Title
In-field Emissions from Cookstoves in Rural Indian Households

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Publication Date
2017

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA,
IRVINE

In-field Emissions from Cookstoves in Rural Indian Households

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Environmental Health Sciences

by

Robert Weltman

Thesis Committee:
Associate Professor Rufus D. Edwards, Chair
Associate Professor Scott M. Bartell
Professor Michael T. Kleinman

2017

DEDICATION

To

My Grandparents

May your legacy continue to teach, inspire, and protect

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LIST OF ACRONYMS AND SYMBOLS

OC – Organic carbon.

EC/BC or EC – Elemental/black carbon.

CO – Carbon monoxide.

CO2 – Carbon dioxide.

$PM_{2.5}$ – Particles which pass through a size-selective inlet with a 50% efficiency cut-off at a 2.5 micron aerodynamic diameter.

TSP – Particles of approximately 0-20 micron aerodynamic diameter. This measurement always encompasses $PM_{2.5}$ and some larger particles, but does not have a specific upper limit to the efficiency cut-off for particles.

MCE – Modified combustion efficiency, defined as the ratio of carbon dioxide to the sum of carbon dioxide and carbon monoxide on a molecular basis.

ERs – Emission rates, defined as the mass of a given material per unit time.

EFs – Emission factors, defined as the mass of a given material per unit mass by dry weight.

WBT – The Water Boiling Test, a test designed to evaluate cookstove emissions and efficiency in a controlled laboratory setting.

MANOVA – Multivariate analysis of variation.

WHO – World Health Organization.

σ – Sample standard deviation.

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ACKNOWLEDGMENTS

I owe a great deal of appreciation to my current graduate adviser, and thesis chair, Associate Professor Rufus D. Edwards, who has acted as an unwavering bastion of support and advice. Dr. Edwards' expertise, coupled with his devotion to acting as a mentor, has allowed me to exceed beyond my own expectations.

I would also like to thank my committee members; Associate Professor Scott M. Bartell and Professor Michael T. Kleinman, both of whom were vitally instrumental in helping me learn the fundamentals of public health and environmental health sciences. Without masterful advice from Dr. Bartell about R Studio this thesis would not have been possible. Dr. Kleinman's on-going support for my research was also crucial in transforming my thesis into a meaningful document and the utility of my work is due in great part to his guidance.

In addition, Professor Robert Phalen, who suggested I may be interested in working in Dr. Edwards' lab, led me to my current research. His thoughtful concern, robust encouragement, and delivering of accolades helped me both stay on-track in graduate school and take great pride in my work.

I thank everyone at the University of California, Irvine for allowing me into the community, and specifically the department of environmental health sciences and the School of Medicine for providing assistance in a myriad of forms. Special thanks go to the support staff that has been so wonderful in helping me navigate through graduate school.

Financial support, including the funding for the research in this thesis, was provided by the American EPA. Eternal thanks go to the American taxpayers who have provided me the opportunity to pursue my dreams and ambitions.

Finally, thanks go to my friends and family who provided me constant support throughout my work.

ABSTRACT OF THE THESIS

In-field Emissions from Cookstoves in Rural Indian Households

By

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Master of Science in Environmental Health Sciences

University of California, Irvine, 2017

Associate Professor Rufus D. Edwards, Chair

Assessing the climate-change implications and burden-of-disease contributions from solid-fuel burning relies on robust estimates of emissions. Laboratory measurements of solid-fuel burning in ‘improved’ cookstoves are utilized to predict their emissions and effects on both climate and human health, although in-field measurements have been shown to differ from laboratory measurements. This paper presents in-home measurements of one ‘improved’ cookstove – the Philips forced-draft advanced combustion stove – alongside measurements of traditional cookstoves in Haryana, India. When compared to traditional cookstoves, the Philips stove produced less fine particulate matter ($PM_{2.5}$) and organic carbon per kilogram of dry fuel (p-values = 0.039 and 0.033 respectively), and burned less fuel (p-value = 0.011) and emitted less carbon monoxide, $PM_{2.5}$, and organic carbon (p-values = 0.003, 0.030, and 0.038 respectively) per minute. Increases in fine particulate matter and organic carbon for dung-burning cookstoves, seen in laboratory measurements from Haryana, were not observed for Philips stoves. The traditional cookstoves, and the Philips stove, all fail to meet the World Health Organization cookstove particulate emission-rate targets, with the geometric mean of the Philips stoves being, on average, a factor of approximately 30 too polluting, and the traditional stoves >100, for indoor stoves. Reductions in emission rates were not well typified by laboratory water boiling tests

(WBTs) and in-field fuel consumption rates differed greatly from the WBT. WBTs of dung and wood underestimated particulate emission factors from traditional cookstoves by factors of 2.4-6.0 for the Chula, depending upon fuel type, and by a factor of 23.1 for the Haro/Angithi stoves.

INTRODUCTION

Background on Emissions of Solid Fuel Cookstoves. Traditional cookstoves burning solid fuels emit large amounts of greenhouse gases and products of incomplete combustion, relative to their delivered energy, due in part to the poor energy efficiency of traditional cookstoves (Arora, Pooja & Jain, 2015; Jetter & Kariher, 2009). PICs consist of a variety of gasses and particles that impact human health and the atmospheric energy balance, including organic carbon (OC), elemental/black carbon (EC/BC), carbon monoxide (CO), carbon dioxide (CO2), fine particulate matter ($PM_{2.5}$), and hydrocarbons. Modified combustion efficiency (MCE), the ratio of carbon emitted as carbon dioxide to carbon dioxide plus carbon monoxide, is often utilized as a surrogate for combustion efficiency (Urbanski, 2013). Emission inventories of aerosol pollutants from cookstoves are necessary in bottom-up models to evaluate climate-change mitigation policies as well as in designing and implementing policies to reduce household, regional, and global air pollution (Winijkul, Fierce, & Bond, 2016).

Demographics of Solid Fuel Cooking. Currently approximately half the world's population (3 billion individuals, 39%) live in households utilizing primarily solid-fuel as the primary energy provision for cooking (figure 0.1), while approximately 550 million individuals live in households where cooking is done outdoors (figure 0.2), and an estimated 185 million individuals live in households where dung is the primary fuel for cooking (figure 0.3).

