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Health and Climate-Relevant Pollutant Concentrations from a Carbon-Finance Approved Cookstove Intervention in Rural India

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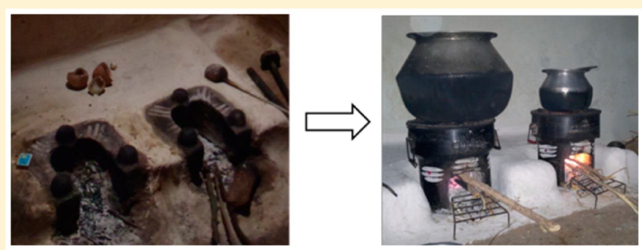
Supporting Information

ABSTRACT: Efforts to introduce more efficient stoves increasingly leverage carbon-finance to scale up dissemination of interventions. We conducted a randomized intervention study to evaluate a Clean Development Mechanism approved stove replacement impact on fuelwood usage, and climate and health-relevant air pollutants. We randomly assigned 187 households to either receive the intervention or to continue using traditional stoves. Measurements of fine particulate matter ($PM_{2.5}$) and absorbance were conducted in cooking areas, village center and at upwind background site. There were minor and overlapping seasonal differences (post- minus preintervention change) between control and intervention groups for median (95% CI) fuel use (−0.60 (−1.02, −0.22) vs −0.52 (−1.07, 0.00) kg day^{-1}), and 24 h absorbance (35 (18, 60) vs 36 (22, 50) × 10^{-6} m^{-1}); for 24 h $PM_{2.5}$, there was a higher (139 (61,229) vs 73(−6, 156) μg m^{-3})) increase in control compared to intervention homes between the two seasons. Forty percent of the intervention homes continued using traditional stoves. For intervention homes, absorbance-to-mass ratios suggest a higher proportion of black carbon in $PM_{2.5}$ emitted from intervention compared with traditional stoves. Absent of field-based evaluation, stove interventions may be pursued that fail to realize expected carbon reductions or anticipated health and climate cobenefits.



INTRODUCTION

Burning solid fuel (wood, dung, agricultural residues, and coal) in traditional stoves for cooking and heating negatively affects the health and welfare of nearly 3 billion people, mostly in low and middle-income countries.[1] Household air pollution (HAP) emitted from solid fuel combustion contributed to an estimated 2.9 million premature deaths and 81.1 million disability-adjusted life-years in 2013.[2] It is also an important contributor to emissions of climate-forcing pollutants.[3−6]

Traditional solid fuel cookstoves emit HAP associated with childhood pneumonia, chronic obstructive pulmonary disease in women, lung cancer, cataracts, and tuberculosis,[7−11] and combustion-derived $PM_{2.5}$ more generally is associated with ischemic heart disease and stroke.[12] Inefficient combustion of biomass emits black carbon (BC) which has also been associated with cardiovascular and respiratory morbidity and mortality[13,14] and is thought to have the second largest radiative forcing after CO_2.[3,15] Household biomass combustion is a major contributor of BC emissions; in Africa and Asia, the sector is thought to account for 70% of the region's BC emissions.[3] Efficient, low-polluting cookstoves and fuels have the potential to achieve cobenefits for health and climate. Cookstoves that reduce fine particulate matter ($PM_{2.5}$) and carbon monoxide (CO) exposures may improve respiratory and cardiovascular health compared to use of traditional stoves.[16−22] More efficient stoves and fuels have been proposed as mitigation strategies to reduce BC emissions.[23] However, only a few studies have quantified BC from cookstove interventions, and they suggest that while some intervention cookstoves reduce BC emissions,[24,25] others may actually emit more BC than traditional stoves.[26,27]

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Major development efforts aim to replace traditional cooking devices with more efficient stoves and fuels (i.e., "improved" cookstoves).[28−30] Many of these efforts are financed through carbon markets, in which greenhouse gas (GHG) emission reductions from "improved" cookstoves are sold as carbon credits to investors to offset existing GHG emissions.[31] Of the 8.2 million improved cookstoves distributed in 2012 and tracked by the Global Alliance for Clean Cookstoves (Alliance), half received carbon financing.[32] Despite the instability of carbon markets since 2011, carbon finance was still the single largest financier (36% of funding) of cookstove projects in 2013, with governments being the second largest at 25%.[33]

Several national and international efforts are leveraging carbon financing loans to scale up stove interventions. India's National Biomass Cookstove Initiative, launched in 2009, plans to utilize carbon markets to expand their effort to distribute millions of improved biomass cookstoves over the next decade.[28,34] In 2014, the Alliance launched a Clean Cooking Loan Fund to leverage private sector finance, such as from carbon financing, to scale up cookstove interventions globally.[35]

Carbon financing has been posited to hold transformative potential for the household energy sector in part because it is seen as self-sustaining with potential for scale-up with the market, in comparison to traditional donor-based interventions that can terminate when funding ends.[36] Several financing schemes incorporate improved cookstoves,[37] of which the largest is the Clean Development Mechanism (CDM), established under the UN Framework Convention on Climate Change.[38] Only CDM-issued carbon credits can be sold on the compliance market as part of Kyoto Protocol obligations; via that market, governments and regulated agencies may purchase credits to offset GHG emission-reduction obligations. Separately (outside of the Kyoto Protocol), any carbon financing program can sell carbon credits on voluntary markets, to be purchased by individuals and organizations to offset carbon emission for social responsibility.

