood and mixed fuel tests in (left) the breathing zone, and (right) the plume zone. In this plot, a red star under the boxes means that the mean values for hardwood and mixed fuel tests are statistically different for that stove technology class (at the 95% confidence level, $p < 0.05$).

worst- to best-performing, where higher BC indicates lower performance): ND2 < ND1< ND3 < FD2 < FD1. When statistical significance is taken into account, however, the findings suggest that (a) adoption of all selected ICs, with the exception of ND1, is expected to reduce BC plume zone concentrations when compared to mud stoves. It should be noted that the data on the reduction of concentration levels are closely related to reductions in BC emissions because of the proximity of the concentration measurements. However, by themselves the data on concentrations are not sufficient to quantify overall emissions reductions. The findings also suggest that (b) of the stoves tested, only FD1 is likely to mitigate existing BC-related health effects for the cook by reducing breathing zone concentrations.

The lower mean BC concentrations measured during the IC cooking tests may be attributed to one or both of the following improvements over the traditional mud cookstove: First, all of the ICs tested include some form of insulation around the combustion chamber. This insulating material reduces heat loss and raises the chamber temperature; cleaner combustion results as more combustible gas is burned.[33] Second, as discussed earlier, in contrast to the oxygen-lean conditions often present in a mud cookstove (which result in partial combustion and thus higher BC concentrations), each IC offers some mechanism of improved air supply to the combustion chamber.[22] It should be noted that the worst-performing stove in terms of mean BC concentrations (ND2) is a direct combustion stove (unlike all the other ICs, which include the microgasification feature). These data reaffirm the importance of microgasification for cleaner combustion.[22,35]

Fuel use data are presented in red in the lower panels of Figure 2 (with mean values presented in Table 1). Only FD1, FD2, and ND1 demonstrate significant fuel savings over the mud stove with mean reductions of 36%, 44%, and 32%, respectively (Figure 2, lower right).

Intratechnology Performance Variation of Stove Models. The above discussion highlights not only significant intertechnology differences, but also the striking intratechnology differences among stove models of a given technology class. Even when considering only hardwood cooking sessions in the standardized experimental setup, significant variance exists within the ND and FD classes. For example, among ND stoves, mean BC reduction in the breathing zone varies widely (22–55%), and the mean BC concentration of ND2 is 72% greater than that of ND3. In comparison, there is less variation in plume zone concentrations, as the reduction in BC concentration (mean value) in the plume zone for ND1, ND2, and ND3 is 32%, 28%, and 39%, respectively. Akin to ND stoves, variation of stove performance between the two FD stoves is greater in the breathing zone (85% and 56% BC reduction compared to the mud stove for FD1 and FD2, respectively) than in the plume zone (86% and 67% for FD1 and FD2, respectively). Even in the standardized cooking environment (same food, fuel, cook, cooking space, and season), the wide variance in "within technology" concentration measurements underscores the importance of considering stove-specific BC mitigation potential.

Variation of Stove Performance in a Standardized Environment. This experimental work also reveals significant performance variance from the same stove model over multiple cooking sessions (for example, note the vertical length of the box-plots for stoves ND1 and FD2 in Figure 2, upper right). These stoves are characterized by high standard deviation of mean BC concentration (expressed as percentage of mean value) during multiple trials in both breathing and plume zones. Variation in BC concentrations in the breathing zone for ND stoves (between 17% and 49%) and FD stoves (between 18% and 51%) are similar. In the plume zone, the variances in concentration for each stove are comparatively lower, although FD stoves still show lower variance (between 10% and 28%) than ND stoves (between 17% and 39%). Out of all stove models, FD1 emerges with the lowest standard deviations in performance: 10% and 18% in the plume and breathing zones, respectively.

Variation in Stove Performance Due to Fuel. We present data comparing mixed fuel and hardwood tests by stove class in Figure 3. We measured a mean BC concentration for the traditional mud cookstove using mixed fuel (MF) of

430 ± 97 μg m^{-3} in the plume zone or 28% higher than when hardwood is used. However, use of mixed fuel over hardwood is not likely to alter BC-related health effects in either the traditional mud cookstove or the ICs, as there is no statistically significant difference in BC breathing zone concentration between fuel types (Figure 3, left panel). Nevertheless, in the plume zone (Figure 3, right panel) ND stoves using mixed fuel have more than double the BC concentration in the plume zone than when using hardwood (statistically significant increase of 119%), with a mean BC concentration of 491 ± 110 μg m^{-3}. FD stoves produced a mean BC concentration of 149 ± 57 μg m^{-3} or an increase of 91% over hardwood (though not statistically significant at 95% confidence level).

Relevance of Results. The variation in performance among the five ICs tested in this study should raise caution about IC assumptions and terminology, particularly as some so-called "improved" stoves in the natural draft category may at times perform even worse than a traditional mud cookstove. Across metrics, FD stoves outperform ND stoves in terms of reduction in BC concentrations. FD stoves should be considered for dissemination as improved cookstove programs worldwide begin to consider climate metrics as selection criteria. FD1, which emerged as the best performing IC, has been distributed to 438 households in the *Project Surya* area. Our results also have significant implications for health and climate impact studies, as impact estimates based on ND stoves would underestimate the BC reduction potential from ICs. In this regard, this study highlights the need for repeated tests to confirm statistical significance of mitigation potential.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Figures for climate–cookstove connection and expermental setup of test kitchen; tables for stove manufacturers and features, testing dates and times, summary statistics for individual stove tests; and additional text for data correction procedures. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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