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Fuel efficiency and air pollutant concentrations of wood-burning improved cookstoves in Malawi: Implications for scaling-up cookstove programs

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A B S T R A C T

Developing countries are grappling with how to reduce household air pollution (HAP) from cooking with solid fuels and the traditional three stone fire (TSF). Laboratory studies have shown that improved cookstoves may offer reductions in fuel use, emissions of carbon monoxide (CO) and fine particulate matter ($PM_{2.5}$), yet there is limited evidence from "real-world" settings showing how improved stoves perform compared to the traditional TSF. Our study takes place in a semi-controlled setting in Malawi and was designed to quantify fuel efficiency improvements and air pollutant concentration reductions capabilities of two improved cookstoves. We perform a Water Boiling Test to compare the TSF with the locally produced clay stove known as the Chitetezo Mbaula (CM) and the Philips gasifying stove. We find that the CM uses 53% of the fuel used by the traditional TSF, and produces 59% of CO, and 50% of $PM_{2.5}$ of the TSF. The Philips stove uses 31% of the fuel, and produces 38% of CO, and 22% of $PM_{2.5}$ of the TSF. We consider the potential for the wide-scale adoption of these technologies given their relative costs and conclude that lower-cost, intermediate quality cookstoves are an important and realistic first step toward reducing HAP.

Introduction

Recent studies on the health, environment, and climate impacts of household cooking practices in the developing world have attracted the attention of key stakeholders such as international organizations, multi- and bi-lateral donors, non-governmental organizations, private sector investors, and researchers (Lim et al., 2013; Ramanathan and Carmichael, 2008; Zhang and Smith, 2007). Biomass fuel use and traditional cooking technologies have been linked to health problems including acute respiratory infection (ARI) in children under five, chronic obstructive pulmonary disease (COPD) in adults, low birth weight, and a myriad of other negative health complications (Ezzati and Kammen, 2002; Fullerton et al., 2008; Mishra et al., 2004; Smith et al., 2011). Furthermore, biomass fuel use for cooking and heating is known to contribute to deforestation and forest degradation, particularly in peri-urban areas, the outskirts of refugee camps, and rural areas with high population densities (Arnold et al., 2006). Finally, incomplete combustion of biomass results in black carbon and other types of particulate matter, major contributors to regional climate change, which has medium and long run consequences for food security, economic growth and development (Ramanathan and Carmichael, 2008; Schellnhuber et al., 2013). Improved cookstove (ICS) interventions have been shown to have some effect on reducing health complications including severe pneumonia and low birth weight (Smith et al., 2011; Thompson et al., 2011), and to reduce fuel consumption and associated emissions (Bailis et al., 2007; Pilishvili et al., 2016; Rosa et al., 2014; Suresh et al., 2016).

Our study takes place in Malawi where cookstoves are at the forefront of the policy agenda of several sectors including energy, environment, health, and gender. The effects of dependence on woody biomass fuels are apparent in national health outcomes; HAP was ranked as the most important cause of Disability-Adjusted Life Years (DALYs) in 2010, and lower respiratory infections are the second leading cause of death in Malawi and the leading cause of death for Malawian children under 5 (Fullerton et al., 2009; GBD, 2013. Mortality and Cause of Death Collaborators, 2015; Gordon and Graham, 2006). In addition, Malawi has a rapidly growing population expected to increase

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from 14.8 million to 45 million by 2050 (NSO, 2010). Among Malawi's growing population, there is almost universal dependence on biomass fuels for cooking; 99% of households rely on solid fuels (UNICEF, 2008). Access to biomass fuels is constrained by resource degradation. Malawi has one of the highest rates of deforestation in sub-Saharan Africa, estimated at 2.8% per year (MNREE, 2010); it is estimated that between 1990 and 2010, forest cover declined from 41% to 34% (FAO, 2010). The dominant natural forest type in Malawi is miombo woodland, which has varying levels of degradation that are strongly correlated with population density and nearness to urban markets (Kambewa and Utila, 2008). In 2013, then President Joyce Banda announced a policy objective to distribute 2 million cookstoves to Malawian households by 2020. The National Cookstove Steering Committee has since created a cookstove database, maintained by The Movement for Bio-Energy Advocacy, Utilisation, Learning, and Action (MBAULA), to track the progress of this ambitious goal. The most recent reports show that over 500,000 ICS have been distributed, which is 25% of the way to 2 million stoves by 2020 (MBAULA, 2017a). Given the pressing national health burden, regional resource degradation, the localized carbon hotspot in the Southern African region (Ramanathan and Carmichael, 2008), and the ongoing national policy efforts, Malawi makes for an excellent test case to investigate the potential for addressing the trilemma of health, forest, and climate conditions through widespread improved cookstove use.

