Supporting Information

New emission factors and efficiencies from in-field measurements of traditional and improved cookstoves and their potential implications

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Contents: Page

Section S1. Quality assurance and control and sources and estimates of uncertainty:

Overall Thermal Efficiency: Households usually store water in large plastic containers or covered pots leading to the assumed 75° temperature change for sensible heat calculations (297K to 372K). Ambient temperatures in the test region range from 18-35°C. Uncertainty in sensible heat calculations was estimated using a ±10-degree temperature difference which leads to a 12% relative uncertainty in sensible heat. Before obtaining a higher quality scale, food and wood mass uncertainty were 10%. Water and food mass to calculate latent heat was weighed using a scale with 2-gram resolution leading to very small error relative to the sensible heat. Most food ingredients have high water content. Non-invasive infrared measurements, controlling for heated vapors, was identified as a promising way to measure water temperature that should be tested in future work.

Modified Combustion Efficiency: Carbon dioxide and carbon monoxide gas concentration uncertainty was calculated at 15 ppm or 3% of range (0-5000ppm) and 2.1 ppm (0-140ppm), respectively. Details on the calibration can be found in Figures S3 and S4. When propagated, MCE relative uncertainty is less than 3%.

Carbonaceous aerosol particulate analysis: Quartz fiber filters were pre-baked in an oven at 500°C for 24 hours and stored in amber glass jars spaced with aluminum foil disks. Filters were analyzed with a Sunset OCEC Analyzer using the NIOSH 5040 protocol. Sample filters were blank subtracted using the median blank filter values from each jar.

Figure S1: Types of stoves tested in the field (clockwise from top left); Philips HD4012-LS with reinforced pot stand, Gyapa woodstove, threestone fire and local coalpot.