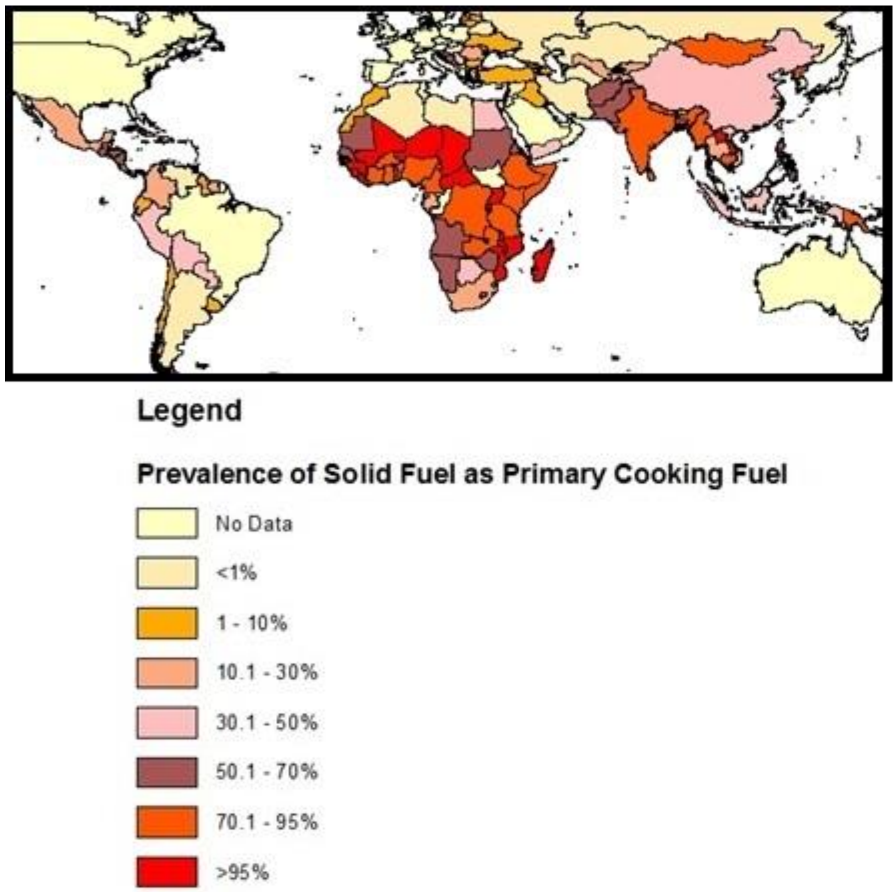

Figure 0.1: Prevalence of solid fuel use for primary energy provision for cooking.

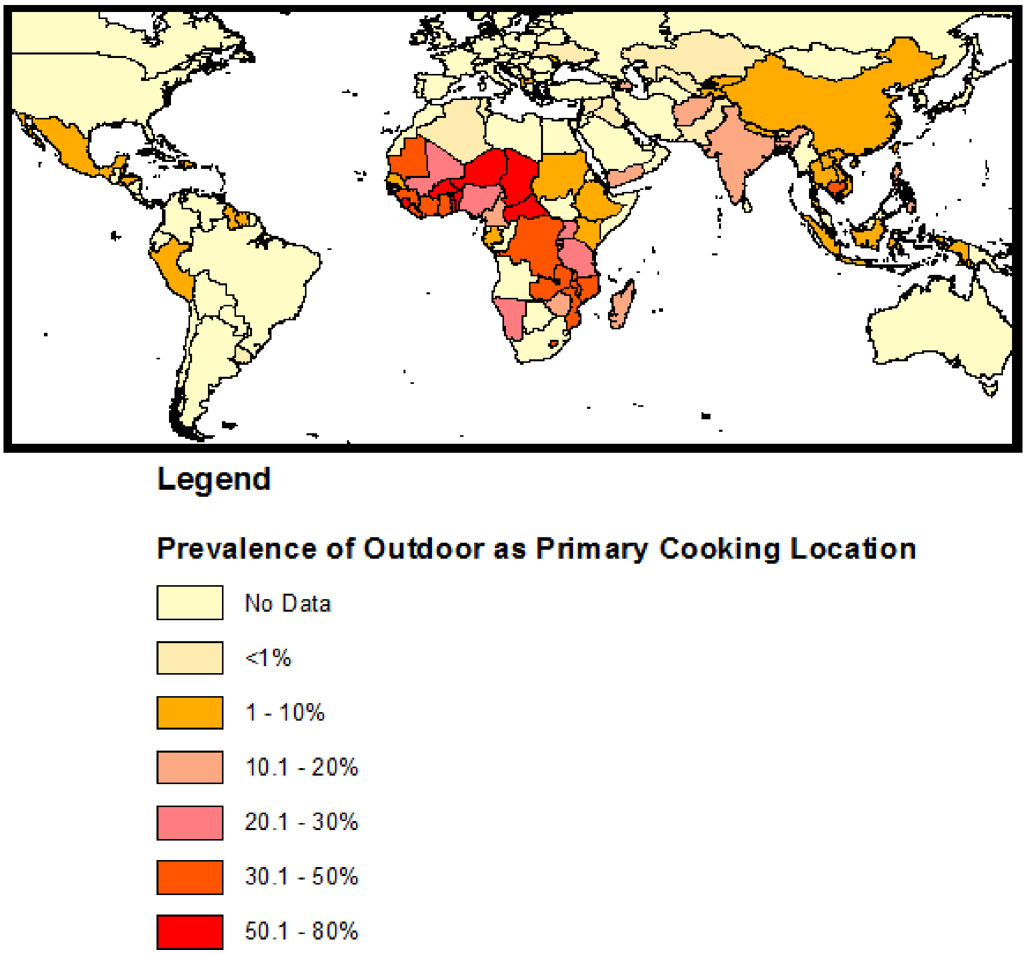

Figure 0.2: Prevalence of outdoor cooking as the primary cooking location for households.

