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Reductions in Indoor Black Carbon Concentrations from Improved Biomass Stoves in Rural India

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ABSTRACT: Deployment of improved biomass burning cookstoves is recognized as a black carbon (BC) mitigation measure that has the potential to achieve health benefits and climate cobenefits. Yet, few field based studies document BC concentration reductions (and resulting human exposure) resulting from improved stove usage. In this paper, data are presented from 277 real-world cooking sessions collected during two field studies to document the impacts on indoor BC concentrations inside village kitchens as a result of switching from traditional stoves to improved forced draft (FD) stoves. Data collection utilized new low-cost cellphone methods to monitor BC, cooking duration, and fuel consumption. A cross sectional study recorded a reduction of 36% in BC during cooking sessions. An independent paired sample study demonstrated a statistically significant reduction of 40% in 24 h BC concentrations when traditional stoves were replaced with FD stoves. Reductions observed in these field studies differ from emission factor reductions (up to 99%) observed under controlled conditions in laboratory studies. Other nonstove sources (e.g., kerosene lamps, ambient concentrations) likely offset the reductions. Health exposure studies should utilize reductions determined by field measurements inside village kitchens, in conjunction with laboratory data, to assess the health impacts of new cooking technologies.

■ INTRODUCTION

Black carbon (BC), a component of fine particulate matter ($PM_{2.5}$) that is generated during incomplete combustion of fossil and biomass fuels (e.g., wood, crop residues, cow dung), is linked with negative health[1] and climate[4] impacts. A recent study in China found that the effects of the BC component of $PM_{2.5}$ on morbidity may be more significant than the effects of fine particles in general.[2,3] This is consistent with other studies which have documented that exposure to $PM_{2.5}$, the metric used in most health exposure studies, is not a reliable proxy for health outcomes.[5,6] In fact, targeting residential burning of biomass (for cooking, heating, and lighting), be it with improved biomass, electric, or other more modern stoves and fuels,[7,8] is thought to have the greatest potential overall health benefits of all measures to reduce BC.[9] Indeed, the average concentrations of BC in the range of 10−1000 $\mu g\ m^{-3}$ measured indoors in India may pose a serious threat to women and children subject to soot laden smoke from traditional stoves.[10,11]

From a climate perspective, BC is the dominant absorber of visible solar radiation in the atmosphere, and is considered to be the second largest contributor to global warming after carbon dioxide.[4] BC additionally has a short life of days to weeks (compared with longer-lived greenhouse gases) and contributes to increased melting of glaciers through direct and indirect effects, making it a key target in climate mitigation strategies.[4,12,13]

Improved stoves can reduce emissions of BC. Project Surya[14] study demonstrated that improved forced draft (FD) stoves, which utilize a battery powered fan (charged using grid electricity or a solar panel) to improve combustion, achieve almost twice the reductions in BC concentrations in a controlled kitchen when compared with natural draft stoves.[10]

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This same study found that in some instances, a natural draft stove actually increases emissions of BC. An earlier study[15] conducted in rural Mexico demonstrated that while one model of natural draft improved stove (brick Patsari) decreased elemental carbon emissions by approximately 60%, another model (mud-cement Patsari) increased emissions of elemental carbon (by a factor of 2.7). Therefore, in the studies presented here, Project Surya selected the improved FD stove, which while more expensive, would be expected to more reliably reduce BC emissions when used in place of a traditional stove. The emergence of lower-cost FD stoves, along with comprehensive solutions to providing power to homes, will increase the scalability of these highly efficient biomass stoves.