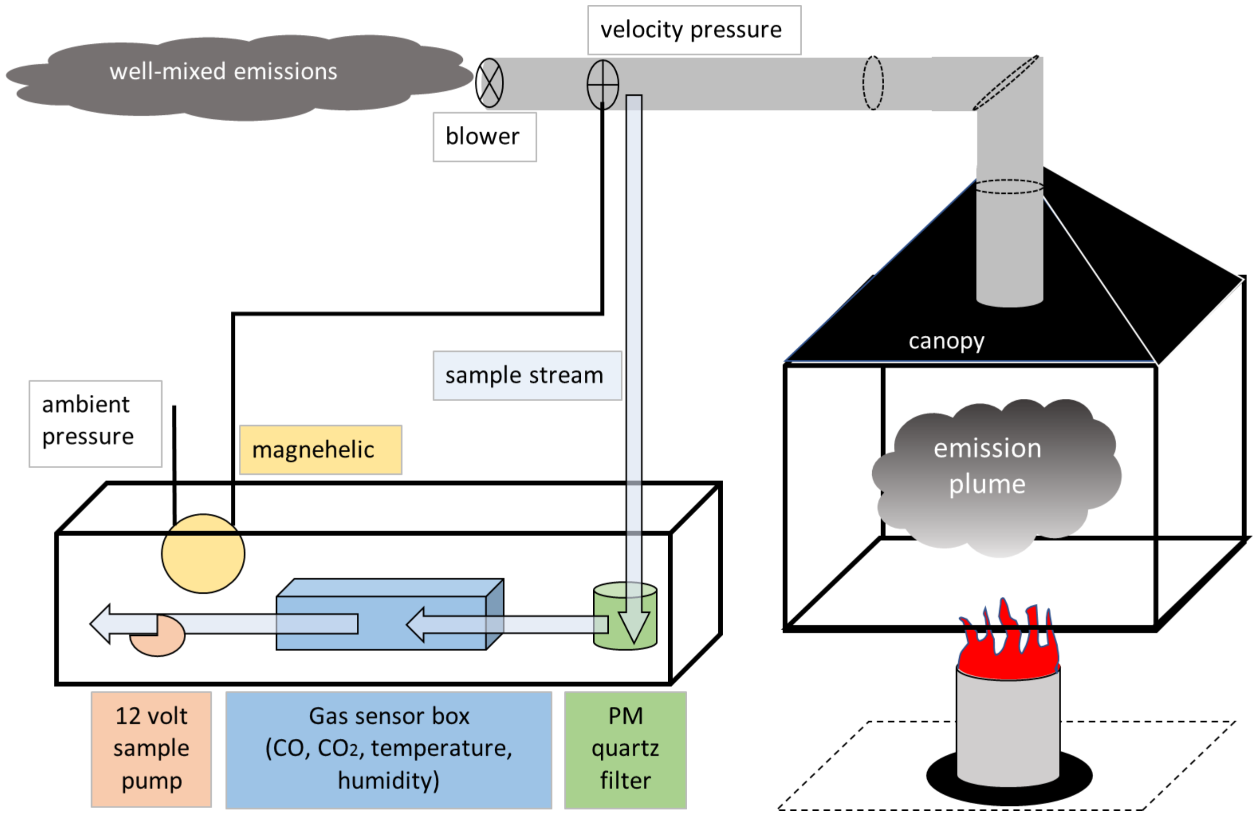


Figure S2: The EPOD sampling schematic employs the partial emission capture technique complete with a canopy over the stove, a blower to mix the emissions and a sample stream where PM is collected and gas phase species are measured in addition to environmental variables (i.e. temperature and humidity).

Table S1: Sample information – number of each sample type.

Meal	Beans	Jollof Rice	Rice	Rice & Beans	Rice & Soup	TZ & Soup	Vegetable Soup	**Total**
Threestone	1	1	3	1	1	10	4	**21**
Coalpot	0	3	0	0	1	6	0	**10**
Gyapa Wood	3	2	3	1	1	7	1	**18**
Philips Charcoal	1	4	2	1	2	3	1	**14**
Philips Wood	0	3	2	0	0	5	2	**12**
Total	**5**	**13**	**10**	**3**	**5**	**31**	**8**	

Season	Harmattan	Heavy_Rainy	Hot_dry	Light_Rainy	Transition	**Total**
Threestone	10	7	4	0	0	**21**
Coalpot	0	7	0	3	0	**10**
Gyapa Wood	7	8	1	2	0	**18**
Philips Charcoal	1	5	1	4	3	**14**
Philips Wood	6	4	1	1	0	**12**
Total	**24**	**31**	**7**	**10**	**3**	

Moisture level	Low	Medium	High	**Total**
Threestone	12	5	4	**21**
Coalpot	10	0	0	**10**
Gyapa Wood	9	6	3	**17**
Philips Charcoal	14	0	0	**14**
Philips Wood	9	3	0	**12**
Total	41	18	16	

Pot Size	Small	Medium	Large	**Total**
Threestone	1	10	10	**21**
Coalpot	3	5	2	**10**
Gyapa Wood	0	12	6	**18**
Philips Charcoal	4	9	1	**14**
Philips Wood	1	5	6	**12**
Total	**9**	**41**	**25**	

Table S2: Overall field test results of stove/fuel combinations.