In this study, we evaluate the relative fuel efficiency and air pollutant concentrations of two improved cookstove options for Malawi compared to the baseline technology (three-stone fire or TSF) through conducting a Water Boiling Test (WBT) in a simulated kitchen, field-based setting. We hypothesize that the reductions will be modest compared to those measured under laboratory conditions. While laboratory-based studies are ideal for characterizing detailed stove performance, field-based studies are more reflective of conditions and methodologies seen in realistic household cooking environments (Aung et al., 2016; Edwards et al., 2014). The simulated kitchen setting used in our study includes the benefits of a controlled lab study by employing a standardized protocol of controlled and reproducible methods, while also incorporating more realistic elements of stove use practice that are representative of actual households (e.g., real kitchen setting, locally-sourced fuel, Malawian stove operator, and ventilation conditions comparable to a typical Malawi kitchen). This study design may allow pollutant concentration reductions and fuel efficiencies to be reliably benchmarked for the use of future policy makers seeking representative metrics for comparing improved stoves. By highlighting studies that recreate realistic cooking environments but are standardized enough to compare results from different stove types, we provide information that will help policymakers design and implement policies that have high potential for impact on multiple objectives of improving health, forest condition, and climate.

Methods

Cookstoves

This study evaluates the performance of three wood-burning stoves available in Malawi: the traditional three-stone fire, the Chitetezo Mbaula ('protecting stove' in Chichewa, the local language of Malawi), and the Philips HD4012 fan stove. The three-stone fire, the baseline technology in this analysis, is by far the most common stove in Malawi due to its traditional usage and lack of financial cost. >95% of households in Malawi rely on the three-stone fire as their primary cooking technology (Jagger and Perez-Heydrich, 2016). The Chitetezo Mbaula is a locally produced natural-draft portable cookstove made of fired ceramic. It was developed in Malawi over 15 years ago and has undergone several design improvements over time to incorporate as much as possible the design principles of rocket stoves for complete combustion and fuel efficiency. The optimal design has been agreed upon by local developers and users and is currently being standardized by the Malawi Bureau of Standards (Roth, 2014). The stove is made of molded clay with a hole fashioned in the side to allow air and fuel entry, with fixed pot rests on the top. The Chitetezo Mbaula represents the most affordable end of the improved stove market at ~US$2.50 per stove in Lilongwe's retail market. It is estimated that over 500,000 households are currently using the Chitetezo Mbaula in Malawi (MBAULA, 2017a). The Philips HD4012 fan stove is a fan-forced, top-lit, updraft gasifier stove produced in Lesotho and imported into Malawi where it is sold in urban areas for approximately US$90. It can be batch loaded with fuel such as pellets and operated as a top-lit updraft stove, or can be continuously fed with small pieces of biomass (e.g., fuelwood or crop residues). In addition to being sold on the market, over 10,000 of these stoves have been distributed for free in the Cooking and Pneumonia Study (CAPS) in Malawi, the world's largest cookstove intervention trial (Ardrey et al., 2016). Gasifier stoves influence emissions by injecting air into the top and bottom of the combustion chamber, which reduces the amount of CO produced from incomplete combustion (Roth, 2011). In a study testing the performance of numerous biomass cookstoves, the Philips HD4012 fan stove was among the best performers in terms of energy efficiency and pollutant emissions (Jetter et al., 2012). Fig. 1 shows the three stoves used in the study

Fuel

The primary fuel used for this analysis was wood from a locally sourced, semi-deciduous indigenous tree (*Uapaca kirkiana*). Dry, locally sourced grasses were used to assist in starting the fires. The wood fuel was selected for representativeness of local use and was kept at market-purchased size (approx. 30 to 40 cm long, approx. 2 to 3 cm in diameter) for the tests conducted with the three-stone fire and Chitetezo Mbaula. Smaller pieces of fuelwood or wood pellets are usually used as fuel in the Philips stove. The purchased wood was too large for the Philips stove, so the wood was chopped to somewhat regularly-sized pieces (approx. 12 cm long, approx. 1 to 2 cm in diameter) to fit the dimensions of the combustion chamber.

Test kitchen

The tests were conducted in a single-room, standalone, brick-walled, thatch-roofed kitchen (approx. 192 × 131 cm, 180 cm high) with limited ventilation constructed to reflect the style of a kitchen building in rural Malawi (see Fig. 2). The kitchen had a single large opening (approx. 79 × 120 cm) that served as the door. In one corner of the kitchen, additional ventilation was provided by four brick-sized openings (10 × 30 cm) located 110 cm above the floor. Small ventilation openings were also located near the ceiling on opposite ends of the kitchen. The stoves were placed on the floor along the side wall of the kitchen, closest to the brick-sized ventilation holes. A tripod supporting the monitoring equipment was placed 1 m from the cookstove. Tests were conducted only under dry conditions with minimal wind in an effort to minimize ventilation variation between tests.