Laboratory and emission factor studies indicate that replacing traditional mud stoves with improved biomass cookstoves could produce significant health and climate benefits because of the reductions in emissions.[16,17] However, controlled tests (which take place in laboratory or controlled kitchens) are necessary but do not represent real-world conditions and do not capture variations in the field of factors like fuel type, fuel moisture content, and cooking practices.[18,19] According to the study conducted in Mexico, the products of incomplete combustion emitted from traditional stoves in rural kitchens almost double when compared to water boiling test emissions in simulated kitchens, largely because real-world cooking encompasses much more than boiling water.[15] Further, these controlled tests do not account for contributions from noncooking sources both indoors and outdoors, and therefore are not sufficient to fully determine personal exposures.[8]

Field data is needed in real-world kitchens to quantify the actual reductions in BC concentrations that can be expected when a household switches to an improved stove. In addition to collecting air samples in the field, cooking duration can be measured to document the extent to which an improved stove is incorporated into daily cooking. Indeed, even the best performing stove cannot produce better air quality if it is never used. The current lack of data under real-world conditions is due to multiple factors, including the associated cost and challenges in collecting field measurements.

The studies presented in this paper were conducted in India, where two-thirds of the population cook on traditional stoves using biomass,[20] and residential biomass burning is the largest source of BC.[21] The latest Global Burden of Disease (GBD) 2010 assessment estimates that in India, household air pollution resulting from solid cooking fuels can be linked to approximately 1.04 million premature deaths and 31.4 million disability-adjusted life years,[22,23] accounting for nearly 6% of the national burden of disease.

The studies presented in this paper extend previous work conducted by Project Surya by (1) presenting data from real-world kitchens and under real-world conditions in India where women are cooking food for their family with no constraints placed on the type or size of the meal they are cooking, (2) utilizing minimally invasive sampling devices that do not interfere with or change actual cooking practices, and (3) significantly increasing the number of BC measurements collected in a field setting, with data collection taking place in 26 households and across 277 cooking sessions. Data was collected using novel cell-phone based instruments and a miniature aerosol sampler that is low-cost and scalable for field studies.[11,24]

■ MATERIALS AND METHODS

Study Location. Two independent studies were conducted in the Indo-Gangetic Plains[25] in rural India, one of the regional hotspots of Black Carbon induced atmospheric solar heating:[4] A cross-sectional study (BC_CS) was conducted in Khairatpur and a paired sample (without control)[26,27] study (BC_PS) was conducted in Ashrafpur. The two villages (located approximately 15 km apart) were selected from the state of Uttar Pradesh based on their proximity to the established field office, and are representative of the region with respect to demographics, cooking habits, and stove and fuel types used. The traditional stove most commonly found in this region is a U-shaped mud stove without a chimney constructed almost free of cost using local soil mixed with crop residue (hereafer referred to as a "traditional mud stove"). The resulting structure is suitable for burning almost all types of locally available fuelwood and other biomass. Based on data from community leaders, an estimated 90% of the households used firewood, crop residue, and cow dung in traditional stoves to meet their cooking energy needs. This is consistent with census data for the region which states that 54% use fire wood, 11% use crop residue and 28% use cow dung as primary fuel for cooking.[20] The primary occupation for approximately two-thirds of the households is agriculture, with annual household earnings of about $1000.

Household Selection. After an initial survey in each village, study participants were selected based on an oral consent indicating the households' willingness to participate, at least 5 km away from other large-scale sources of BC (namely diesel vehicles and brick kilns), availability of biomass stoves, kitchen type (see below), income, and family size. Households that had access to LPG stoves were excluded from the selection process. Survey data on occupation and annual income was used to ensure that selected households belonged to the same socio-economic status with annual incomes ranging from 725 to 1280 USD, earned primarily through farming and day labor.

Households were selected to have one of two types of kitchens: *indoor* kitchens, which are enclosed by four walls and receive minimal ventilation, primarily through a window or a small opening near the roof; and *semiopen* kitchens, which have three walls, and are usually situated adjacent to an open courtyard. Given the open structure of the semiopen kitchens, the air exchange rates vary extensively within semiopen kitchens, and also between the semiopen and indoor kitchens. BC_CS households (n = 22) across both FD (n = 10) and traditional (n = 12) stoves were reasonably well matched in terms of household size (all households had 5−8 adults) and kitchen type (all but one household, using an FD stove, had semiopen kitchens). For BC_PS (n = 4), two households had semiopen kitchens, and two households had indoor kitchens.