Stove and fuel	Stats	Mean firepower kW	Food mass cooked kg	Cooking time min	MCE %	HTE %	OTE %	Specific Fuel Consumption (kg fuel per kg food)	Emission Factor (g*kg dry fuel^{-1})					EC/OC %	EC/TC %
									CO	CO_2	PM	OC	EC		
Threestone with wood	N	20	17	21	15	14	17	17	15					15	15
	mean	6.8	8.5	96	93.3	24.0	21.7	0.30	70	1541	4.2	2.1	0.2	7.7	7.1
	median	7.1	9.6	97	92.4	22.8	17.0	0.30	77	1551	3.7	1.9	0.1	7.4	6.9
	COV	26	42	20	4.4$^{\Psi}$	55$^{\Psi}$	53$^{\Psi}$	47$^{\Psi}$	29$^{\Psi}$	4$^{\Psi}$	79$^{\Psi}$	79$^{\Psi}$	91$^{\Psi}$	52$^{\Psi}$	49$^{\Psi}$
Gyapa with wood	N	17	14	18	18	14	14	14	18					18	18
	mean	5.4	7.2	91	94.5	25.8	24.2	0.27	58	1570	2.6	1.2	0.4	32.5	22
	median	5.2	5.3	84	95.1	24.1	22.1	0.23	51	1584	2.4	1	0.3	25	20
	COV	48	61	39	5.4$^{\Psi}$	49$^{\Psi}$	48$^{\Psi}$	49$^{\Psi}$	42$^{\Psi}$	4$^{\Psi}$	53$^{\Psi}$	52$^{\Psi}$	217$^{\Psi}$	180$^{\Psi}$	139$^{\Psi}$
Philips with wood	N	11	10	12	11	10	10	10	11					11	12
	mean	4.1	6.2	74	95.9	37.3	35.8	0.19	45	1628	2.5	1.2	0.3	22.7	16.3
	median	3.8	5.3	64	95.8	35.7	34.4	0.15	51	1602	1.4	0.7	0.2	14.8	12.9
	COV	29	60	35	4.2$^{\Psi}$	70$^{\Psi}$	70$^{\Psi}$	69$^{\Psi}$	58$^{\Psi}$	6$^{\Psi}$	78$^{\Psi}$	78$^{\Psi}$	339$^{\Psi}$	233$^{\Psi}$	190$^{\Psi}$
Philips with charcoal	N	14	12	14	13	12	12	12	13					13	13
	mean	3.7	5.2	91	93.9	26.0	24.4	0.21	92	2234	1.6	0.8	0.1	12.2	5.9
	median	3.1	3.6	94	94.6	26.5	25.0	0.20	79	2288	1.1	0.6	<<0.1	2.3	2.3
	COV	67	61	31	7.7$^{\Psi}$	46$^{\Psi}$	47$^{\Psi}$	44$^{\Psi}$	63$^{\Psi}$	8$^{\Psi}$	88$^{\Psi}$	83$^{\Psi}$	314$^{\Psi}$	185$^{\Psi}$	153$^{\Psi}$
Coalpot with charcoal	N	10	10	10	10	10	10	10	10					10	10
	mean	3.3	6.2	107	88.0	29.0	25.6	0.28	187	2148	0.8	0.4	<<0.1	1.9	1.9
	median	3.3	5.3	106	89.5	29.7	26.2	0.23	164	2195	0.8	0.4	<<0.1	1.7	1.7
	COV	32	60	27	8.5$^{\Psi}$	55$^{\Psi}$	56$^{\Psi}$	49$^{\Psi}$	25$^{\Psi}$	5$^{\Psi}$	52$^{\Psi}$	52$^{\Psi}$	34$^{\Psi}$	55$^{\Psi}$	53$^{\Psi}$

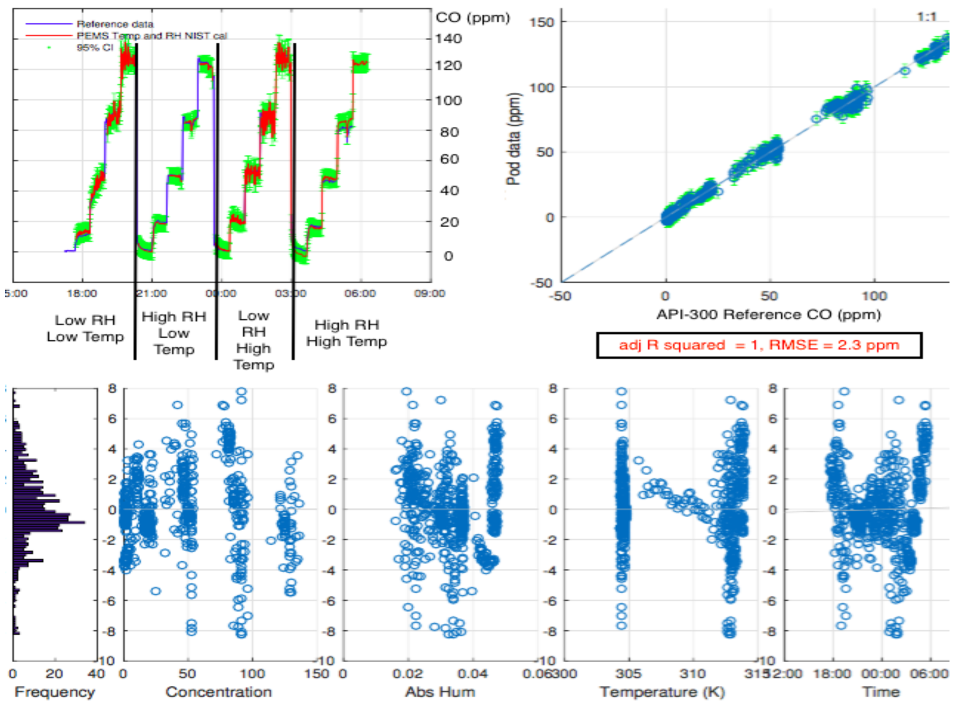
Mean, median and coefficients of variation (COV, %) for various performance metrics are presented for the five stove/fuel categories. EC/OC values calculated from fuel basis EFs.