The extent to which health and climate cobenefits can be achieved through carbon-financed cookstove intervention programs has not been systematically evaluated. Carbon financing schemes have been primarily concerned with reduced fuelwood use and emissions of CO_2 and methane, two GHGs included in the Kyoto Protocol.[39] Reductions of other HAP pollutants that are important for health and climate are desirable but not accounted for in the current carbon crediting programs because they are not part of the Kyoto Protocol. Under the CDM, CO_2 savings are obtained from reduction in nonrenewably harvested fuelwood use.[40] The CO_2 savings typically are converted into carbon credits using laboratory-based Water Boiling Tests results on stove efficiency and fuelwood usage. Default values for emission factors result in large uncertainties.[37,41] Laboratory results are rarely replicated in the field because of variations in food and fuel types, cooking and behavioral patterns.[26,42−44] Several large-scale energy intervention programs failed to demonstrate benefits to users despite demonstrated improved laboratory efficiencies compared with traditional stoves.[45,46] Finally, stove technology choices and their trade-offs[6] as well as behavioral (stove usage) patterns[47,48] will impact whether and how much climate and health cobenefits can be achieved. These results suggest a causal chain of conditions needed for a cookstove intervention to achieve climate and health cobenefits, specifically: (1) the intervention stove must significantly reduce fuel wood use, and climate- and health-relevant pollutants under actual use; (2) households must substitute intervention stoves for traditional stoves; and (3) interventions must be community-wide or air pollution exposure must be primarily determined by the household's own stove.

Within this context, we partnered with a local non-governmental organization (NGO) implementing a CDM-approved cookstove intervention program in rural India. Our goal was to evaluate an approved carbon financed program for its potential to provide climate and health cobenefits. The study investigated whether replacement of traditional stoves with intervention stoves under a carbon-finance approved program: (1) reduced fuelwood consumption (primary intent of the CDM program); (2) lowered 24 h $PM_{2.5}$ and BC indoor concentrations (health and climate cobenefits); and (3) led to actual substitution of traditional stoves with intervention stoves. As carbon financing of stove interventions scale up globally, the study aims to contribute to the development of evidence-based policies to maximize benefits from stove interventions.

■ MATERIALS AND METHODS

Setting. The study site was in Koppal District of northern Karnataka, India. Most households (99%) in this region burn biomass fuels in three stone fires or traditional stoves made of mud or clay for cooking and heating of bath water[49] (Supporting Information (SI) Figure S1). The majority of households cook inside their main home, though some use outdoor cooking sheds with thatched walls extended from the main house structure.

In 2011, the partner NGO received the first cookstove-related CDM approval in India. They planned to distribute 40 000 fuel-efficient cookstoves to 21 500 households in rural Karnataka in exchange for carbon credits totaling 43 215 tCO_2/year over a period of 10 years.[50] The intervention stove approved by the CDM was a single-pot "rocket-style" biomass cookstove with an elbow-shape insulated combustion chamber made of lightweight ceramic (SI Figure S2−S3). Rocket stoves fall under natural draft stove category where structural modifications are made to enhance air flow, and are considered the most basic of "improved" cookstoves types. They are cheaper compared to more advanced biomass stoves such as forced draft stoves, and gasifiers. The stove was manufactured in Karnataka and could be used with the same locally available fuelwood as used in traditional stoves. Laboratory tests of the intervention stove measured thermal efficiency of 30.8% (vs 10% for a traditional stove) and an estimated 67% reduction in fuelwood consumption relative to a traditional stove.[51−53] No emission tests were conducted in laboratory or field as these were not required for CDM approval. The carbon credit calculation for this project is provided in SI 1.

The market price of the intervention stove was 1398 Rupees (approximately US$21). For the CDM program evaluated here, households paid a one-time registration fee of 200 Rupees (approximately equivalent to the cost of two traditional stoves) and received two new intervention stoves.[52] The sale of carbon credits helped subsidize the rollout of the intervention stoves including project operations, stove maintenance and monitoring.[53] Participating households did not receive any direct financial incentives; households were informed through stakeholder consultations about benefits of intervention stoves including reduced fuel wood use and greenhouse gas emissions, and improved well-being for women.[52]

Prior to launching the full CDM program, the partner NGO conducted a pilot intervention program in Hire Waddarkal

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(HW) Village in Koppal District in northern Karnataka. Activities included removal of traditional stoves from homes receiving the intervention; constructing raised clay walls around the new stoves to make them look similar to the traditional set up; monitoring the use of new stoves; and assisting users with stove operation and maintenance. These activities were similar to those planned as part of the NGO's full CDM stove intervention program.

Experimental Design. We implemented a one-year evaluation study from September 2011 to August 2012 in HW Village that coincided with the NGO's pilot intervention program; the study investigators were independent of this intervention program. A subset of households was randomly assigned to receive the intervention stove a year earlier than others, with the remainder serving as controls.