Improved Stove and Training. From 2009 to 2010, selected households received forced draft (FD) stoves for free. FD stoves were used due to their high thermal efficiency and ability to substantially reduce BC and other particulate matter emissions.[10] A Philips FD model (HD4012) was used for BC_CS (thermal efficiency with wood chips as fuel: 38.7%).[28] The Philips stove was subsequently withdrawn from the market in India. Therefore, a TERI FD stove (SPT0610; manufactured by Phoenix Udyog Limited, Himachal Pradesh, India) closely matching the Philips HD4012 model in terms of performance and design (thermal efficiency with wood chips as fuel: 39.3%),[28] was selected for BC_PS. A Government of India recommended third party stove testing laboratory using a Bureau of Indian Standards protocol ensured the stoves met minimal thermal efficiency ($\geq$35%), and PM emission per energy delivered to cooking pot ($\leq$350 $mg/MJ_{delivered}$).[29] The stoves will meet the TIER 3 rating in terms of thermal efficiency and emissions of $PM_{2.5,}$ and CO, as defined by the International Standards Organization-International Workshop Agreement (ISO-IWA) Guidelines for evaluating cookstove performance.[30]

Women in each household were trained to operate and maintain the stove and battery pack, with an emphasis on how traditional mud stoves differ from FD stoves. A chart entitled "Do's and Do nots" was provided to each household in the local language. The stove usage was monitored for 1 week by the field staff and local volunteers, who provided hands-on training and feedback on efficient stove operation. Based on observations from the field that households used both the traditional mud stove and the FD stove in daily practice for different tasks ("stove stacking"[31−33]), an additional training session was added to address common barriers to FD stove usage. This training included the use of FD stoves to bake rotis (Indian flatbread), keeping the FD battery charged, and how to chop fuel. Because the BC_PS study took place over a year after the initial training had been conducted in that village, a one-week refresher training was provided to the participating households before this study began.

Fuel Procurement. Households using FD stoves used only chopped wood as fuel because the combustion chamber in these stoves is not suitable for low calorie fuels such as dung cakes. For BC_CS, participants selected and procured their own fuels and ignition material. Households with traditional mud stoves used fuel mixes consisting of wood, seasonal crop residue, and dung cakes. The proportion of each component in the fuel mix varied by day and by household based on availability, and was not monitored. Households with FD stoves collected and chopped their own fuel wood, and were instructed to use cut pieces of sun-dried wood for best results. For BC_PS, sun-dried cut Eucalyptus wood (the common species in the region) was provided to the participating households for use in both traditional mud and improved FD stoves. Traditional mud stove users were given 8 kg of fuel each day, in approximately 30 × 3 × 3 cm pieces. FD stove users were given 5 kg of fuel each day, in approximately 8 × 3 × 3 cm pieces. For ignition, households used their own crop residue and kerosene, which is a common practice in the area. Fuel was replenished every day after measuring the remaining wood from the previous day for this study. The moisture content of fuel wood was not measured for either study.

Instrumentation and Monitoring. For both studies, study staff and locally recruited volunteers were appointed to each household to monitor each cooking session, conduct data collection tasks, and report anomalous observation in cookstove usage or instrument operation.

Black Carbon Sampling. Both studies were conducted using a novel cell phone based black carbon monitoring system (BC_CBM) that integrates a miniature aerosol sampler (MAS), specially produced by the University of California at San Diego researchers, and a cellphone for filter image collection. The MAS consists of a (i) battery operated micro air pump (manufactured by Sensidyne Inc., AAA series micro air pump model-20), (ii) 25 mm diameter closed aluminum filter holder (BGI Inc., Waltham, MA), (iii) battery for continuous power supply and (iv) circuit to maintain and regulate the flow rate as battery voltage varies. The MAS flow rate for the samplers typically ranged from 100−300 cc min^{-1}, and was recorded by a data logger on the sampler. BC was collected on quartz filters (Pall Corporation).