Ψ - $COV_{log\ normal} = \sqrt{e^{(ln(10) \times std_{10})^2} - 1}$, where std_{10} is the standard deviation of log_{10} transformed metric.

Table S3: Mixed model results showing comparisons of ICS to traditional counterparts in additon to various stove perfomance variables.

	Emission Factor (g*kg dry fuel^{-1})								EC/OC		Emission Factor (g*MJdelivered^{-1})						MCE		HTE		OTE		Specific Fuel Consumption	
	CO		CO_2		PM		EC				CO		CO_2		PM									
	% diff.	p	% diff.	p	% diff.	p	% diff.	p	% diff.	p	% diff.	p	% diff.	p	% diff.	p	% diff.	p	% diff.	p	% diff.	p	% diff.	p
Philips Wood	**-46 (-65,-18)↓**	**<0.01**	**13 (0,28)↑**	**0.04**	-13 (-53,61)	0.64	-22 (-71,111)	0.62	-12 (-63,107)	0.76	**-51 (-69,-22)↓**	**<0.01**	-2 (-22,23)	0.85	-13 (-53,62)	0.65	**6 (0.6,12)↑**	**0.03**	-9 (-23,8)	0.27	-6 (-21,10)	0.42	**-50 (-65,-27)↓**	**<0.01**
Gyapa Wood	-21 (-41,7)	0.12	5 (-4,14)	0.29	-18 (-47,27)	0.36	**122 (9,353)↑**	**0.03**	**202 (63,459)↑**	**<0.01**	-7 (-34,32)	0.66	3 (-14,22)	0.78	-12 (-45,39)	0.57	3 (-1,7)	0.12	-1 (-13,12)	0.83	-1 (-12,12)	0.88	-13 (-38,21)	0.38
Moisture medium	29 (-2,70)	0.07	7 (-2,15)	0.11	43 (-4,113)	0.07	-22 (-59,49)	0.44	**-49 (-71,-11)↓**	**0.02**	18 (-17,67)	0.33	7 (-10,26)	0.44	55 (-2,143)	0.06	-2 (-5,01)	0.22	-8 (-18,5)	0.20	-8 (-18,4)	0.18	**-33 (-51,-7)↓**	**0.02**
Moisture high	33 (-7,90)	0.11	6 (-5,17)	0.28	-33 (-60,14)	0.13	**-77 (-90,-47)↓**	**<0.01**	**-69 (-85,-37)↓**	**<0.01**	27 (-19,98)	0.28	11 (-11,37)	0.35	-30 (-61,25)	0.21	-6 (-7,1)	0.17	0 (-15,17)	0.99	-1 (-15,16)	0.92	**-39 (-60,-8)↓**	**0.02**
Firepower	3 (-8,14)	0.62	-1 (-4,2)	0.63	13 (-3,32)	0.12	15 (-10,47)	0.26	2 (-18,26)	0.87	**20 (6,35)↑**	**<0.01**	**17 (10,24)↑**	**<0.01**	13 (-3,32)	0.11	-0.4 (-2,1)	0.59	**-16 (-19,-12)↓**	**<0.01**	**-15 (-20,-12)↓**	**<0.01**	NaN	NaN
Firepower*Gyapa	5 (-8,19)	0.48	0 (-4,3)	0.92	-4 (-20,14)	0.63	4 (-22,38)	0.79	9 (-15,39)	0.50	-1 (-16,18)	0.93	1 (-7,9)	0.86	-2 (-21,23)	0.87	-0.4 (-2,1)	0.54	0 (-6,7)	0.86	0.3 (-6,6)	0.92	NaN	NaN
Firepower*Philips	-7 (-28,19)	0.54	-2 (-9, 6)	0.62	10 (-24,60)	0.60	-9 (-50,65)	0.74	-20 (-52,34)	0.38	1 (-25,34)	0.97	8 (-7,24)	0.30	8 (-25,60)	0.62	-0.1 (-3,3)	0.94	-10 (-18,0.2)	0.23	**-10 (-18,0)↓**	**<0.05**	NaN	NaN