Households were initially recruited for the study by the partner NGO based on CDM program eligibility criteria that they (1) did not use liquefied petroleum gas (LPG); (2) used traditional cookstoves that they were willing to remove from the home; (3) had a household of less than 11 occupants; (4) were not seasonal migrants; and (5) were willing to pay the registration fee. For our evaluation study, eligible households from the CDM intervention program were also required to (1) have at least one female cook over 25 years old who was neither pregnant at enrolment nor a current or previous smoker; and 2) provide oral informed consent. Of the 300 households in the CDM pilot village, 202 were eligible to participate in the CDM program. Of these, 187 households met the additional eligibility criteria for the evaluation study (SI Figure S5).

The study randomly assigned the households to either receive the intervention (n = 96, or 32% of the 300 homes in the study village) or to continue cooking with their traditional stoves (n = 91, 30%). Baseline (preintervention (pre)) measurements of household air pollution concentrations and fuelwood use were collected from September to December 2011. The intervention group received new stoves after baseline measurements were completed. Identical follow-up measurements (postintervention (post)) were then conducted in control and intervention homes from March to August 2012, with a minimum of 124 days (average of 194 days) between pre- and postintervention measurements. Control households were given the option to receive the intervention stoves at the end of the one year study period.

The study protocol was approved by institutional review boards at the University of Minnesota (IRB code #1104S97992), St. John's Medical College (IERB Study ref No. 103/2011) in India, and the University of British Columbia (CREB #H14−03012).

The study included a range of air quality, health, fuelwood use, and time-use measurements: (1) 24 h integrated gravimetric measurements of indoor and outdoor fine particle mass ($PM_{2.5}$) and absorbance (a measure of BC);[54] (2) continuous measurement of in-plume emissions and indoor concentrations of CO_2, CO, BC, and $PM_{2.5}$ in a subset of samples; (3) blood pressure and health symptoms of adult women; (4) fuelwood usage, and (5) time spent cooking and collecting fuelwood. This paper reports on the integrated sampling air pollution measurements and fuelwood usage.

Questionnaires. Household questionnaires were administered to participants to collect socio-demographic information, including age, gender, education, caste, family size, income, and household assets.[55] Information on presence and number of smokers in the household, and physical characteristics of the house that could potentially impact indoor air quality was gathered, including presence of chimneys, windows and doors, gaps between wall and roof, and dwelling type (attached or shared wall with neighbor). In the postintervention evaluation, we added questions on the type and number of stoves used during the indoor air pollution measurement and the frequency of intervention stove usage on most days and reasons for use or disuse in intervention households.

Questionnaires were modified from those used in other studies[56] and from the Living Standard Measurement Study on household survey.[57] The questions were first evaluated by local NGO staff for social and cultural appropriateness, translated and back-translated between English and Kannada, and pilot tested in a community near the study village.

Fuelwood Weight and Moisture. Households' fuelwood piles were weighed before and after a 24 h period over two consecutive days to obtain a 24 h average following the Kitchen Performance Test protocol.[58] Pre- and postintervention fuelwood weighing was completed in a total of 178 households. The water content of the weighed fuel was measured with a moisture meter (BD-2100, Delmhorst Instrument Co., Towaco, NJ) by selecting three fuel logs from the weighed fuel pile and taking three measurements on each log, which were then averaged to estimate the wood moisture per fuelwood pile. Wood moisture readings were obtained from 164 households during both the pre- and postintervention evaluations.

Measurement of Household and Ambient Air Pollution. Air pollution was measured over a 24 h period at three locations: within cooking areas, at a fixed site in the center of the village, and a location 1-km in the predominant upwind direction of the village (SI Figure S4). Cooking area measurements were conducted to assess 24 h indoor air pollution concentrations in line with World Health Organization (WHO) HAP guidelines, a metric that is most relevant for health assessment.[59] In the study region, households typically cook two main meals per day (morning and evening). Air monitoring instruments were placed approximately 100 cm from the edge of the combustion zone and at least 150 cm away from doors and windows in accordance with the Standard Operating Procedure for Installing Indoor Air Pollution Instruments in a Home.[60] PM mass samples were collected 60 cm above the floor to approximate a cook's breathing zone when squatting or sitting next to the stove. Postintervention measurements took place in the same location as during the baseline assessment.

Fixed site monitors at the center and upwind of the village were used to assess ambient air quality. Paired (village center and upwind) ambient measurements were collected over a 4 week period in both the pre- and postintervention phases, and consisted of 11 measurement-days (pre; September 2011) and 14 measurement-days (post; July to August 2012). Air quality measurements in the village center continued during days with indoor (cooking area) measurements.