In each study, the MAS was placed in the "breathing zone", located 0.6 m away from the stove and 0.7 m above the ground, where the woman spends most of her time during cooking (Figure 1).[10] For BC_CS each cooking session was monitored separately: approximately 3 h samples were collected for each cooking session (typically one in the morning and one in the evening) during the sampling period. Twenty four hour air samples were collected for BC_PS to monitor BC concentrations in the kitchen, which included morning and evening cooking sessions as well as noncooking hours. Samplers were run for 24 h to additionally minimize the disturbance of visitors to the households and accommodate travel by researchers to and from the remote villages. Independent ambient, or background, BC was not collected in either study.

Figure 1. Image taken from BC_PS. Sampler located in the breathing zone. Stove instrumented with WiCS cookstove sensor (yellow cable) to track the cooking time and fuel usage.

Black Carbon Filter Analysis. After each air sampling period, the filter was removed from the sampler, and a photograph was taken and uploaded using the study cell-phone for analysis to determine black carbon loading.[11] In this system, the BC loading on a quartz filter is determined via automated image-analysis on the BC_CBM server, which accurately estimates BC to within a root mean squared error of less than 10% (absolute accuracy to within 20%) of a gold-standard BC reference instrument.[11] The server automatically extracts and scales the color of the filter in the image (using the reference card, also included in the picture) and converts it to BC loading on the filter using a pre-established, calibrated scale. BC concentration is obtained using the following equation:

$$BC_C[\mu g\,m^{-3}] = (BC_L[\mu g\,cm^{-2}]\cdot A[cm^2])/V_F[m^3] \quad (1)$$

Where BC_L is the loading on the filter as determined by the BC_CBM system, and A is the area of the particulate accumulation on the filter. V_F is the volume of air that passes through the filter, and is the product of the MAS flow-rate and the recorded exposure duration for the filter. This method used no fractionation of particle size (BC, without size differentiation, has been shown to have health consequences)[1] and has since been validated through comparison with a number of gold standard methods including an Aethalometer, thermal optical filter-based methods, and a photo-acoustic soot spectrometer in a number of studies, for example, ref 11.

This method was selected based on the cost and ease of use in a field study; filters can be analyzed in the field and do not need to be packaged, refrigerated, and shipped to a laboratory for analysis. A primary limitation of the BC_CBM technique however is that it integrates over the sampling period and does not provide real-time (hourly or more frequent) data, which makes it difficult to differentiate the ambient concentrations from those observed during cooking sessions. Also, identifying peak concentrations within cooking sessions is not possible with this technique.

Cookstove Usage and Fuel Consumption. Cookstove usage and fuel consumption were only monitored for BC_PS. A wireless cookstove temperature monitoring sensor system (WiCS) was deployed to monitor cooking duration and fuel consumption[24] in order to explore other factors that might affect measured BC concentrations in rural kitchens. This system uses a thermal sensor that is attached to the outside of a traditional mud or FD stove via a standardized metal probe[24] to monitor the cooking sessions (Figure 1). The WiCS device uploads temperature data to the centralized WiCS database wirelessly. Computer algorithms are then used to automatically estimate cooking duration and fuel consumption based on temperature excursions from ambient.[24] For example, temperature data recorded over a period of 30 hours obtained from one of the participating households (Figure 2) exhibits two evening cooking events lasting from approximately 7.30–9.30 pm (local time), as well as a shorter morning cooking event lasting from approximately 7.30–9.00 am (local time). The cooking events have been identified automatically by the server which adds the gray highlighted bars and a summary of cooking duration and fuel consumption for each day.