MCE_std	0.5 (-2,3)	0.77	0.7 (-0.2,1.5)	0.12	2 (-2,7)	0.32	2 (-5,10)	0.51	0 (-6,6)	0.98	0 (-4,4)	0.90	0.5 (-1,2)	0.58	3 (-2,8)	0.24	0 (-0.3,0.3)	0.91	0 (-1.6,1)	0.60	-0.3 (-1.5,1)	0.65	-3 (-6,1)	0.11
MCE_std*Gyapa	7 (-3,18)	0.19	0.3 (-1.3,2)	0.74	7 (-1,16)	0.10	**36 (19,55)↑**	**<0.01**	**33 (18,48)↑**	**<0.01**	18 (-1,41)	0.06	**-8 (-16,0)↓**	**<0.05**	11 (-12,39)	0.38	-1 (-2,0)	0.12	2 (0,13)	0.05	5 (-1,12)	0.12	-11 (-26,6)	0.18
MCE_std*Philips	**20 (4, 37)↑**	**0.01**	0.4 (-3.5,4.5)	0.83	-8 (-20,14)	0.40	**52 (10,109)↑**	**0.01**	**73 (31,129)↑**	**<0.01**	**22 (5,42)↑**	**0.01**	2 (-6,9)	0.69	-8 (-25,12)	0.38	-1 (-3,3)	0.23	3 (-3,8)	0.34	2 (-3,8)	0.43	13 (-2,30)	0.08
Food Production Rate	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	**-1 (-1.2,-0.4)↓**	**<0.01**	**-1 (-1.2,-0.8)↓**	**<0.01**	-0.2 (-0.7,0.4)	0.54	NaN	NaN	**1.1 (1,1.3)↑**	**<0.01**	**1.1 (1,1.3)↑**	**<0.01**	NaN	NaN
ICC (btw/btw+wthn)	0.46		0.75		0.98		0.74		0.66		NA		NA		NA		0.44		NA		NA		NA	
n	43		43		43		43		43		38		38		38		43		38		38		38	
R^2	0.30		1		1		1		1		0.93		0.98		0.76		0.23		0.97		0.97		0.74	
Philips Charcoal	**-77 (-92,-34)**	**<0.01**	20 (-8,55)	0.42	**-58 (-90,81)↓**	**0.04**	4 (-90,948)	0.39	**668 (13,5E3)↑**	**0.04**	**-91 (-97,-69)↓**	**<0.01**	-21 (-49,23)	0.27	-68 (-94,82)	0.18	**35 (14,59)↑**	**0.04**	-2 (-31,41)	0.92	16 (-17,62)	0.38	-24 (-47,11)	0.15
MCE_std	11 (-5,31)	0.19	-2 (-5,3)	0.16	27 (2,59)	0.22	19 (-22,81)	0.97	-7 (-31,24)	0.60	**25 (3,51)↑**	**0.03**	0 (-7,7)	0.97	26 (-5,67)	0.10	-2 (-4,1)	0.44	-7 (-17,5)	0.93	-1 (-6,4)	0.65	NaN	NaN
Firepower	14 (-13,49)	0.32	**-7 (-13,-1)↓**	**0.04**	7 (-26,56)	0.69	26 (-10,78)	0.16	-25 (-53,22)	0.24	**39 (5,83)↑**	**0.03**	**13 (2,26)↑**	**0.02**	29 (-15,95)	0.20	-5 (-9,0)	0.06	**-23 (-29,-16)↓**	**<0.01**	**-24 (-30,-18)↓**	**<0.01**	NaN	NaN
Firepower*PhilipsC	-5 (-30,29)	0.72	0 (-8,8)	0.95	-13 (-43,33)	0.49	NaN	NaN	**111 (21,268)↑**	**0.01**	-9 (-33,25)	0.54	2 (-9,15)	0.71	-10 (-44,42)	0.62	3 (-2,9)	0.38	2 (-9,10)	0.97	2 (-7,11)	0.71	NaN	NaN
Food Production Rate	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	NaN	**-2 (-3,-1.3)↓**	**<0.01**	**-1.7 (-2,-1.4)**	**<0.01**	**-2 (-3.3,-1)↓**	**<0.01**	NaN	NaN	**1.8 (1.5,2)↑**	**<0.01**	**1.9 (1.6,2.1)↑**	**<0.01**	NaN	NaN
n	23		23		23		23		23		22		22		22		23		22		22		22	
R^2	0.82		0.83		0.70		0.66		0.75		0.91		0.96		0.71		0.86		0.98		0.98		0.56	