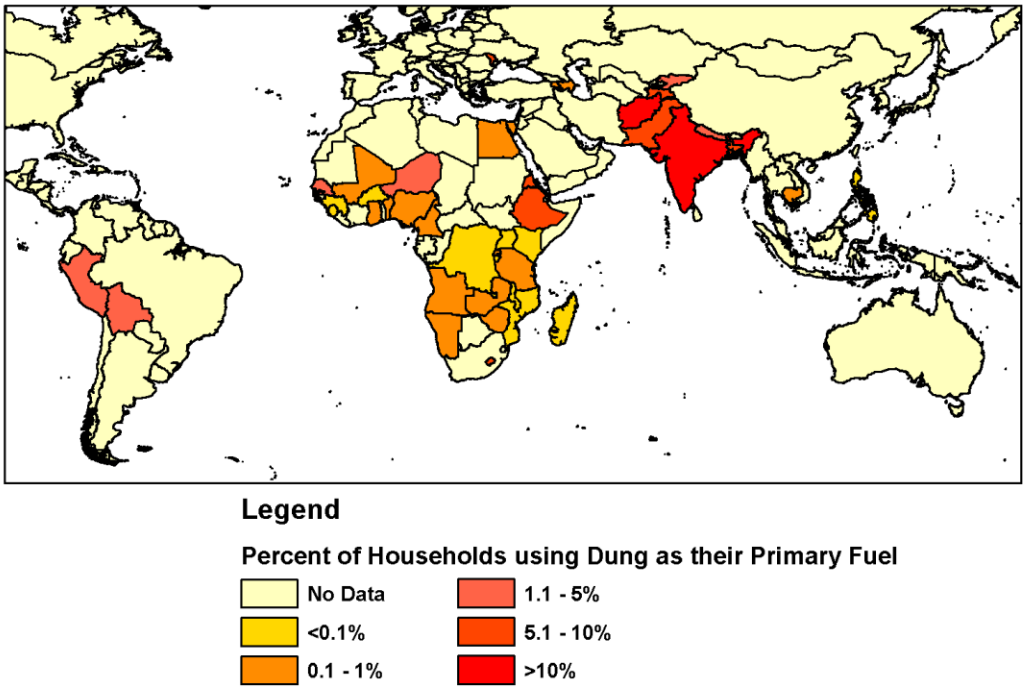

Figure 0.3: Prevalence of dung as the primary cooking fuel for households.

The majority of dung use, as the primary household cooking fuel, is in South Asia, with India reporting the largest population using dung as a primary cooking fuel of any country (Gautam, et al., 2016). An estimated nine-hundred million Indians (73.6%) live in homes that rely primarily on solid fuels, mostly wood and animal dung, for their everyday cooking and the vast majority (90.5%) of these Indian households utilize open-fire cookstoves called "Chulas" that are not located under chimneys (Bhat, et al., 2007). Household air pollution from solid fuels has been estimated to have caused 3.5 million premature deaths and 4.3% of the global disability-adjusted life years in 2010 (Lim, et al., 2012). Southeast Asia has the highest estimated regional concentration of ambient fine particulate matter attributed to household cooking (Chafe, et al., 2014). Recent studies also suggest the majority of BC and OC in India can be attributed to residential coal and biomass use for cooking and heating (Klimont, et al., 2009; Ohara, et al., 2007; Saud, et al., 2012).

Improved Combustion in Cookstoves. Improved-stove programs seek to offset carbon emissions and reduce PICs relative to delivered energy. Previous laboratory research has shown that the Philips forced air two-stage combustion stove has higher efficiency and better emission performance than traditional cookstoves, but these emission differences vary based upon the fuel type utilized (Jetter & Kariher, 2009; Jetter, 2012; Muralidharan, et al., 2015). Furthermore, recent research has highlighted differences between laboratory testing and in-field observations, suggesting the need for in-field observations in evaluating emissions from cookstoves (Bailis, et al., 2007; Berrueta, Edwards, & Masera, 2008).

Cookstove Assessment and Laboratory Emission Factors. Typical assessment of stove interventions relies on evaluating emission reductions and combustion efficiency improvements when replacing traditional stoves. Testing in laboratories or simulated kitchens, using water boiling tests (e.g. WBT version 4.1.2*) provides a standard to judge stoves against one another, but these measurements may not be representative of typical cooking in rural homes (Bailis, et al., 2007; Berrueta, Edwards, & Masera, 2008; Roden 2006; Johnson, et al., 2009). Alternatively, controlled fuel burning tests are utilized to provide emission estimates for various fuel types (Saud, et al., 2012); although this ignores the effect that stove type and cooking conditions may have on emissions. Therefore, even when extensive laboratory research has identified potential emission reductions associated with improved stove programs, in-field measurements are required. Previous laboratory research has identified reductions in $PM_{2.5}$ and carbon monoxide per kg of dry fuel when switching from a traditional cookstoves to the Philips forced-air stove (Muralidharan, et al., 2015).

* http://www.pciaonline.org/files/WBT4.1.2_0_0.pdf

Specific Aims. This paper seeks to quantify emission factors (EFs) from in-field observations of independent, and varied, cooking events, and compare these to literature values obtained via laboratory experiments – both in simulated kitchens, using WBTs, and in controlled fuel burning. The differences in in-field EFs between traditional open-fire Chula cookstoves and the Philips stoves are also examined. Fuel consumption rates, and emission rates (ERs), are compared between in-field observations and laboratory emissions testing for both traditional cookstoves and Philips advanced cookstoves. Furthermore, differences between emissions caused by burning only wood or a combination of both wood and dung are discussed for the Philips stove. Hypothesis testing was also utilized to elucidate potential benefits in replacing traditional cookstoves with the Philips stove by examining when non-equivalent emissions are unlikely to be the consequence of random sampling error. EFs and ERs are reported for the Angithi/Haro, although the low number of samples (n=5), and high variability in emissions, limits the precision of these estimates.