While lab-based WBTs are conducted in a fume hood where emissions are not subject to circulation within the test facility, the tests in this study were conducted in a kitchen with uncharacterized ventilation. There was insufficient ventilation to remove all of the emissions from the first phase of the WBT prior to the start of the second phase, and the emissions from the second phase prior to the start of the third phase. As a result, the results related to emissions during the second and third phases may be biased upward.

Test protocol

The tests were conducted following the protocols outlined in version 4.2.2 of the Water Boiling Test (GACC, 2013). The Water Boiling Test is less representative of typical stove use than the Controlled Cooking

Fig. 1. Biomass burning stoves included in this study. From left to right: three-stone fire, Chitetezo Mbaula, and Philips HD4012 fan stove.

Test (CCT) or the Kitchen Performance Test (KPT), but it was selected for its sensitivity to differences between stoves and simplicity of execution. Each test consisted of three phases: a high-power cold-start phase, a high-power hot-start phase, and a low-power simmer phase. The cold-start phase required the stove to be initially at room temperature, while the hot-start phase was conducted immediately following the cold-start phase while the stove retained heat from the cold-start phase. The two high-power phases evaluated the stove's performance by heating 5 l of room-temperature water to a boil; these phases are intended to give an indication of how the stove's thermal mass impacts efficiency and emissions. The low-power simmer phase was conducted immediately following the high-power hot-start phase. The simmer phase evaluates the stove's performance while maintaining the water's temperature at 3 °C below the local boiling point (96.1 °C at 1100 m in Lilongwe) for 45 min. Efficiency-related metrics for each phase were calculated based on fuel consumption, temperature changes, and water evaporation during each phase.

The WBT was originally developed as a measure of fuel use efficiency, but it can also be used to calculate emission-related metrics when CO and PM are monitored. Given that our study was conducted in a kitchen with uncontrolled ventilation, instead of calculating traditional emission-related metrics, average concentrations of CO and $PM_{2.5}$ were determined for each phase of the WBT. The monitoring equipment was positioned 1.5 m above the ground and 1 m from the cookstove. All tests were conducted by the same research assistant. Twelve tests were conducted with the Chitetezo Mbaula ($N = 6$) and Philips stoves ($N = 6$), and eight tests with the three-stone fire. A larger number of tests were conducted for the three-stone fire because results were more variable than with the other two stoves.

Household air pollution characterization

$PM_{2.5}$ samples were collected using a pump connected to a single-stage impactor and a 2 μm polytetrafluoroethylene (PTFE) filter downstream of the impactor. CO concentrations were measured in 10 s increments with CO data loggers (Lascar Electronics, model EL-USB-CO). To improve precision, each phase of each test was monitored by two sets of $PM_{2.5}$-measuring equipment and three CO data loggers as shown in Fig. 2. The results from the CO data loggers were averaged together after correction with a device-specific calibration factor. The averaged CO data had an average coefficient of variation of 10.3% across all twenty tests. Duplicate $PM_{2.5}$ measurements had an average coefficient of variation of 2.4% across all phases of all tests. The moisture content of the wood was measured with an Ohaus MB23 Moisture Analyzer (*Parsippany*, *NJ*).

Household survey and personal exposure monitoring

We use data collected during a rural household survey ($N = 401$) in Machinga and Kasungu Districts focused on household energy use (see Jagger and Jumbe, 2016 for details of the sample and study area) to inform the hypothetical intervention calculations made in Implications section. In addition to a household socioeconomic survey, a subsample of primary cooks ($N = 100$) were monitored for 24-hour exposure to CO and $PM_{2.5}$. This study was reviewed and approved prior to its start by the Institutional Review Board (IRB) at the University of North Carolina at Chapel Hill; participants provided written consent.

Results

Efficiency-related metrics

A large number of quantitative assessments can be calculated from the results of WBTs that aid in comparing the performance of different stoves. We restrict our interest to measures related to how quickly a stove can deliver energy to a pot (i.e., time-to-boil) and measures related to efficiency (i.e., thermal efficiency and fuel use).

Fig. 2. Test kitchen and monitoring equipment.

The top panel of Fig. 3 shows the time-to-boil results for the cold- and hot-start high-power phases of the WBT. Time-to-boil is the time required to bring five liters of room-temperature water to a boil. Relative to the three-stone fire, the Philips stove had shorter times (30% (p-value = 0.018) and 6% (p-value = 0.244) shorter for the cold-start and hot-start phases, respectively), while the Chitetezo Mbaula had longer times (28% (p-value = 0.145) and 25% (p-value = 0.011) longer for the cold-start and hot-start phases, respectively). Half of the differences in the time-to-boil metrics for the improved cookstoves relative to the three-stone fire were significant (p-value <0.025 for two-sided t-tests).