Model results are reported as percent differences from reference with 95% confidence interval of this percent reduction (See Figure S5 for a visual example). Significance (marked as red) is assessed at 5%, with p-values. Arrows signal the direction of the difference from reference. N is the number of observations used in the model and R^2 is the adjusted correlation. NaN signifies a term not used in model or not applicable. *ICC* is the interclass correlation coefficient and defined as the ratio of between-household-variation (btw) to the sum of between and within household variation (btw+wthn). Specific fuel consumption is kg of dry fuel burned per kg of food produced.



34

Figure S3: Calibration results for Alphasense B-4 CO electrochemical sensor using an API CO-300 reference monitor calibrated using reference gas standards; Five-step CO reference and sensor time series with varying temperatures and humidity (top left), correlation scatterplot (top right) and residuals (bottom). Particular attention was paid to covering extreme temperatures and humidity experienced in the field.

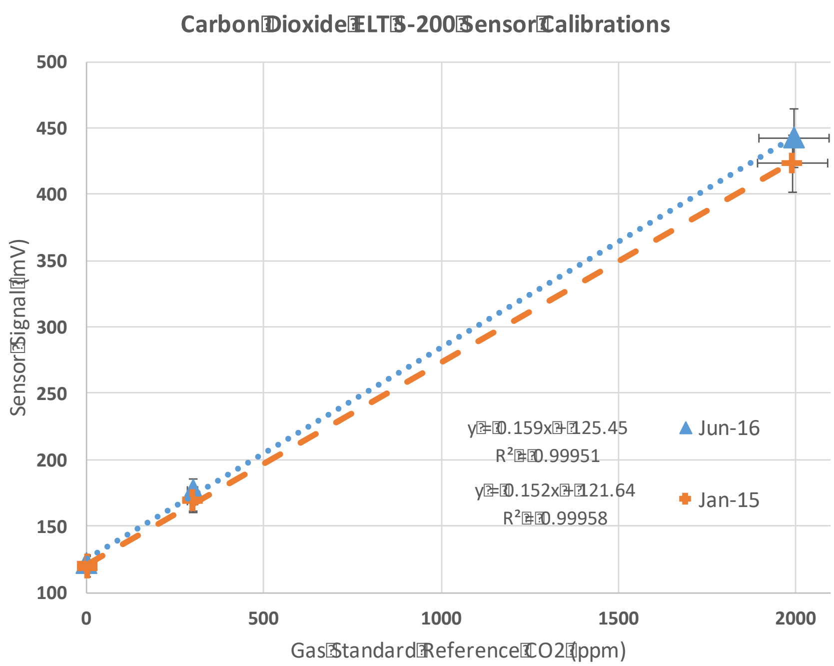


Figure S4: Carbon dioxide ELT S-200 IR calibration results using a LICOR 840a analyzer calibrated using three NIST traceable gas standards from 2015 (crosshairs) and 2016 (triangles) with 5% uncertainty bounds, showing high linearity and insignificant sensitivity changes over sampling interval.