$PM_{2.5}$ samples were collected on 37 mm Teflon filters (EMD Millipore, MA) placed downstream of a cyclone (BGI Inc., Waltham, MA)) with a 2.5 μm aerodynamic-diameter cut point connected to a battery-operated pump (Apex Pro, Casella CEL, UK) (SI 2). Filters that sampled shorter than 24 h but met a minimum sampling duration criteria of 16 h were adjusted with correction factors drawn from distributions developed from colocated time-integrated and real-time $PM_{2.5}$ (DustTrak Aerosol Monitor 8520, TSI Incorporated, Shoreview, MN) and BC (microAeth model AE51, AethLabs, San Francisco,

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Table 1. Selected Baseline Characteristics of Randomized Households[a]

characteristics	control (n = 91)	intervention (n = 96)	p-value[b]	control- after drop out (n = 87)	intervention- after drop out (n = 79)	p-value[c]
number of rooms in house	2.0 ± 1.0	2.2 ± 1.1	0.19	2.0 ± 1.0	2.3 ± 1.2	0.14
family size	6.1 ± 1.9	5.8 ± 2.0	0.35	6.1 ± 2.0	5.8 ± 2.0	0.30
house type (shared wall with neighbor) (%)	83	84	0.95	82	82	1.00
roof material (*improved, i.e. corrugated iron, zinc, metal sheets, cement, concrete, tiles*) (%)	53	52	1.00	52	52	1.00
floor material (*finished floor, i.e. ceramic, marble tiles, cement/concrete, stone*) (%)	67	75	0.30	68	75	0.42
area of irrigated land owned (acre)	1.8 ± 2.8	1.6 ± 2.8	0.42	1.9 ± 2.8	1.5 ± 2.8	0.17
TV (%)	20	28	0.24	21	28	0.37
motorcycle (%)	12	9	0.72	13	8	0.42
chimney above stove (%)	36	39	0.79	37	38	1.00
smokers in home (%)	36	36	1.00	35	37	0.93
no windows (%)	27	26	0.95	28	27	1.00

[a]Data are mean ± SD or number (%). p-Values are two-tailed t tests for continuous normally distributed variables, and Wilcox-test for non-normal distributed data; chi-square tests for categorical variables. [b]Between control and intervention groups as randomized. [c]Between control and intervention groups that remained until end of the study.

CA) indoor measurements (SI 3). To assess day-to-day variability, we conducted two additional 24 h air pollution measurements (i.e., continuous 72 h) in a random 10% sample of pre- and postintervention homes.

Teflon filters were pre- and postweighed in triplicate on a microbalance (Sartorius M3P) in temperature and humidity controlled environment. $PM_{2.5}$ mass concentration was obtained by dividing blank-corrected filter mass by sampled air volume (SI 4). As in previous studies measuring BC from residential biomass combustion,[25] absorbance was measured by filter reflectance analysis using a Smoke Stain Reflectometer (SSR) (Model 43D, Diffusion Systems Ltd., London, UK) in a room with minimal light (ISO 9835:1993).[61]

A weather station (model PWS 1000 TB, Zephyr Instruments, East Granby, CT) was placed in the center of the village next to the community measurement location and recorded temperature, relative humidity, atmospheric pressure, wind speed, and wind direction every 30 min.

Statistical Analysis. Household physical and socio-demographic characteristics were compared between control and intervention groups using a chi-squared test for categorical variables and a t-test for continuous variables to assess whether randomization was successful. Day-to-day variability in air pollutant concentrations was assessed using the nonparametric Friedman test for repeated measures. We used the Wilcoxon rank-sum test for unpaired samples to compare ambient concentrations between upwind and village center sites and between pre- and postintervention seasons. The Wilcoxon signed rank sum test for matched-subjects was used to assess changes in fuelwood use, fuelwood moisture, and indoor air concentrations of $PM_{2.5}$ and absorbance between pre- and postintervention seasons. In addition, we used mixed-effect models with random intercepts at household level to evaluate impact of stove use on log-transformed indoor HAP concentrations controlling for key covariates such as ambient conditions (temperature, humidity, and outdoor $PM_{2.5}$ or Abs concentrations), presence of chimney, and wood quantity and moisture. We calculated least-squares mean to assess percent change in HAP concentrations within and between stove use groups. Model assumptions were verified using normal quantile plots to inspect normality of random effect, and residuals of the mixed effect model.

Statistical comparisons were first conducted with households divided into assigned groups (control versus intervention, "intent-to-treat"); then intervention households were divided into those following/not following protocol ("per-protocol", i.e., did/did not exclusively use the intervention stove), and statistical analyses were repeated. Intent-to-treat evaluates the effectiveness of the overall intervention while per-protocol assesses stove efficacy. Analyses were conducted using R statistical software.[62]

■ RESULTS

Intervention and control groups were similar for key characteristics relevant to indoor PM concentrations, including socioeconomic status, the number of tobacco smokers in household, chimney ventilation, or the number of windows in the home, indicating selection bias was unlikely and that randomization was successful (Table 1; SI Table S5 with complete list of baseline characteristics). All households burned wood as their primary fuel in traditional cookstoves, with the exception of one household that reported using both fuelwood and LPG as primary fuels. The majority of homes (88%) reported cooking indoors on most days, with smaller numbers of households cooking outdoors (5%) or both (7%). Of the 187 households that initially participated in the study, 166 remained for postintervention measurements, with drop-out rates in the control and intervention groups of 4% (n = 4) and 18% (n = 17), respectively (SI Figure S5). Reasons for drop out were because either households were unavailable for follow-up (n = 4 control; n = 3 intervention), or no longer wanted the intervention (n = 14 intervention). The households that dropped out of the study following baseline assessment were also similar to those that remained in the study (SI Table S5). Similarly, the control (n = 87) and intervention (n = 79) households that that remained in the study were similar in key characteristics (Table 1).