Methods

Stove Types. The stoves tested include: the Angithi/Haro, Chulas without chimneys, and the improved Philips stove (figure 1.1). The Angithi is made entirely of mud and fuel is loaded via the top. Cooking is done on top of the Angithi by placing a large, partially-covered, metal pot on top of smoldering cow or buffalo dung patties. Temperature is controlled by adding dung, adjusting the fuel within the fire, or by removing the metal pot from the stove. A related stove, the Haro, is a semi-permanent Angithi-type stove set in the ground. The Chula is made of mud and consists of three walls and a base of bricks covered with mud plaster. Fuel is loaded in the front of the Chula. Released heat is adjusted by the size and quantity of fuel loaded or by adjusting the distribution of fuel within the Chula. The Phillips forced-draft advanced combustion stove has been suggested as a more efficient alternative stove for solid fuels but was designed primarily to burn woody biomass. The Philips stove utilizes a battery-powered blower to provide constant airflow into the combustion chamber to improve combustion.

Figure 1.1: Pictures of all stoves tested. The Haro, a portable Angithi, filled with smoldering dung during emissions sampling (A), a fixed Angithi utilizing smoldering dung to cook animal feed (B), a fixed Chula and sampling equipment pictured before emissions began (C), a fixed Chula loaded with brushwood pictured during indoor cooking of bread (D), a Philips stove loaded with brushwood during outdoor cooking (E), and a close-up of a used Philips stove (F).

Sample Selection. Three villages were identified within the SOMAARTH demographic site and individual households were sampled based on typical stove types including 12 Chulas, 5 Angithis/Haros, and 12 Phillips stoves. Sampling consisted of either two meals or day-long tests depending on what was typical of the household.

Fuel Assessment. The total mass of fuel utilized was calculated by weighing the total fuel before and after each cooking event using a postal scale (Model PE10, Pelouze, China). Fuel moisture was assessed in the field using a 9-volt digital moisture meter for both wood and dung patties (Model: 50270, SONIN Inc., China). Moisture measurements for dung patties were adjusted in accordance with Gautam et al. 2016 (Gautam, 2016). Fuel selection, meal-type, loading, and fire-tending were determined by the individual cooks.

Emissions and Courtyard Sampling Emissions were sampled via a modified method of Johnson et al. 2009 and analyzed for CO2, CO, $PM_{2.5}$, EC and OC (Johnson, et al., 2009). In brief, three-pronged metal probes were hung above each stove and air sampling pumps (PCXR-8s, SKC Inc. Universal, Pennsylvania, USA) pumped stove emissions through conductive tubing during cooking events. Ambient courtyard aerosols were similarly moved via air sampling pumps for background evaluation. Flows were evaluated via a Mesalabs Defender 530 before and after each cooking event to ensure they have not varied more than 10%. Pumps were turned on before cooking begins so that entire cooking events were captured and turned off when cooking was not taking place. Johnson et al. reported less than a 1% difference between MCE between sampling hoods and the three-pronged probes used in this study (Johnson, et al., 2009). Similarly, Zhang et al. also reported no significant changes in emission ratios between flue gas and hood samples (Zhang, et al., 2000).

Size selection of aerosols was achieved using a SCC 1.062 (Triplex) personal sampling cyclone (Triplex, BGI Incorporated, Waltham, MA). Polytetrafluoroethylene filters (Polytetrafluoroethylene filter with PMP support ring, 2.0 µm, 47 mm, Skc Inc., Fullerton, CA) were pre-weighed on a Cahn-28 electrobalance after equilibrating for a minimum of 24 hours in a humidity and temperature-controlled environment. 47 mm quartz filters (Grade QM-A Quartz Filter, circle, 47 mm, GE Healthcare Life Sciences, Pittsburgh, PA) were prebaked before use. EC/OC loading on quartz filters was determined by the thermal optical method on 1cm punches using a Sunset analyzer at the University of Illinois Urbana Champaign, described in detail elsewhere (Boparai, Poonam, Jongmin Lee, and Tami C. Bond, 2008). Except for during sample collection, filters were stored and transported frozen, and once received were kept at -80 ºC prior to analysis.

Concentrations of CO2 and CO were analyzed in emission samples for carbon oxides using a TSI Q-Trak 7575, and adjusted for background ambient concentrations. The TSI Q-Trak 7575 demonstrated good linearity with stainless steel canisters analyzed by GC FID with methanizer at Don Blake's group at UCI.

Carbon balance. ERs and factors for gasses and $PM_{2.5}$ were determined using the carbon balance method (Berrueta, Edwards, & Masera, 2008; Smith, 1994). In brief, ERs and EFs were determined by weighting the minute-by-minute ratios of pollutant emissions by the total gaseous carbon emitted during the burn and multiplying by the total emitted carbon. Total carbon in the fuel was calculated by first converting the total mass of fuel utilized to a carbon basis by assuming standard values of 45.4% of the dry wood's mass, and 33.4% of the dry dung's mass, was carbon and then subtracting the carbon in ash, which was calculated by assuming standard values of 1.23% of the dry wood's mass, and 14.4% of the dry dung's mass, was converted into carbon ash (Zhang, et al., 2000).

Hypothesis Testing and Statistical Analyses. The first set of hypotheses tested concerns the differences between wood-fueled and dung-and-wood-fueled emissions from the Philips cookstoves. The Satterthwaite Approximation for Two-Tailed Two-Sample T Tests for Independent Samples with Unequal Variances (hereafter simply referred to as "T Tests") was utilized to compute p-values and compare significance between EFs and ERs for CO, $PM_{2.5}$, EC, and OC, alongside fuel-consumption rates, for the wood-fueled and dung-and-wood-fueled tests from the Philips cookstoves. In order to be conservative in controlling for Type I errors, the Bonferroni correction was utilized for multiple comparisons when using T Tests and each hypothesis test was reported with a p-value and relevant significance level. Comparisons between the wood-only and mixed-fuel EFs/ERs and fuel consumption rates for both fuel combinations on the Philips stoves are thus meant to be used to conservatively state only observable, statistically significant, differences between mixed-fuel and wood-only fires in Haryana homes utilizing Philips stoves.