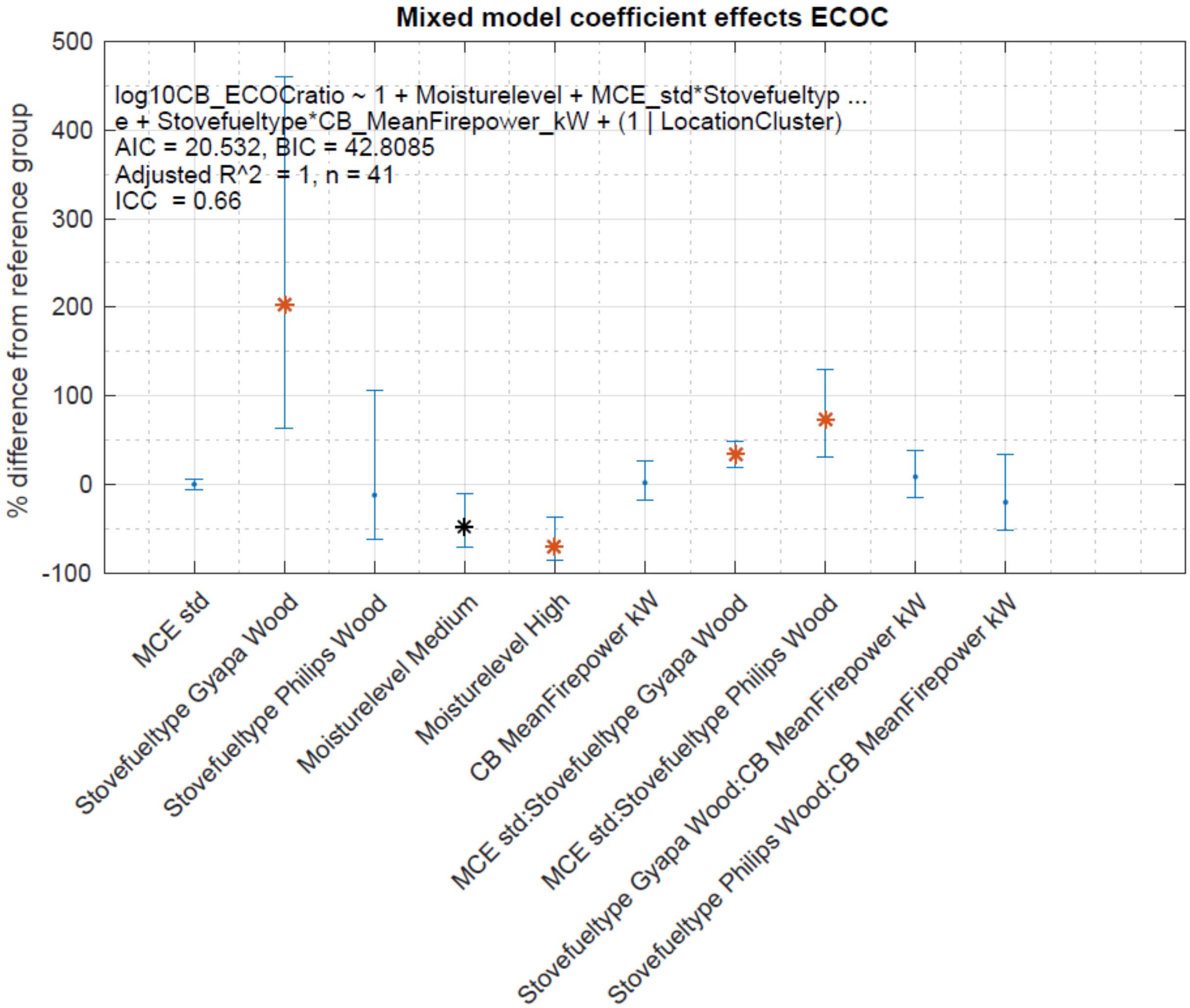


Figure S5: Visual representation of mixed model results for EC/OC outcome for wood-fueled stoves. Blue dots represent average estimate percent differences from reference with black asterisks signifying significance at the 5% level and red/orange asterisks signifying significance at the 1% level. Error bars represent 95% confidence interval of estimate. For example, EC/OC is on average 200% larger for the Gyapa stove than the threestone fire (reference). Likewise, medium and high moisture levels are linked to 49 and 69 percent less EC/OC than low moisture (reference), respectively. Lastly, the Gyapa and Philips modified combustion efficiency fluctuation interactions are both significant at explaining higher EC/OC relative to the threestone MCE fluctuation interaction.