Self-reported data suggested 60% of intervention homes that remained in the study followed the intervention protocol (exclusively using intervention stoves during household air pollution measurement); the remaining 40% used a combination of intervention and traditional stoves ("mixed stove"). Among the intervention homes that responded to questionnaires that elicited their views on the intervention stoves (n = 71), 37% had no problems with the new stoves. The remainder

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Table 2. $PM_{2.5}$ Concentrations and Absorbance Based on Intent-to-Treat and Per-Protocol Analysis[a]

treatment/stove use groups	pre-intervention N^b	pre-intervention median[c] (IQR: first Q-third Q)	post-intervention N^b	post-intervention Median[c] (IQR:first Q-third Q)	N^d	seasonal difference (post-pre) in paired households[e] (95% CI)
				$PM_{2.5}$ ($\mu g/m^3$)		
Intent-to-Treat						
control	78	246 (111–457)	81	408 (217–700)	72	139 (61, 229)
intervention	69	221 (121–491)	70	299 (147–669)	61	73 (−6, 156)
Per-Protocol						
exclusive intervention stove	41	208 (121–399)	45	273 (144–605)	39	51 (−58, 161)
mixed stove	28	229 (128–716)	25	440 (208–900)	22	92 (−18, 327)
		Absorbance (10^{-6}/m)				
Intent-to-Treat						
control	78	31 (16–40)	79	47 (28–110)	71	35 (18, 60)
intervention	70	30 (16–40)	69	52 (34–108)	60	36 (22, 50)
Per-Protocol						
exclusive intervention stove	42	27 (15–39)	44	50 (32–95)	38	31 (16, 45)
mixed stove	28	31 (19–42)	25	70 (41–136)	22	48 (19, 85)
		Absorbance/$PM_{2.5}$ Mass Ratio (m^2/g)				
Intent-to-Treat						
control	78	0.11 (0.08–0.15)	79	0.15 (0.10–0.24)	71	0.04 (0.01, 0.06)
intervention	69	0.12 (0.07–0.15)	68	0.19 (0.14–0.31)	59	0.09 (0.06, 0.13)
Per-Protocol						
exclusive intervention stove	41	0.12 (0.07–0.15)	44	0.20 (0.14–0.31)	38	0.08 (0.04, 0.13)
mixed stove	28	0.12 (0.07–0.15)	24	0.18 (0.13–0.31)	21	0.11 (0.05, 0.19)

[a]*N* = sample size; IQR = interquartile range; CI = confidence interval. [b]Exclude drop outs. [c]Concentrations from unpaired data. [d]Sample size of paired households (those with both pre- and postintervention measurements), excluding dropouts. [e]Wilcoxon signed-rank test of median difference and 95% CI for before and after intervention for paired households.

reported difficulty making rotis (local bread) (54%), poor stove-quality (4%), needing to cut wood into smaller pieces (3%), food tasting different (1%), and taking longer to cook (1%).

The median 24 h fuelwood use was slightly reduced during post versus pre (medians among all households: 3.6 kg d^{-1} (post), 4.2 kg d^{-1} (pre)). The median changes (post−pre) were −0.72 kg d^{-1} for homes using intervention stoves only, −0.20 kg d^{-1} for intervention homes using multiple stove-types, −0.60 kg d^{-1} for nonintervention homes. Differences between control and intervention groups were not statistically significant based on ITT ($p = 0.74$) or per-protocol analyses ($p = 0.95$; SI Table S6; SI Figure S10). Fuelwood moisture was not significantly different ($p > 0.5$) between the stove use groups (SI 5).

The mean outdoor temperature was lower and humidity was higher during the baseline season (September − December, postmonsoon/winter) than postintervention (February − August, predominantly dry/summer) (SI Table S7).

Regional and Village-Level Ambient Concentrations. The 24 h background air pollution concentrations measured upwind of the village were low, with higher concentrations in the center of village (SI Table S7). The differences in $PM_{2.5}$ concentrations between upwind and center of village were 13 $\mu g/m^3$ (95% CI: 8, 24) in preintervention season and 18 $\mu g/m^3$ (−1, 62) in the postintervention season (SI Table S7). For Abs levels, the upwind and village center differences were 2.7 × 10^{-6}/m (1.4, 3.9) in preintervention season and 1.6 × 10^{-6}/m (0.5, 2.9) in postintervention season (SI Table S7). Seasonally, the postintervention season generally experienced slightly higher mean $PM_{2.5}$ and Abs concentrations compared to preintervention season; mean (SD) concentrations during pre- and postintervention seasons were: $PM_{2.5}$ = 4 $\mu g/m^3$ (3.1) and 5 $\mu g/m^3$(0.5); Abs = 0.3 × 10^{-6}/m(0.3) and 1.2 × 10^{-6}/m(0.9) for upwind; and $PM_{2.5}$ = 23 $\mu g/m^3$ (15) and 29 $\mu g/m^3$(23); Abs = 3.3 × 10^{-6}/m (2.1) and 3.2 × 10^{-6}/m (2.2) for village center sites (SI Table S7). Details on number of ambient samples analyzed are in SI 6.