Thermal efficiency is the ratio of the heat delivered to the water in the pot to the fuel energy used. As seen in the bottom panel of Fig. 3, the thermal efficiency was highest for the Philips stove and lowest for the three-stone fire for all high-power phases of the WBTs. Relative to the three-stone fire, the thermal efficiencies for the Philips stove were 125% (p-value = 0.012) and 384% (p-value = 0.002) higher for the cold-start and hot-start phases, respectively. The Chitetezo Mbaula showed more modest improvements of 36% (p-value <0.001) and 117% (p-value = 0.001) for the cold-start and hot-start phases, respectively. All of the differences in the thermal efficiencies for the improved cookstoves relative to the three-stone fire were significant.

The results for specific energy consumption and fuel use benchmark value are shown in Fig. 4. Specific energy consumption during the low-power simmer phase is a measure of the combustion energy needed to keep the water in the pot near the boiling point. Both improved cookstoves had similarly reduced specific energy consumptions relative to the three-stone fire: 68% (p-value = 0.075) lower for the Philips stove and 57% (p-value = 0.120) lower for the Chitetezo Mbaula. The fuel use benchmark value provides a relative measure between stoves for fuel consumption over all three phases of the WBT. The fuel use benchmark value is the average of the amount of fuel used during the cold- and hot-start phases, plus the amount of fuel used during the low-power simmer phase. The fuel use benchmark values for the three stoves followed the same trends as for the specific energy consumption. Relative to the three-stone fire, the fuel use benchmark was reduced by 69% (p-value = 0.009) for the Philips stove and 47% (p-value = 0.041) for the Chitetezo Mbaula.

The results from WBT studies conducted by other organizations are also shown in Figs. 3 and 4. Only results from studies using five-liter pots, as was used in this study, are included as pot size can influence metrics such as time-to-boil and thermal efficiency (Jetter et al., 2012). All of the comparison studies were conducted in laboratory settings, except that of Vaccari et al. (2012), which was conducted in the field. The stove-to-stove trends in the efficiency results from this study are in general agreement with the other studies shown in Figs. 3 and 4. The largest differences between the results from this study and the average results of the other studies is seen in the thermal efficiency results shown in Fig. 3. Specifically, three of measurements from this study are >25% lower than the average of the other studies (i.e., TSF hot start 34% lower, CM cold start 27% lower, and CM hot start 37% lower), while Philips hot-start was 29% higher than the other studies. The same large differences are not seen in the time-to-boil results, even though time-to-boil is strongly correlated with cooking power (Jetter et al., 2012). The fuel use benchmark value for the Chitetezo Mbaula was 28% higher than the results retrieved from the Clean Cooking Catalog (catalog entry #693, 2017). Overall, the efficiency