Another set of hypotheses tested concerns the differences between laboratory-based tests of solid fuels (dung/wood) in Haryana and in-field emissions from the Philips cookstoves. T Tests were utilized to compute p-values and compare significance between laboratory-based EFs for $PM_{2.5}$, EC, and OC, for both Haryana dung and wood burns against the Philips advanced cookstoves. In order to be conservative in controlling for Type I errors, the Bonferroni correction was utilized for multiple comparisons when using T Tests and each hypothesis test was reported with a p-value and relevant significance level. Comparisons between the Philips advanced cookstove and laboratory-based EFs for both Haryana dung and wood are thus meant to be used to evaluate real, significant differences between in-home EFs from advanced cookstoves and laboratory-based fuel burns, by fuel type.

The final hypotheses tested are that of null difference between the Chula traditional stove and the Philips stove for ERs (mg/min) and EFs (g/Kg dry fuel) for CO, $PM_{2.5}$, and EC/OC; MCE; and fuel consumption rates. Multivariate analysis of variance (MANOVA) testing was utilized to compute p-values for differences between the Chula traditional stove and the Philips stove for ERs (mg/min) and EFs (g/Kg dry fuel) for CO, $PM_{2.5}$, and EC/OC, in addition to MCE and fuel consumption rates. Because potential differences between traditional cookstoves and the Philips stove provide opportunities to reduce pollutant exposure, reductions in statistical power were avoided. No correction for multiple comparisons were utilized for the MANOVA testing in reporting statistically significant findings, because comparisons are meant to be used as pilot data to evaluate potential differences between traditional cookstoves and the Philips stove, although Bonferroni-adjusted critical values were reported alongside p-values.

Data was analyzed using R Studio version 3.3.0.

Results

Emission Summary. Table 2.1 shows the EFs and MCE measured by stove and fuel type.

Stove Type	n	MCE	CO_2	CO	$PM_{2.5}$	EC	OC
		g substance/ kg dry fuel					
Fixed Chula w/o Chimney	12	0.91	966	61.5	5.8	0.1	3.1
		0.91 (±0.02)	1010 (±320)	64.5 (±18.3)	7.7 (±5.6)	0.3 (±0.4)	4.4 (±3.9)
Phillips	12	0.94	1299	45.2	2.6	0.1	1.2
		0.94 (±0.03)	1335 (±296)	49.8 (±24.7)	3.8 (±2.5)	0.2 (±0.3)	1.7 (±1.1)
Philips Wood Only	7	0.95	1529	43.9	3.1	0	1.6
		0.95 (±0.03)	1530 (±55)	51.3 (±32.3)	3.9 (±2.7)	0.2 (±0.3)	1.9 (±1.1)
Philips Dung+Wood	5	0.93	1034	47	2	0.1	0.8
		0.93 (±0.02)	1063 (±279)	47.8 (±10.0)	3.2 (±2.4)	0.2 (±0.2)	1.4 (±1.1)
Haro/Angithi	5	0.87	635	61.1	12.5	0.2	8.2
		0.87 (±0.02)	646 (±146)	62.1 (±12.7)	18.3 (±20.2)	0.6 (±1.2)	11.5 (±11.3)

Table 2.1: Emission factors and modified combustion efficiency by stove and fuel type. Values are listed as geometric means, then arithmetic means with standard deviations (σ) in parentheses for EFs, ERs, and characteristics separated by stove type and sub-divided by the type of fuel utilized. EFs are in grams of pollutant per kilogram of dry fuel. Note: sample size is reduced by two for the fixed Chula w/o chimney for EC/OC.

Table 2.2 shows the ERs measured by stove and fuel type alongside the dry fuel consumption.

Stove Type	n	mg substance/minute			g/minute		
		$PM_{2.5}$	EC	OC	Dry Fuel	CO_2	CO
Fixed Chula w/o Chimney	12	108	1	55	18	17.8	1.1
		182 (±192)	9 (±16)	99 (±125)	21 (±10)	19.3 (±7.9)	1.3 (±0.7)
Phillips	12	23	1	11	9	11.7	0.4
		43 (±41)	3 (±3)	19 (±18)	11 (±6)	13.0 (±7.8)	0.5 (±0.3)
Philips Wood Only	7	21	0	11	7	10.4	0.3
		27 (±22)	2 (±3)	13 (±7)	7 (±1)	10.6 (±2.4)	0.3 (±0.2)
Philips Dung+Wood	5	27	2	10	13	13.7	0.6
		59 (±56)	4 (±4)	27 (±26)	15 (±8)	16.2 (±11.7)	0.7 (±0.4)
Haro/Angithi	5	302	4	197	24	15.4	1.5
		424 (±395)	14 (±25)	272 (±231)	31 (±23)	19.4 (±13.2)	1.9 (±1.3)

Table 2.2: Emission rates by stove and fuel type. Values are listed as geometric means, then arithmetic means, with standard deviations in parentheses for ERs and fuel consumption. ERs are in grams of pollutant per minute for gasses and milligrams of pollutant per minute for particles. Dry fuel consumption is listed as grams per minute. Note: sample size is reduced by two for the fixed Chula w/o chimney for EC/OC.

Emission Comparisons. EFs and ERs for CO, $PM_{2.5}$, EC, and OC, alongside fuel-consumption rates for the wood-fueled and dung-and-wood-fueled tests from the Philips cookstoves were compared via T Tests utilizing a Bonferroni correction ($m=3$, $\alpha = 0.016$). No significant differences were observed for EFs and ERs for CO, $PM_{2.5}$, EC, and OC, and fuel-consumption rates for the wood-fueled and dung-and-wood-fueled tests from the Philips cookstoves.

Differences between the Chula traditional stove and the Philips stove for ERs (mg/min) and EFs (g/Kg dry fuel) for CO, $PM_{2.5}$, and EC/OC; MCE; and fuel consumption rates were compared via MANOVA testing to compute p-values for the hypothesis of no effect from stove type on ERs/EFs, MCE, and fuel consumption. While no significant difference was observed in EFs for CO and EC (p-values > 0.1), a significant decrease in $PM_{2.5}$, and OC EFs was observed for the Philips stove (p-values = 0.039 and 0.033 respectively, m=3, $\alpha = 0.016$). A significant decrease in fuel consumption rates (p-value = 0.011, m=3, $\alpha = 0.016$), coupled with the decrease in EFs for $PM_{2.5}$ and OC, lead to a significant decrease in ERs for CO, $PM_{2.5}$, and OC (p-values = 0.003, 0.030, and 0.038 respectively, m=3, $\alpha = 0.016$); in contrast this decrease was not significant for EC (p-value > 0.1). MCE was also significantly increased for the Philips stove (p-value = 0.005, m=3, $\alpha = 0.016$) when compared to the Chula traditional stove.