Analysis of real-time $PM_{2.5}$ concentration measurements in the center of the village revealed two peaks, one in the morning (5−10 a.m.) and a second in the evening (6−8:30 pm), which correspond to cooking periods and illustrates the impact of household biomass combustion on village-level air pollution (SI Figure S11). In addition to household biomass combustion, HW Village had a small, paved road with low traffic (~50 vehicles/day). No other major combustion sources, including agricultural burning, were observed by the field staff in or near the village during the study period.

Indoor Concentrations. In households that had repeated measurements to assess day-to-day variability, $PM_{2.5}$ correlation (mean absolute error) between one-day and multiday averages was 0.84 (176 $\mu g\ m^{-3}$) for the two-day measures ($N = 13$), and

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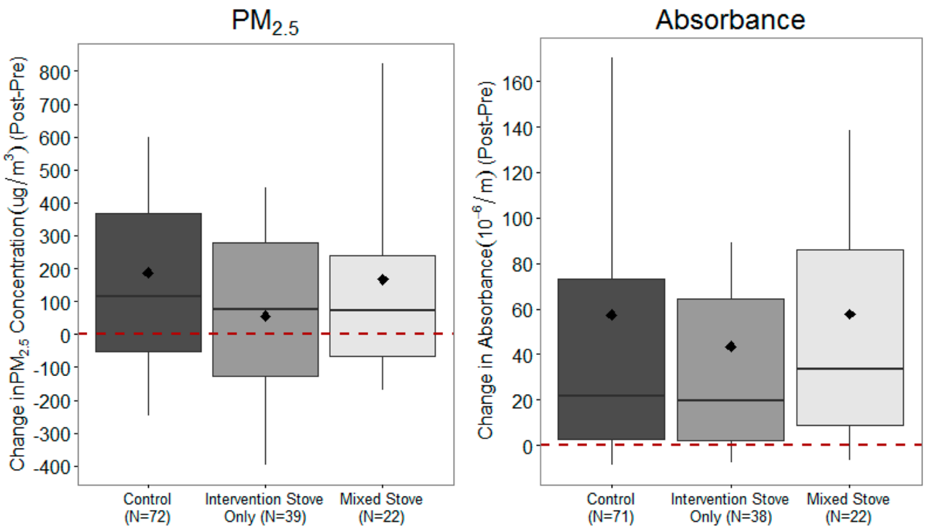

Figure 1. Change in air pollutant concentrations by stove use groups. Note: lower and upper hinges represents the 25th and 75th percentiles, respectively; black line inside the box represents the 50th percentile; lower and upper whiskers represent the 10th and 90th percentiles, respectively; and diamond represents the mean. "Control" households did not receive the intervention. "Intervention" households received the new stoves and followed protocol. "Mixed Stove" households received the new stoves but decided to also use preintervention stoves.

0.92 (128 μg m^{-3}) for three-day measures (N = 16) (SI Figures S12–S13). The Abs correlation (mean absolute error) between one-day and multiday averages was 0.71 (18 μg m^{-3}) for the two-day measures, and 0.93 (54 μg m^{-3}) for three-day measures. This finding suggests that our 24 h air pollution measurements were representative of longer duration measurements (i.e., 48 h and 72 h) (SI 7).

A majority of homes in all groups experienced higher $PM_{2.5}$ concentrations and Abs in the postintervention season (Table 2), with median change (post-pre) for both pollutants above zero (Figure 1 (as per-protocol); SI Figure S14 (ITT)). However, the magnitude of the $PM_{2.5}$ increase was smaller for the exclusive intervention stove users than for the control group (51 μg m^{-3} (95% CI: −58, 161) versus 139 μg m^{-3} (61, 229)), and this was corroborated by mixed effect model analysis (SI Table 10). Postintervention season was a marginally significant (p = 0.07) modifier of the effect of stove use on indoor $PM_{2.5}$ concentrations (SI Table S8). Specifically, the exclusive intervention stove homes had 26% lower (−53%, 18%)) indoor $PM_{2.5}$ compared to control in the postintervention season (SI Table S11).

All stove use groups experienced an increase in absorbance in the postintervention season compared to preintervention (Table 2; SI Table S9 and S10). Absorbance:$PM_{2.5}$ ratios were higher in the postintervention season in all stove use groups (SI Figure S15), though the intervention stove users experienced twice the increase compared to control (exclusive intervention stove homes: 0.08 μg m^{-3} (0.04, 0.13); and mixed stove homes: 0.11 μg m^{-3} (0.05, 0.19)) versus 0.04 μg m^{-3} (0.01, 0.06)) (Table 2). The increase in ratio was marginally larger (p = 0.07) for the mixed stove group compared to the control.

Chimney homes were associated with 58% and 38% lower $PM_{2.5}$ and Abs concentrations, respectively, compared to nonchimney homes (SI 8). HAP concentrations by chimney status are provided in SI Figures S16–S17.