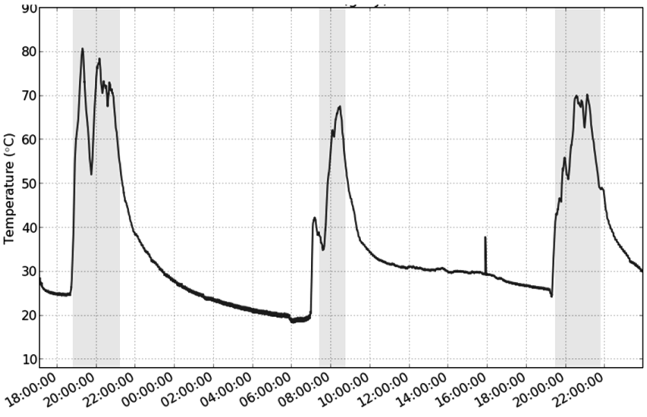

Figure 2. Temperature data recorded over a period of 30 hours from a participating household; snapshot taken from WiCS[24] Web site (solid lines) and cooking events automatically detected by servers (gray bars).

Study Design. *Cross Sectional Study (Experiment BC_CS).* An independent study was carried out from January eighth to February 24th, 2012 (winter) in Khairatpur in a cross sectional study in 22 households. Twenty-four households were enrolled. Four households were monitored at a time due to limited field resources. In each monitoring period, two households were instructed to cook meals on traditional mud stoves only and two households were instructed to use FD stoves only. Sampling took place in each household for up to 4 days (up to eight cooking sessions). A total of 131 BC samples were collected. After excluding two households where only 1 sample was collected, a total of 129 samples were considered for analysis; 65 samples collected across 12 households using traditional mud stoves, and 64 samples collected across 10 households using FD stoves.

Paired Sample Study (BC_PS). Data collection was conducted in Ashrafpur from April 24th to May 30th, 2013 (summer) using a paired sample design in four households. A total of 74 24-h samples were collected across 20 days of sampling. During the first 10 days of sampling, all four households were instructed to use only their traditional mud stove for all cooking tasks; 39 samples were collected during this period. All households were subsequently instructed to use only the FD stove for all cooking tasks, and 35 more samples were collected. Such "before and after" samples control for household factors such as cooking idiosyncrasies, kitchen geometry, and ventilation.

Data Analysis. An open-source statistical analysis tool (R) was used for data analysis. For each study, the percent reduction was calculated using all of the samples for households separated by stove type. A two-tailed unpaired T-Test was used because of the effect of individual differences among households. The coefficient of variance (CV), defined as the ratio of the standard deviation to the mean, is used to quantify the variability.

RESULTS AND DISCUSSION

Summary of Main Results. This is one of few studies to monitor BC concentrations in uncontrolled rural kitchen environments. The primary results from the two independent intervention studies, the cross-sectional study (BC_CS) and the paired sample study (BC_PS) are

- Replacing the traditional mud stove with the forced draft (FD) stove achieves 36–40% reduction in the mean indoor BC concentration irrespective of whether data is collected in a paired (before-after) or cross-sectional study: a statistically significant ($p < 0.001$) 40% reduction in the BC concentration for the BC_PS intervention, and a similar reduction of 36% for the BC_CS intervention, albeit with a suboptimal statistical significance ($p = 0.08$) (The means and standard deviations are contained in Table 1 and corresponding plots in Figure 3).

Table 1. Summary Data for Each Study, BC Concentrations Are Stated As (Mean ± SD) (%CV)

	paired sample (BC_PS)		cross sectional (BC_CS)	
	N	BC concentration ($\mu g\ m^{-3}$)	*N*	BC concentration ($\mu g\ m^{-3}$)
traditional stove	39	26.2 ± 11.5 (44%)	65	91.7 ± 52.9 (58%)
forced draft (FD) stove	35	15.8 ± 6.3 (40%)	64	58.9 ± 19.5 (33%)
reduction		40%		36%
t-test p-value[1]		<0.001		0.08