Potential Impact on Indoor Air. A modified Box Model (equation 1) was utilized to highlight the average steady-state indoor concentrations of $PM_{2.5}$ that would arise due to the ERs for the Philips, Chula, and Angithi stoves operated unvented, that are presented in Table 2.3 (Johnson et al., 2011). Inputs for the modified Box Model are provided in "WHO IAQ guidelines: household fuel combustion – Review 3: Model linking emissions and air quality" (Johnson, et al., 2014).

Equation 1. $C_t = G/\alpha V$

Where:
C_t = Steady-state concentration of $PM_{2.5}$ in mg/m^3
G = Geometric mean of emission rate of $PM_{2.5}$ in mg/minute
α = Nominal air exchange rate in $minutes^{-1}$
V = Kitchen volume in m^3

Table 2.3 shows the indoor kitchen concentrations of $PM_{2.5}$ in $\mu g/m^3$ that would arise due to various ERs for the Philips, Chula, and Angithi/Haro.

Stove Type	Geometric Mean	Arithmetic Mean	Arithmetic Mean – σ/2	Arithmetic Mean + σ/2
Philips	51.1	95.6	50.0	141.1
Chula	240.0	404.4	191.1	617.8
Angithi/Haro	671.1	942.2	503.3	1381.1

Table 2.3: Indoor kitchen concentrations of fine particulate matter expected from cookstove emission rates. Values are for a nominal air exchange rate of 15 min^{-1} and a kitchen volume of 30 m^3.

Discussion

Differences Between Philips Cookstoves and Laboratory Measurements of Fuel Burning. EFs for $PM_{2.5}$, EC, and OC from the Philips cookstoves utilizing only wood and laboratory wood-burning experiments (Saud, et al., 2012) were compared via T Tests utilizing a Bonferroni correction ($m = 3$, $\alpha = 0.016$). Saud et al. reported emission factors for $PM_{2.5}$, EC, and OC from laboratory wood and dung burning measured via a controlled burn-cycle and dilution sampler. For Haryana, emission factors for $PM_{2.5}$, EC, and OC were reported as 4.11 ± 1.66, 0.42 ± 0.07, and 0.78 ± 0.41 and 15.17 ± 3.78, 0.54 ± 0.34 and 3.78 ± 0.47, grams per kilogram dry fuel for wood ($n = 92$) and dung-burning ($n = 38$) respectively. While laboratory wood-burning experiments were found to have higher OC EFs than the Philips cookstoves utilizing only wood (factor of ~4, p-value = 0.0043, m=3, $\alpha = 0.016$), differences between $PM_{2.5}$ and EC EFs were non-significant (p-values > 0.02). EFs for $PM_{2.5}$, EC, and OC from the Philips cookstoves utilizing mixed fuels and laboratory dung-burning experiments (Saud, et al., 2012) were also compared using T Tests utilizing a Bonferroni correction (m=3, $\alpha = 0.016$). All EFs were greater for the laboratory dung-burning experiments compared to the Philips cookstoves utilizing mixed fuels (p-values = 0.0143, 0.0088 for EC and OC respectively and p-value <0.0001 for $PM_{2.5}$, $\alpha = 0.016$). Emission factors for laboratory wood and dung burning for $PM_{2.5}$, EC, and OC were an average factor of ~5, ~3, and ~3 times larger, respectively, compared to field tests.

Laboratory-based testing of cookstoves utilizing the WBT employs 3 separate phases of testing; a cold start, a hot start and a simmering phase (Water Boiling Test version 4.2.3). Dry wood consumption rates for Philips stoves during each phase of the WBT are 5.7 ± 0.1 for the simmering, 15.5 ± 0.6 for the cold start and 17.5 ± 0.9 g/min for the hot start phases (Jetter, et al., 2012). For a traditional 3-stone fire burning wood corresponding fuel consumption rates are 15.9

± 1.5, 27.1 ± 2.7, and 31.9 ± 2.7 g/min for the simmering, cold start, and hot start respectively (Jetter, et al., 2012). In contrast, fuel consumption rates for the Philips stove during uncontrolled tests in 3 villages in Haryana were 7 ± 1 g/min and 21 ± 10 g/min for the Chula stoves (Table 2.2). This finding suggests that the WBT does not accurately capture fuel consumption rates, implying that the burn cycle for the WBT differs from in-field cooking.

Differences Between Field Measurements and WBTs for Particle Emissions of Traditional Cookstoves. The geometric mean EFs for total suspended particles (TSP), a measurement that encompasses $PM_{2.5}$ and particles with larger aerodynamic diameters (up to 20-50 microns depending on the measurement), from WBTs of traditional cookstoves for various fuel types are reported in Table 3.1 alongside field values for $PM_{2.5}$, and factor differences (Smith, et al., 2000). Because TSP includes both $PM_{2.5}$ and particles with larger aerodynamic diameters, the values for WBTs represent slight over-estimations of the $PM_{2.5}$ EFs and the factor differences in table 3.1 are therefore conservatively low.

Fuel Type	Cow Dung in Haro	Cow Dung in Chula	Wood in Chula	All Chula Tests
Geometric Mean Grams TSP per Kilogram Dry Fuel (WBT)	0.54	2.19	0.65	1.19
Geometric Mean Grams $PM_{2.5}$ per Kilogram Dry Fuel (Field)	12.5	5.16	3.87	5.85
Factor Difference	23.1	2.4	6.0	4.9

Table 3.1: Factor differences between water boiling tests and field measurements of particulate emission factors. Geometric mean EFs for TSP by both stove and fuel type for both WBTs and field tests alongside factor differences. These EFs were generated based on WBTs of traditional cookstoves (Smith, et al., 2000).