■ DISCUSSION

To our knowledge, this is the first study to independently and rigorously evaluate a cookstove intervention program approved for carbon financing in a real world setting. The primary goal of the CDM, and other carbon markets is to lower emissions of climate warming pollutants through reduction in nonrenewable fuelwood use. The results of our study suggest that the intervention stove approved by CDM program did not significantly reduce fuelwood consumption compared to traditional stoves. Exclusive intervention stove use homes had slightly lower $PM_{2.5}$ concentrations compared to control, however abs:$PM_{2.5}$ ratio was higher in that group.

Our fuelwood use results are important because the CDM approval process assumed, based on laboratory testing of stove efficiency, that in-field nonrenewable fuelwood use—a key variable in carbon credit calculations and therefore a primary financial driver of the intervention—would be lower with the intervention, compared to the traditional stove. Some field-based tests suggest natural draft cookstoves consume the same or higher fuel wood compared to traditional stoves.[24,63] It is also possible that in our study lack of fuelwood savings may be attributable to intervention households cooking larger sized meals or more dishes than they had previously done due to initial "suppressed demand".[64,65] Households may have "suppressed demand" as a result of high energy costs associated with traditional stoves that consume large quantities of fuelwood. More efficient stoves that reduce fuelwood have lower energy costs in the form of reduced time spent collecting fuelwood or its purchasing costs. Therefore, it is possible that the energy demand of intervention households in the study were partially met by the intervention stove, thus improving their welfare, but without providing measurable fuelwood (and carbon) savings. Per-protocol analysis provides insight into mixed stove homes where suppressed demand may be at play. Mixed stove homes had the lowest reduction in fuelwood use (post-pre) of all groups despite having statistically significantly lower fuelwood moisture compared to the baseline, suggesting that these homes used more fuelwood compared to other groups. In fact, some

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mixed stove homes used three stoves (two intervention stoves and one traditional stove).

While reductions in health and climate relevant pollutants from cookstove interventions are desirable, this study demonstrates that they may not be occurring in practice. All groups experienced an increase in $PM_{2.5}$ concentrations and Abs levels in the postintervention season though the $PM_{2.5}$ increase was lower for the intervention group compared to the control. The increase in $PM_{2.5}$ concentrations could be related to seasonal changes unrelated to the intervention. Stove use behavior, such as how users start or tend fires, may also be a factor.[26] In the mixed stove group, the increase in PM concentrations could also be due to households using multiple stove types (or more than two stoves) due to "suppressed demand".

Whereas previous field-based studies have shown natural draft (ND) stoves can significantly reduce PM concentrations compared to traditional stoves, these have been based on tests in a limited number of households[66] or from controlled cooking tasks.[63] On the other hand, larger-scale randomized interventions with controlled populations, similar to our study, have shown ND stoves do not consistently reduce HAP.[45,46]

The study's finding on Abs has important climate implications. The intervention households had twice the absorbance:$PM_{2.5}$ ratio compared to control households, suggesting that emissions from the intervention stoves had stronger absorption compared to traditional stoves. A laboratory investigation of improved biomass stoves, including the intervention stove used in this study, found significant reductions in PM concentrations and emissions factors, however, emission factors for BC and the elemental carbon (thermal-optical method for measuring BC) fraction of PM were three to seven times higher than that of three-stone fire tests.[27] Previous studies also suggest that when compared to traditional stoves, some rocket or ND cookstoves had higher BC emission factors[67] or emitted higher BC concentrations when mixed fuels (wood, agricultural crop residue, and cow dung) are used.[24] Currently, no carbon market accounts for BC in their offset calculation methodology.[37,39,68] The Gold Standard, a carbon finance program in the voluntary sector, is in the process of developing a methodology to account for BC in their financing approach.[69] These efforts can promote quantification of particle composition from cookstoves to emphasize technologies that generate verifiable reductions in climate warming pollutants beyond CO_2.

Chimneys significantly reduced HAP concentrations by as much as 58% for $PM_{2.5}$ compared to nonchimney homes. This is lower but not drastically different from estimates from several studies, including interventions, that found 70% of PM emissions can be vented outdoor.[6] Unlike other chimney stove interventions where chimneys were part of the stove structure designed to directly vent smoke from stove to outdoor, chimneys in our study homes were not attached to the intervention stove directly. Therefore, less smoke may be directed through the chimney. While natural draft mud stoves with chimneys have been shown to significantly reduce indoor HAP concentrations compared to traditional stoves,[70−73] venting indoor HAP to outdoors is not beneficial for climate particularly when BC and other climate warming pollutants are released into the atmosphere. High ambient air pollution levels in a community can also impact personal exposure levels and contribute to adverse health outcomes. However, in our study, average indoor concentrations are still an order of magnitude higher than outdoor levels (370 versus 23 ug/m^3); even at peak cooking times, ambient PM concentrations only ranged from 25 to 75 ug/m^3 (SI Figure S11). The population exposure in our study is dominated by indoor exposure where it accounted for 96% of the total time-weighted average exposure (SI 8), and suggests the importance of a person's own cookstove as the main source of exposure.