- The similar reduction of 36–40% for the BC_CS and the BC_PS interventions substantiates the robustness of the main finding of this study because of the substantial differences between the design of the two studies, the season, and the daily sampling duration. BC_CS was a cross-sectional study conducted during the winter of 129 cooking sessions (approximately 3-h samples) collected in 22 households. Whereas BC_PS involved comparisons of the BC before and after the introduction of the FD

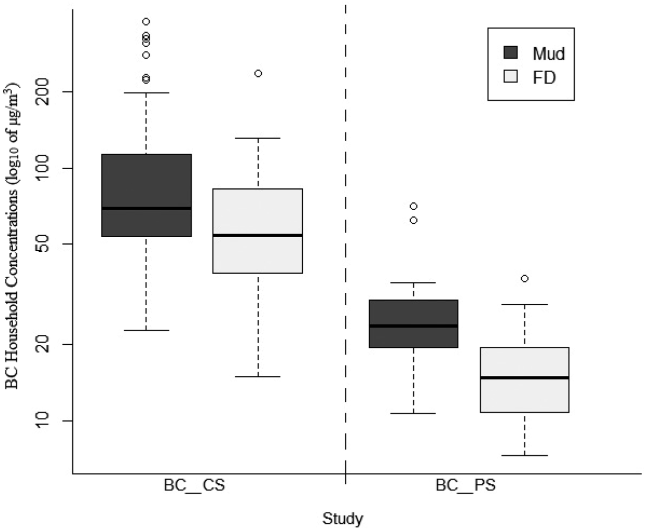

Figure 3. BC concentrations summarized by stove type for both the cross sectional (BC_CS) and paired sample (BC_PS) studies.

stove using 74 24-h time averaged samples of the BC concentration collected during the summer months in 4 households.

The data have major implications for understanding exposure to BC:

- The cooking period average (BC_CS) BC concentrations are 3.5–3.9 times higher than the 24 h average (BC_PS) concentrations, regardless of stove type (Table 1). This is because a major source of emissions is cooking (and lighting, which is used during cooking in the kitchen), and cooking emissions were averaged with background concentrations during noncooking hours for the 24-h sample (Figure 3).
- The FD stoves decreased the frequency of high BC concentrations (>100 μg m^{-3}) during cooking hours.[10] BC concentrations exceeding 100 μg m^{-3} were recorded during cooking sessions in almost one-third of homes with traditional stoves (29%), compared with only 11% of homes cooking with FD stoves.

Attributing the Reduction in BC Concentrations. Data in controlled and laboratory settings indicates that a reduction in indoor BC concentrations can be expected when switching to FD stoves. For example, an 86% reduction in BC concentrations was documented when switching from a traditional mud stove to an FD stove in a controlled kitchen (with no other major sources of BC) located on the periphery of the Indian villages where the BC_CS and BC_PS studies were conducted.[10] This reduction is similar to a reduction in emission factors documented in a U.S. laboratory of 0.88 g kg^{-1} for a three-stone fire and 0.06 g kg^{-1} for a Philips FD, which, when taking into account the 60% reduction in fuel when using a FD stove, corresponds to an overall reduction of 99% of the BC emissions.[34] Given the 61% average reduction in fuel consumption documented in BC_PS when households switched from traditional stoves (5.2 ± 1.09 kg; mean ± SD; CV: 21%) to FD stoves (2.2 ± 0.48 kg; CV: 22%), with no statistically significant change in cooking duration between the traditional stove usage (171 ± 20 min.; CV: 11%) and FD (154 ± 29 min; 19%), it can be assumed that the FD stoves reduced cooking related emissions. (Fuel consumption and cooking duration were not measured for BC_CS.) Further, the 36% reduction measured in the BC_CS study is nearly identical to the 40% reduction documented in the independent BC_PS study. Finally, a reduction in BC concentrations (and fuel consumption) is documented for every household in BC_PS after switching to the FD stove (Figure 4). (This comparison was not possible for BC_CS because each household used only one type of stove during the study.) Given the consistency of the results across households, across the two independent field studies presented in this paper, and with previously presented laboratory studies, we can be reasonably sure that the reduction in BC concentrations detected when households switch to improved stoves can indeed be attributed to the FD stoves.