EFs for TSP, based on the WBT, indicated that the Haro produces a factor of ~4 decrease in particulate matter per kilogram of dry fuel compared to the Chula (0.54 vs 2.19 gTSP/kg dry fuel). This finding is in direct contrast to the field measurements of the Haro/Angithi and Chula stoves where the trend is that of decreasing EFs for particulate matter from the Angithi/Haro to the Chula. Notably, geometric mean EFs for the Haro/Angithi stoves in field tests were a factor of 23.1 times greater than when these same stoves were utilized for WBTs. EFs for the Chula stoves were also amplified in field tests when compared to WBTs. For dung-only fires, the average Chula emits 2.4 times greater particulate emissions per kilogram of dry fuel in field measurements when compared to WBTs and this factor is 6.0 times greater for wood-only fires. For all Chula field-tests, including dung-only, wood-only, and mixed-fuel fires, the geometric mean EF was a factor of 4.9 times higher than the WBTs.

Exposure Assessment. The World Health Organization (WHO) has emission-rate targets necessary for meeting WHO indoor air quality guidelines for CO and $PM_{2.5}$ for both unvented and vented stoves (Johnson, et al., 2014). Vented stove emission-rates of $PM_{2.5}$ must fall under 0.8 mg/min and CO must be below 0.59 g/min to reach acceptable levels of indoor air quality. All stoves failed to meet $PM_{2.5}$ emission-rate targets even for vented stoves, with the geometric mean of the Philips stoves being, on average, a factor of ~30 too polluting, the Chula stoves ~150, and the Angithi ~400, for indoor stoves (Table 2.2). While venting these stoves may lead to ERs that are acceptable for indoor air quality, these rates create an exceptional need to vent ~97%, ~99%, and ~99.7% of the $PM_{2.5}$ emitted to meet WHO indoor air quality guidelines. In contrast to the $PM_{2.5}$ ER guidelines, the Philips stove wood-only tests were below the CO ERs necessary for acceptable levels of indoor air quality, while all other tests exceeded the 0.59 g/min cut-off (Table 2.2), with the exception of the aggregate of all Philips tests.

Philips as Improved Solid-Fuel Cookstove. The results of this study suggest that the Philips forced draft stove produces less PIC than the Chula and Angithi and Haro stoves, both per kilogram of dry fuel and per minute, and operates at a greater combustion efficiency. Most significantly, the Philips stove is able to meet emission-rate targets from the WHO for CO from indoor cookstoves – suggesting that capturing the emitted particulate matter may partially or fully mitigate the bulk of the health effects caused by solid-fuel utilization in cookstoves. In contrast to this finding, $PM_{2.5}$ ERs from solid fuels are found to vastly exceed the rates that are protective of health, by two orders of magnitude, in traditional cookstoves (Table 2.2). Average $PM_{2.5}$ concentrations that would arise due to the various ERs for the Philips, Chula, and Angithi/Haro in this study cannot meet the WHO IAQ guidelines of ≤10 micrograms per cubic meter, nor are they close to meeting the interim target of ≤35 micrograms per cubic meter (Table 2.3). This finding suggests that advanced cookstoves and/or vented cookstoves can significantly reduce $PM_{2.5}$ exposures in rural communities. Because traditional, and improved, cookstoves can also be utilized outdoors, there is also a great need to model exposures and neighborhood pollutant levels when stoves are cooking outdoors.

Differences between stove types and fuel types indicate a greater need for separating fuel usage by stove type and a need for more research into the variables that influence both ERs and EFs. Because the difference between fuel burned on an Angithi/Haro or Chula and on a Philips cannot be captured by laboratory fuel-burning experiments without these stoves, and there is a need for further evaluation of traditional cookstoves conducting actual cooking events. One noteworthy finding of this study is that OC/$PM_{2.5}$ emissions differences by fuel type, that are observable in laboratory-based experiments and even in traditional cookstoves, do not necessarily persist when utilizing an advanced cookstove. It is possible that these differences do exist, and were not detected due to the modest sample sizes in this project, implying that further research is needed to clarify the relationship between fuel type and emissions. Likewise, additional research is needed to characterize EFs/ERs for the various solid fuels used in rural India (including sugarcane, mustard, rice, wheat, maize, and many other crops) and any potential reduction in fuel usage or pollutant emissions that can occur with an improved cookstove (Saud, et al., 2011).

The Philips stove is not well characterized by the cold or hot-start phases of the WBT, and the simmering phase better typifies fuel consumption for the Philips stoves in typical households. For both the Philips and Chula stoves the in-field fuel consumption rates were closer to those seen in the simmering phase of the water boiling test, and were considerably lower than those seen in the cold start and hot start. To achieve equivalent fuel consumption rates in the laboratory for controlled testing, a weighting of approximately 14.3% of the fuel should be consumed in the cold-start phase combined with 86.7% from the simmering phase.

It is noteworthy that reductions in EFs of PICs are observed almost uniformly for both dung-and-wood fed fires and wood-fed fires in the Philips advanced cookstove compared to the traditional cookstoves. This finding suggests that laboratory-based burns of solid fuels do not accurately characterize the differences in EFs when dung and wood are burned in the Philips advanced cookstove, and that the exportability of laboratory-based burns to individual cookstoves may be limited or even contradictory. The lack of significant differences in EFs, between the mixed-fuel and wood-only burns, suggests that close attention should be paid to the utility of any cookstove and fuel combination, and the subsequent EFs and ERs that result. Because these EFs and ERs may vary based upon the user’s cooking demands, additional research should focus on elucidating differences in fuel consumption rates – as EFs alone may obfuscate potential health benefits that result from switching to alternative fuel and/or stove combinations. Additionally, relationships between particulate matter and gaseous EFs were not uniform across the stoves – notably, Angithi/Haro stoves produced less CO per kilogram of dry fuel while emitting more

$PM_{2.5,}$ EC, and OC – providing further evidence that neither CO nor $PM_{2.5}$, and EC/OC EFs can be used as a surrogate for total PIC without including the other values.