Adoption of the intervention stove was not complete in our study; 40% of intervention households used a mixture of traditional and intervention stoves. Stove or fuel stacking[74] where households use old and new stoves and fuels is prevalent in many settings, including interventions.[45,46,48,75,76] It is possible that if the intervention stoves were more efficient and were able to significantly reduce fuelwood use and HAP concentrations, greater substitution of traditional with intervention stoves might have occurred. However, in our study population, the major reason for continuing to use traditional stoves were their ease and ability to make rotis (traditional bread) properly compared to the intervention stoves. Stove stacking can also influence HAP exposure both within and outside a household environment. Per-protocol analysis in our study revealed that stove stacking in mixed stove homes had a higher seasonal increase (post-pre) in $PM_{2.5}$ and Abs levels compared to homes that strictly used intervention stoves.

Based on our findings we provide recommendations for future climate-financed cookstove intervention programs, including a need to align with emerging standards and guidelines. For example, the recently developed International Standard Organization (ISO) International Workshop Agreement (IWA) on Clean and Efficient Cookstoves, provides for the first time an interim guideline for categorizing stove performance for both health and environmental benefits.[77] The IWA uses a five-tiered ranking system for each of the following performance indicators: fuel use/efficiency, total emission, indoor emission, and safety. Traditional solid fuel stoves typically occupy the lowest rank (Tier 0) for all indicators, rocket stoves tend to be in Tier 1 and 2, more advanced biomass stoves in Tier 3, and modern fuel (liquid or gas) stoves in Tier 4.[78] Though modern fuel stoves are ideal for achieving "ambitious health and environmental goals" of the IWA Tier 4,[79] the CDM program does not support Tier 4 stoves because they use fossil fuels, which are not considered renewable. Cost and access to modern fuels also remain substantial barriers for the majority of the rural and poor households.[80] As such, biomass cookstoves are seen as interim solutions because a large part of the world's rural population will continue to depend on biomass fuels in the near future.[81] An increasing number of more advanced biomass cookstoves, such as fan stoves and gasifiers, are becoming available but they are more costly and their field testing remains limited.[78] Limited field testing show advanced biomass cookstoves and modern fuels can significantly reduce HAP concentrations,[24,63,66] though no solid-fuel stove intervention programs to date have reduced exposures to below the WHO guidelines.[82]

Though an increasing number of centers are available that provide stove performance testing against the IWA/ISO standards in standardized laboratory settings,[83] field-testing at the community level remains critical. Laboratory studies cannot capture variability observed in the field, including types of foods cooked, fuelwood types and moisture, and user practices.[26,76] Implementing randomized controlled evaluations is feasible in rural developing country settings with "modest-cost methods".[46] If large-scale trials are not feasible, pilot community-

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based studies would be beneficial prior to scaling-up interventions.

Although there is growing evidence that natural draft/rocket stoves are unlikely to significantly reduce HAP concentrations, the significance of our study lies beyond stove technology assessment. Specifically, this study illustrates the opportunities and challenges of implementing a large-scale climate-financed cookstove intervention. The NGO leading the intervention was a community-based organization with substantial cultural and social capital in the region, a factor that was essential in encouraging households to participate in the stove exchange program. In addition, during the intervention period, the NGO took great care (through daily visits to the village) to ensure that the intervention stoves were locally acceptable, and that stove related issues were promptly addressed. This included, for example, lowering the height of the intervention stoves to fit the ergonomic needs of women. Despite these on-the-ground intensive efforts, adoption and use of the intervention stoves as per the CDM protocol was only seen in 60% of intervention households. When interventions are expanded, even lower compliance may result if stove use monitoring and motivation efforts are not as intensive. Though this particular project was not scaled up in Koppal District due to the 2012 carbon market crash, similar projects are proceeding through carbon markets in other locations in India.

This evaluation was a unique opportunity afforded by the collaboration with a local NGO implementing a carbon-finance approved program, but as a result our study was limited by a relatively small sample size of households that were exclusively using the new intervention stoves. This aspect was due to the high prevalence (~40%) of intervention households that elected to use the intervention stoves and traditional stoves ("mixed stove"/"stove stacking"). Hence, the sample size in the intervention group exclusively using the intervention stoves was smaller than originally intended. However, as the study's purpose was to evaluate the effectiveness of an intervention, the assessment of effectiveness in intention-to-treat analysis (thus accounting for the limited adoption of the intervention) is still highly relevant.

Carbon financing of rural energy intervention programs has great potential to change the landscape of household energy in the developing world, while providing various benefits for health and climate. However, this potential needs to be more rigorously assessed. While cobenefits from cookstove interventions are theoretically plentiful, achieving them can be complex in reality. The recent guidelines for cookstoves under the ISO standards and the development of methods to account for BC by the Gold Standard can assist in helping to align future carbon financed stove interventions with health and climate goals but there is a need for careful and thorough population-based evaluations to ensure that these benefits are achieved.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b06208.

Photos of traditional and intervention stoves, location of study site; details on study design, filter correction methods, $PM_{2.5}$ sampling and analysis; and tables and figures on baseline characteristics, fuelwood use and HAP concentrations, real-time averaged village $PM_{2.5}$ concentrations, assessment of day-to-day variability, mixed-effect model results, Abs:$PM_{2.5}$ mass ratio, chimney effect, and time-weighed total exposure (PDF)

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Notes

The authors declare no competing financial interest.

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