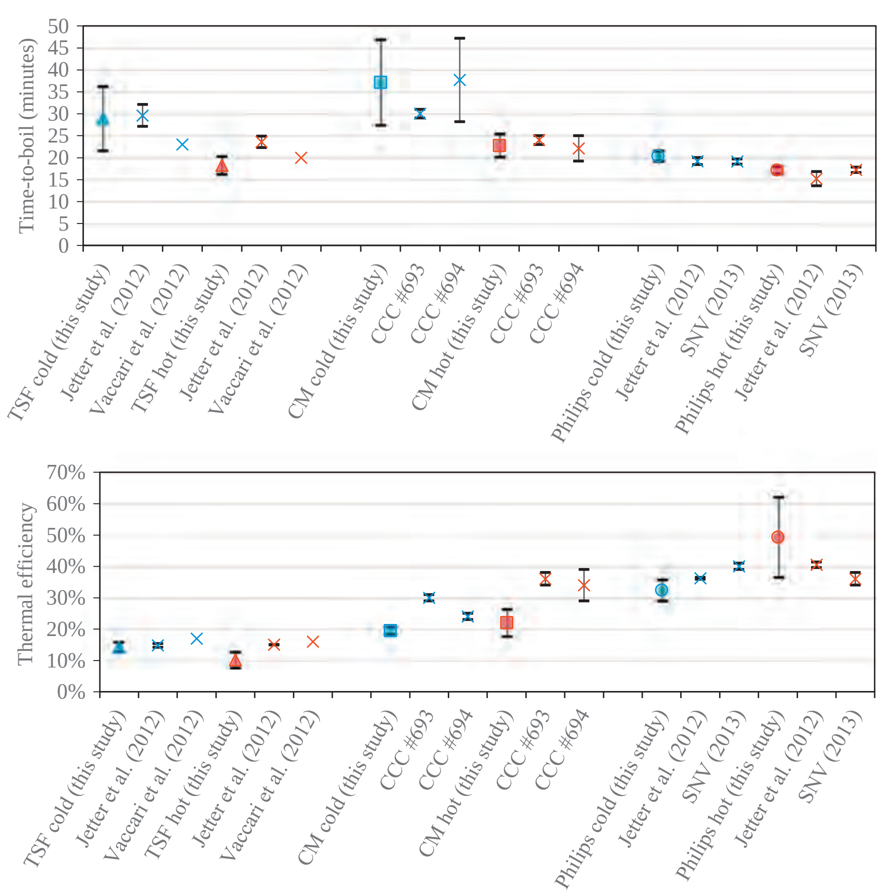

Fig. 3. Time-to-boil (top panel) and thermal efficiency (bottom panel) results for the three-stone fire (TSF, triangle symbols), Chitetezo Mbaula (CM, squares), and Philips (circles) stoves for the cold-start and hot-start high-power phases compared to other studies (× symbols). Error bars represent one standard deviation. Results labeled CCC #693 and CCC #694 are from the Clean Cooking Catalog (retrieved 2017) with the number indicating the catalog test number. Results labeled SNV (2013) is from Sustainable Green Fuel Enterprise (2013).

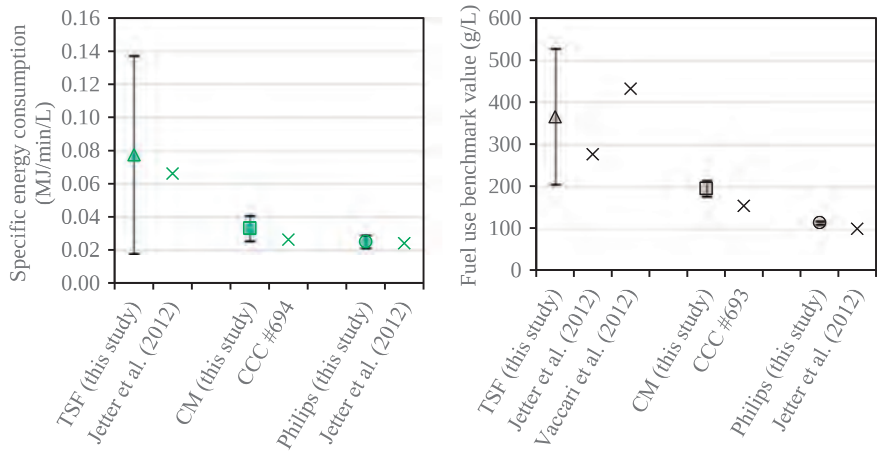

Fig. 4. Efficiency-related results for the three-stone fire (TSF, triangle symbols), Chitetezo Mbaula (CM, squares), and Philips (circles) stoves from this study compared to other studies (× symbols). Results labeled CCC #693 and CCC #694 are from the Clean Cooking Catalog (retrieved 2017) with the number indicating the catalog test number.

results from this study are consistent with other studies, which is expected given the relative simplicity of the measurements.

Pollutant concentration metrics

The average concentrations of CO and $PM_{2.5}$ during each phase of the water boiling tests conducted on the three stoves are shown in Fig. 5. The "Combined results for all phases" provides a single averaged concentration over all phases, analogous to the fuel use benchmark value. The reported values represent the time-weighted average during the two high-power phases and the average during the low-power simmer phase, or

$$C_{combined} = \frac{0.5^{*}(C_{cold}{}^{*}t_{cold} + C_{hot}{}^{*}t_{hot}) + C_{simmer}{}^{*}t_{simmer}}{0.5^{*}(t_{cold} + t_{hot}) + t_{simmer}}$$

where C is the average concentration during a phase, t is the duration of a phase, and the subscripts indicate the phase of the test.

The improved cookstoves had lower average CO and $PM_{2.5}$ concentrations than the three-stone fire for all three phases of the WBT. Two-thirds of the differences in concentrations for the improved cookstoves relative to the three-stone fire were significant (p-value <0.025). The combined results for CO show that the improved stoves had about one-half the average CO concentration as the three-stone fire. The combined results for $PM_{2.5}$ show that compared to the three-stone fire, the Chitetezo Mbaula and Philips stove had about one-half and one-fourth the average $PM_{2.5}$ concentrations, respectively.