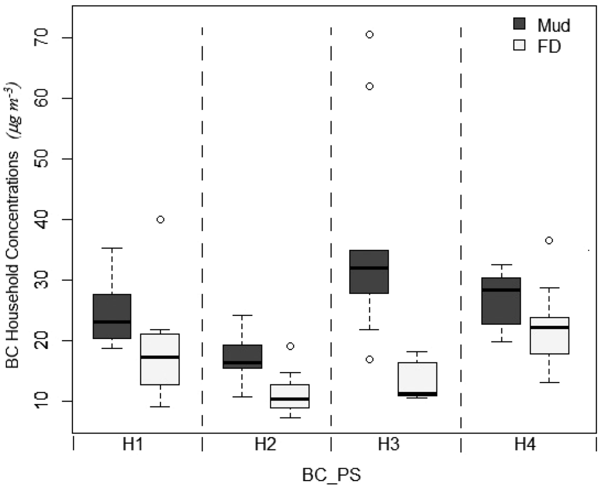

Figure 4. BC concentrations by household, before and after use of FD stove, for BC_PS.

Implications for Health Exposure Studies. The close to 40% reductions in BC concentrations reported here based on field measurements is less than one-half of the 86–99% reductions previously reported in laboratory or other more controlled conditions.[10,34] While the laboratory conditions are relevant for emission inventory estimates, they are unreliable for health-exposure studies.

Part of this difference can be attributed to unaccounted sources of BC within the kitchen, primarily the kerosene lamps. Cooking and lighting are two of the most significant sources of BC inside homes in this region. Specifically, cooking on traditional mud stoves in this region contributes approximately 4.6 g BC per day, using an emission factor of 0.88 g kg^{-1} wood[34] and average daily fuel consumption of 5.2 kg wood (as reported in the BC_PS study). Similarly, lighting contributes approximately 3.3 g BC per day, using an emission factor for a simple wick lamp of 76 g kg^{-1} kerosene and a burn rate of 0.12 g minute^{-1},[35] and assuming that a kerosene lamp is used 6 h each day. Thus, kerosene lamps may contribute almost as much as cookstoves to indoor BC. The fundamental implication is that reductions in emission factors may not be representative of reductions in human exposure to BC, and that field studies include human exposure to all sources, including indoor and outdoor sources.[8]

Understanding and Accounting for the Variability in BC Concentrations. The variability of BC concentrations in the two studies described here ranges from 33% to 58% (Table 1). A coefficient of variance (CV) of 50% is reported for BC concentrations collected for repeated controlled cooking tests on the same stove in a controlled kitchen in rural India.[10] It would be reasonable to expect even higher variability in a more uncontrolled setting. Indeed, CVs ranging from 89% to 120% are reported in a study of $PM_{2.5}$ and CO collected in 98 households in Guatemala[36] and CVs ranging from 58% to 109% for $PM_{2.5}$ and CO are reported in a field study in India.[31] In comparison, the variability of 33% to 58% documented in the BC_PS and BC_CS studies is therefore close to, if not substantially lower than the variability documented in other field cooking studies.

Interestingly variability in semiopen (ventilated) kitchens is almost twice that observed in indoor (unventilated) kitchens. A 58% variability is observed for traditional mud stoves used in semiopen kitchens regardless of study design or location (BC_CS: 91.7 ± 57.7 $\mu g\ m^{-3}$ based on samples from all 12 households; mean ± SD; BC_PS: 26.5 ± 15.5 $\mu g\ m^{-3}$ based on samples from the two semiopen kitchens). The variability for indoor kitchens (only present in BC_PS) is less than half. The greater variability in semiopen kitchens is likely due to variations in ambient concentrations and the mixing between ambient and indoor air, all of which depend on a number of factors including wind speed and direction.