Conclusions

- Significant differences between emissions from wood and dung fuels, captured in controlled burns of fuel in laboratories, were not observed when comparing in-field emissions.
- Reductions in PIC ERs were not well typified by WBTs and in-field fuel consumption rates differed greatly from the WBT methods.
- WBTs of dung and wood underestimated particulate EFs from traditional cookstoves by a factor of 2.4-6.0 for the Chula depending upon fuel type, and by a factor of 23.1 for the Haro/Angithi stoves.
- The Philips forced draft stove produces less products of incomplete combustion than the Chula and Angithi and Haro stoves, both per kilogram of dry fuel and per minute, and operates at a greater combustion efficiency.
- All stoves fail to meet $PM_{2.5}$ emission-rate targets even for vented stoves, with the geometric mean of the Philips stoves being, on average, a factor of ~30 too polluting, the Chula stoves ~150, and the Angithi ~400, for indoor stoves.
- Emission-rate targets from the WHO for CO from indoor cookstoves were met by the Philips stove – suggesting that capturing emitted particulate matter may partially or fully mitigate the bulk of the health effects caused by solid-fuel utilization in cookstoves.

References

Arora, Pooja, and Suresh Jain. "Estimation of organic and elemental carbon emitted from wood burning in traditional and improved cookstoves using controlled cooking test." *Environmental science & technology* 49.6 (2015): 3958-3965.

Bailis, Rob, et al. "Performance testing for monitoring improved biomass stove interventions: experiences of the Household Energy and Health Project." *Energy for sustainable development* 11.2 (2007): 57-70.

Berrueta, Víctor M., Rufus D. Edwards, and Omar R. Masera. "Energy performance of wood-burning cookstoves in Michoacan, Mexico." *renewable energy* 33.5 (2008): 859-870.

Boparai, Poonam, Jongmin Lee, and Tami C. Bond. "Revisiting thermal-optical analyses of carbonaceous aerosol using a physical model." *Aerosol Science and Technology* 42.11 (2008): 930-948.

Chafe, Zoë A., et al. "Household cooking with solid fuels contributes to ambient PM2. 5 air pollution and the burden of disease." (2015).

Edwards, Rufus, Marko Princevac, Robert Weltman, Masoud Ghasemian, Narendra K. Arora, Kirk R. Smith, and Tami Bond. "Modeling Emission Rates and Exposures from Outdoor Cooking." *Atmospheric Environment*. (In Process).

Gautam, Sneha, et al. "Probe-based measurements of moisture in dung fuel for emissions measurements." *Energy for Sustainable Development* 35 (2016): 1-6.

Jetter, James J., and Peter Kariher. "Solid-fuel household cook stoves: Characterization of performance and emissions." *Biomass and Bioenergy* 33.2 (2009): 294-305.

Jetter, James, et al. "Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics useful in setting international test standards." *Environmental science & technology* 46.19 (2012): 10827-10834.

Johnson, Michael, et al. "Quantification of carbon savings from improved biomass cookstove projects." *Environmental Science & Technology* 43.7 (2009): 2456-2462.

Johnson, Michael, et al. "Modeling indoor air pollution from cookstove emissions in developing countries using a Monte Carlo single-box model." *Atmospheric Environment* 45.19 (2011): 3237-3243.

Johnson, M.; Edwards, R.; Morawska, L.; Nicas, M.; Smith, K. R., Review 3: Model for linking household energy use with indoor air quality. *WHO Indoor Air Quality Guidelines: household Fuel Combustion.* 2014.

Klimont, Z., et al. "Projections of SO2, NOx and carbonaceous aerosols emissions in Asia." *Tellus B* 61.4 (2009): 602-617.

Lim, Stephen S., et al. "A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010." *The lancet* 380.9859 (2013): 2224-2260.

Mukhopadhyay, Rupak, et al. "Cooking practices, air quality, and the acceptability of advanced cookstoves in Haryana, India: an exploratory study to inform large-scale interventions." *Global health action* 5 (2012).

Muralidharan, Veena, et al. "Field testing of alternative cookstove performance in a rural setting of western India." *International journal of environmental research and public health* 12.2 (2015): 1773-1787.

Ohara, T. A. H. K., et al. "An Asian emission inventory of anthropogenic emission sources for the period 1980–2020." *Atmospheric Chemistry and Physics* 7.16 (2007): 4419-4444.

Roden, Christoph A., et al. "Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves." *Environmental science & technology* 40.21 (2006): 6750-6757.

Saud, T., et al. "Emission estimates of organic and elemental carbon from household biomass fuel used over the Indo-Gangetic Plain (IGP), India." *Atmospheric environment* 61 (2012): 212-220.

Saud, T., et al. "Spatial distribution of biomass consumption as energy in rural areas of the Indo-Gangetic plain." *biomass and bioenergy* 35.2 (2011): 932-941.

Smith, Kirk R. "Health, energy, and greenhouse-gas impacts of biomass combustion in household stoves." *Energy for sustainable development* 1.4 (1994): 23-29.

Smith, Kirk R., et al. "Greenhouse implications of household stoves: an analysis for India." *Annual Review of Energy and the Environment* 25.1 (2000): 741-763.

Urbanski, S. P. "Combustion efficiency and emission factors for wildfire-season fires in mixed conifer forests of the northern Rocky Mountains, US." *Atmospheric Chemistry and Physics* 13.14 (2013): 7241-7262.

Water Boiling Test (WBT) Version 4.2.3. Global Alliance for Clean Cookstoves. Washington, DC., 2014. http://cleancookstoves.org/technology-and-fuels/testing/protocols.html.

Winijkul, Ekbordin, and Tami C. Bond. "Emissions from residential combustion considering end-uses and spatial constraints: Part II, emission reduction scenarios." *Atmospheric Environment* 124 (2016): 1-11.

Winijkul, Ekbordin, Laura Fierce, and Tami C. Bond. "Emissions from residential combustion considering end-uses and spatial constraints: Part I, methods and spatial distribution." *Atmospheric Environment* 125 (2016): 126-139.

Zhang, J., et al. "Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors." *Atmospheric Environment* 34.26 (2000): 4537-4549.