Emission factors and rates cannot be calculated from the data collected in this study so it is difficult to make direct comparisons to other studies. A comparison of the mass of emissions between stoves in this study can be made if ventilation is assumed to be invariant between tests. Under this assumption, the mass of emissions during a phase of the WBT is roughly proportional to the product of the average concentration during the phase and the duration of the phase. Similar to the fuel use benchmark value, we can define a combined mass ($M_{combined}$) emitted during the WBT as being roughly proportional to the weighted sums of the products of the average concentrations during the phases and the durations of the phases as follows

$$M_{combined} \propto 0.5^{*}(C_{cold}{}^{*}t_{cold} + C_{hot}{}^{*}t_{hot}) + C_{simmer}{}^{*}t_{simmer}$$

The results of the combined mass calculations suggests that CO emissions would be reduced by 41% ($p = 0.002$) and 62% ($p < 0.001$) when changing from a TSF to the CM and Philips stoves, respectively; and $PM_{2.5}$ emissions would be reduced by 50% ($p = 0.002$) and 78% ($p < 0.001$) when changing from a TSF to the CM and Philips stoves, respectively. The laboratory-based WBT study of Jetter et al. (2012 supplement) suggests CO and $PM_{2.5}$ reductions of 93% when changing from the TSF to the Philips stove, higher reductions than were found in this study even though efficiency-related metrics were similar.

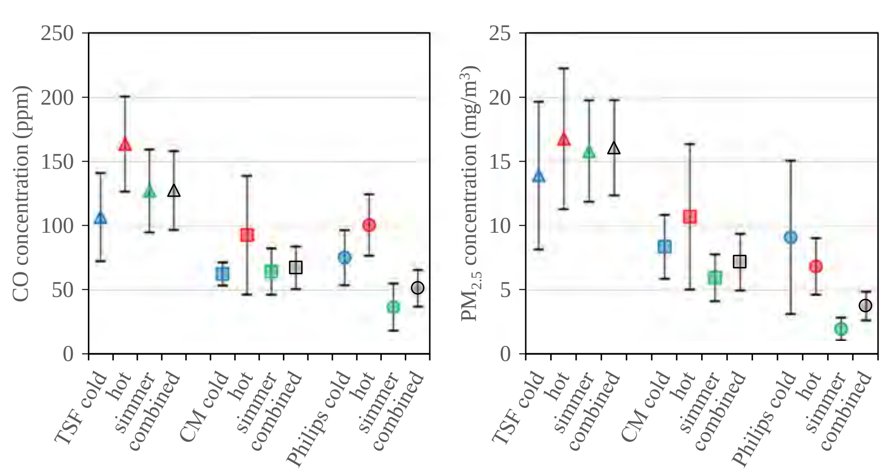

Fig. 5. Average concentrations in test kitchen during the cold-start phase, hot-start phase, simmer phase, and combined phases for the three-stone fire (triangle symbols), Chitetezo Mbaula (squares), and Philips (circles) stoves.

Implications

We seek to estimate the village-level savings that may be achieved from switching from the TSF to the Chitetezo Mbaula or the Philips stove. We extrapolate the percent change results calculated from the WBT (Figs. 4 and 5) to a village-level scale to estimate the impact that a stove intervention might have on emission reductions, fuelwood and time use savings, the number of averted Disability-Adjusted Life Years (DALYs) and the resulting net cost in USD required for each stove. The calculations are made as a function of the rate of adoption, from 0 to 100% (Fig. 6). For example, if there is a 20% adoption rate in the village, 20% of the households are assumed to be exclusively using the ICS, while the remaining 80% continue to use the TSF.

We begin the baseline analysis by assuming that all 100 households in a hypothetical rural Malawian village rely primarily on the TSF. This assumption is very realistic, data from the Integrated Household Survey (IHS) in 2010/11 indicate that >95% of rural households in Malawi use the TSF (GOM, 2012). Given that the vast majority of rural households in Malawi collect fuelwood rather than purchase it, we use self-reported data on time spent collecting fuelwood to estimate the economic burden required for these households to maintain use of the TSF. In our rural household survey, the average number of hours that all members of a household spent collecting fuelwood was reported to be 6.3 h per week per household. For 100 households, the time spent collecting fuelwood becomes 630 h per week per village, and thus 32,760 h per year per village.

Similarly, the average amount of fuelwood collected was estimated at 1878 kg per year per household, or 187,800 kg of fuelwood per year per village. We relate the fuelwood use in kilograms to hectares to better quantify the regional forest impact. From the rural exposure monitoring data set, we find the average moisture content of the fuel (woody miombo biomass) to be 10%. Beginning with the baseline fuelwood use of 187,800 kg of fuelwood per year per village, if we assume a 10% moisture content, the baseline fuelwood is equivalent to 170,700 kg of dry fuelwood. We assume that dry mass can be converted to carbon mass using 47%C (Ryan et al., 2011), resulting in 80,240 kgC per year per village. A study of carbon stocks in miombo woodland in Mozambique found that woody biomass totaled 33.3 tC/ha (Ryan et al., 2011). If we assume similar composition of woodland, we find that the baseline case results in a miombo woodland deforestation rate of approximately 2.41 ha per year per village.