Traditional mud stoves in semiopen kitchens demonstrated the highest variability in both studies and is quantified here. By comparing the variability in semi open kitchens with indoor kitchens, we estimate that about 20% (of the 58% variability) is due to the mixing with ambient air (outdoor BC concentrations were not measured in this study). The BC instrument noise contributes about 10%.[11] The remaining source of variability for both studies is likely due to the variability in fuel consumption (which represents differences in cooking practices). The substantially higher variability observed for traditional stoves in BC_CS may be attributable to the use of uncontrolled ratios of mixed fuels.[10] The variability for forced draft stoves is lower, likely due to the use of consistent fuel (hardwood) and because the indoor BC concentrations are closer to ambient, so mixing with ambient air has less of an impact.

Implications for Large Scale Studies. Field measurements were relatively affordable in this study through the use of the automated miniature aerosol sampler system and cell-phone based instruments, which when combined with appropriate study design, provided relatively low-cost, high-quality data that can potentially support larger-scale field studies in hundreds of households. Access to lower power and automated samplers could further simplify field logistics, allowing even larger scale studies.

Influence of Ambient Sources. It is indeed possible that some or all of the decrease in BC observed in the BC_PS intervention (after the ICs were introduced) may be due to decreases in ambient BC. We did not measure ambient BC during the intervention to answer this question conclusively. Nevertheless, examination of data from a neighboring air quality station located in Kanpur, India (approximately 170 km from the study site)[37] as well as satellite-derived vertical profile of aerosol extinction coefficient, supports our deduction that the decrease in indoor BC observed after the introduction of the FD stoves is largely due to the decrease in BC emissions from the improved stoves.

The station measures surface carbon monoxide (CO, measured using a nondispersive infrared (NDIR) gas filter correlation analyzer; 48i; Thermo Scientific), NOx (42i; Thermo Scientific) and vertical profiles of the aerosol extinction coefficient at 532 nm, Ae (km^{-1}), from a NASA MPLNET (Micro-Pulse Lidar Network) station during our intervention period (May, 2013). Ae was also collected from NASA CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) satellite data, which has been validated over the Indo-Gangetic Basin (IGB).[38] CALIPSO has been used recently to study aerosol radiative forcing over the IGB and to study aerosol composition.[39] Of the three variables, CO and Ae are directly linked with cookstove emissions since the low temperature cookstoves do not emit much NO_x but emit CO and aerosols (BC and OC).

Table 2 summarizes the data for the periods before and after the intervention. We note that CO emissions are statistically the same for the two periods, and furthermore, MPLNET data from Kanpur and CALIPSO data show that Ae increased slightly during the postintervention period. Thus, both the surface data and the vertical profile data show that changes in ambient pollution could not have contributed to the decrease in indoor BC during the post intervention period.

Table 2. Ambient Concentrations from Nearby MPLNET Air Pollution Station and CALIPSO Satellite for BC_PS study, Concentration Are Stated as (Mean ± SD). Aerosol Extinction Coefficients (Ae) (km^{-1}) Are Reported up to 1 km

	before	after	p-value
CO	0.58 ± 0.17	0.71 ± 0.15	0.48
NASA MPLNET: Ae	0.213 ± 0.0237	0.255 ± 0.0252	0.0005
NASA CALIPSO: Ae	0.176 ± 0.0297	0.203 ± 0.0358	0.01

It can also be questioned whether observations at the Kanpur station are indicative of temporal variations over the study location (170 km away). In a related study, we showed that ambient temporal variations measured in a nearby village (20 km away from the BC_PS and BC_CS sites) correlate well with surrounding areas on a scale of hundreds to a thousand km.[40] Furthermore, the Ae data shown in Table 2 corroborates the finding of this earlier study: The MPLNET data collected at the Kanpur station during the pre- and postintervention periods for the BC_PS study, shows similar variations in Ae (in both the sign and the magnitude) as the CALIPSO satellite data (which covers a spatial scale of a few hundred km; Table 2).

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Notes

The authors declare no competing financial interest.

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