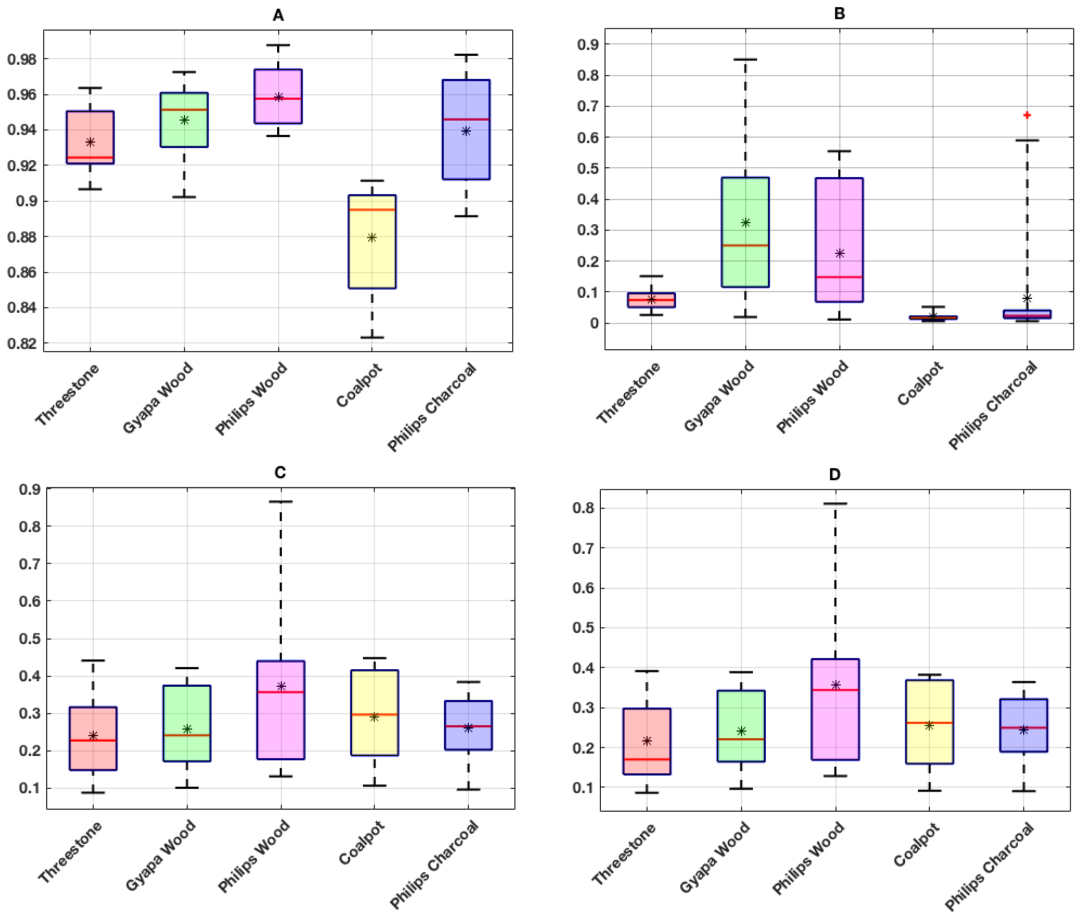


Figure S6: Distributions of A) MCE B) EC/OC values C) HTE and D) OTE by stove/fuel group. Boxes represent interquartile range, line is median, asterisk is mean and whiskers are 5th/95th percentiles. ICS tend to exhibit more variation in performance overall. Differences between mean and median metrics for MCE and EC/OC are most drastic.