To estimate the village-level baseline cost of maintaining use of the TSF, we assume that the time spent collecting fuelwood is lost time that could be spent working for pay. Further, we assume that the household members collecting fuelwood are primarily women. We estimate a daily wage rate in Malawi based on data reported by households in the study sample. The average wage rate reported for women was 350 MK/day (Jagger and Jumbe, 2016). The exchange rate during the time of study (late 2013) was roughly 414 MK to 1 USD (XE, accessed 2017). If we assume a typical wage earner works 8 h per day, then the hourly wage for women is about 0.11 USD per hour. For the 32,760 h spent maintaining use of the TSF, the labor cost is estimated to be ~3604 USD per year per village. We assume there is no capital cost for the TSF baseline technology, therefore the net cost (labor cost + capital cost), is the same as the labor cost for the baseline case.

Using the same assumptions as the baseline case, we estimate the village-level savings achievable by switching to the Chitetezo Mbaula or Philips stove. From the baseline information, we estimate the fuelwood collection rate to be 5.7 kg per hour. We use this value to estimate the hours spent collecting fuelwood for each ICS, which would ideally require less fuelwood and fewer hours as the stove efficiency increases. Using the fuel use benchmark reductions for each stove found from this analysis (Fig. 4), we calculate the fuelwood that would need to be collected (in terms of kg and ha) and the labor cost required for each ICS. We use the Household Air Pollution Intervention Tool (HAPIT), an internet based platform, to estimate the number of averted Disability-Adjusted Life Years possible from switching to ICS (Pillarisetti et al., 2016), assuming the baseline case results in no averted DALYs. During personal exposure monitoring over a 24-h period for primary cooks in rural Malawi we measured a median personal exposure of 348 μg/m^3, which we use as the pre-intervention exposure (see Household survey and personal exposure monitoring section). We apply the $PM_{2.5}$% reductions measured per each ICS in the Pollutant concentration metrics section to obtain hypothetical post-intervention exposure values. We assume the following inputs: counterfactual exposure of 35 μg/m^3, fraction of households using the intervention equal to 1, useful intervention life equal to 1 year for each stove (as we assume that the capital costs are paid upfront rather than over the lifetime of the stove), and we ignore the maintenance and fuel costs for each stove (i.e., 0 USD/yr/HH). Fig. 6 shows the output from the model using these parameters. After varying the fraction of intervention households for HAPIT, we determined that this estimation model follows a linear relationship and the averted DALYs monotonically

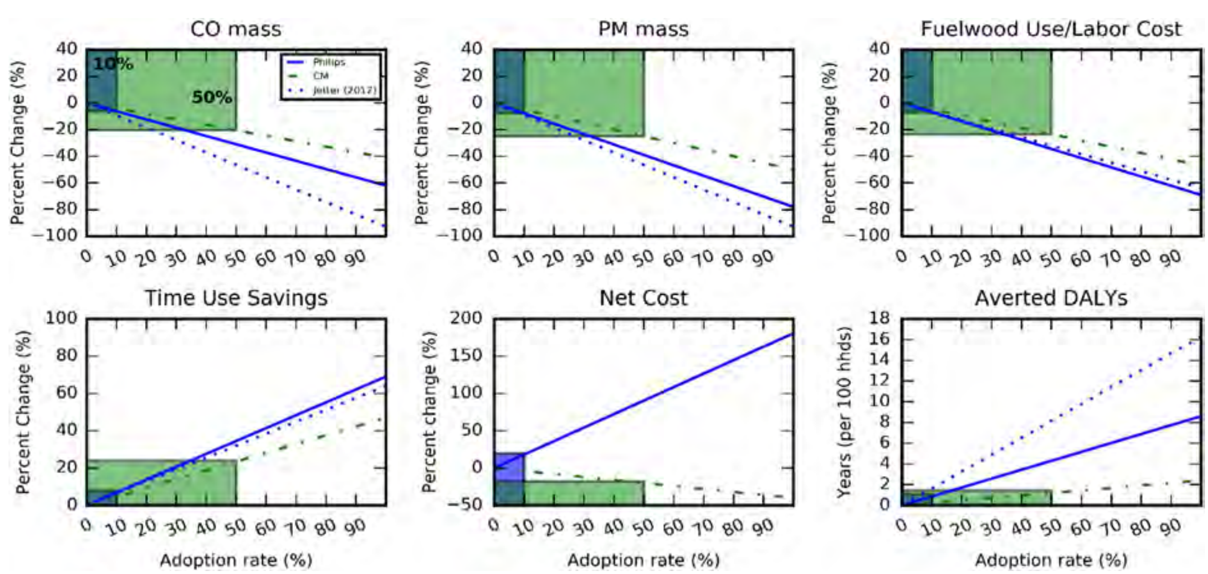

Fig. 6. Results from the hypothetical ICS intervention. All variables are presented in terms of percent change from the TSF baseline case, except for Averted DALYs which is in terms of years per 100 households. We provide lab-based reductions for the Philips stove measured by Jetter et al. (2012) for comparison.

increases as the number of targeted households increases. Finally, to estimate the capital cost required for each stove, we assume the Chitetezo Mbaula is valued at 2.5 USD and the Philips is valued at 90 USD per stove. The net cost for each ICS is then the sum of the labor and capital costs. For this analysis, we assume that the intervention households exclusively use the ICS. We also assume that this is a village-scale analysis and thus may not be linearly related to a country-wide analysis. Some caveats of this basic analysis include ignoring the potential time savings (or expenses) of cooking with the ICS, the wood processing time required to reduce fuelwood to a size appropriate for the Philips stove, and the life-cycle emissions resulting from ICS stove production (Wilson et al., 2016). Furthermore, we assume that the capital cost of the ICS must be paid up-front rather than over the lifetime of the stove, and we do not account for the maintenance costs nor additional fuel costs that may be required for each stove.

In Fig. 6, the averted DALYs are estimated using HAPIT (Pillarisetti et al., 2016), assuming that the baseline number of averted DALYs is 0. The mass emission reductions shown in the figure are found from this analysis (Pollutant and concentration metrics section). Fuelwood use, labor cost, and deforestation (not shown) have the same percent change as they are assumed to be linearly related to fuel efficiency. Fuelwood use (measured in kilograms or hectares) is reduced as fuel efficiency increases (Fig. 4). Labor cost, measured in USD, is proportionally related to the time spent collecting fuelwood, and therefore also is monotonically reduced at the same rate as fuelwood use. Time use savings are inversely related to fuelwood use; as fuel efficiency increases, less fuel is used and therefore less time is spent collecting fuelwood. The net cost is the sum of the labor cost and the capital cost of each stove.

We directly compare two intervention scenarios: 10% of the village switching to the Philips stove or 50% of the same village switching to the Chitetezo Mbaula. Although the Philips stove is considered to be a cleaner stove, the possible CO and $PM_{2.5}$ reductions resulting from 50% uptake of the CM are a factor of ~3.2 greater than the reductions resulting from 10% uptake of the Philips. Regarding fuelwood use, 50% uptake of the CM could reduce the baseline amount by 23.5%, while 10% Philips uptake would only result in a 6.9% reduction of baseline fuelwood use. In terms of forest condition, 50% CM uptake would reduce the deforestation rate to 1.84 ha per year per village while only to 2.30 ha per year per village for 10% Philips uptake, compared to 2.41 ha per year per village for the baseline case. In terms of potential health benefits, a 50% CM uptake for 100 households would result in roughly 1 averted DALYs whereas a 10% Philips uptake would not result in any averted DALYs. To frame the costs of intervention relative to Malawian household income, we use an estimated average household income of 384,409 MK per year or $929 USD (Jagger and Jumbe, 2016). The net cost to maintain the baseline use of the TSF ($3604 USD per 100 households) is equivalent to 3.9% of the village income. A 50% uptake of CM would require a net yearly cost of $2882 USD, 20% cheaper than the baseline case and 3.1% of the estimated village income. Alternatively, a 10% uptake of the Philips would require a net yearly cost of $4255 USD or 18% more expensive than baseline and 4.6% of the yearly village income. For comparison, a 50% uptake of the Philips would require a net yearly cost of $6860 USD or 7.4% of village income. While the CM intervention becomes cheaper to implement as the uptake fraction increases, the Philips intervention becomes more and more costly. The capital cost of the Philips stove always outweighs the labor cost reductions made from decreased fuelwood use.

Discussion

The air pollutant concentration reductions measured in this simulated kitchen, on-site, standardized protocol WBT test, are not as large as reductions suggested by laboratory measurements, despite having similar efficiency related metrics. There are a number of possible reasons for the differences in concentration reductions measured in our simulated kitchen, field-based study versus a laboratory-based study. For example, the stove operator for our study is from Malawi and conducted the tests based on their in-country cooking experience instead of laboratory-based stove operating experience. Another possible reason is that the in-country tests were conducted with equipment that did not give instantaneous feedback on emissions. In many laboratory settings, flue gas is monitored for temperature and concentrations of select emissions, such that the person conducting the tests has instantaneous feedback on stove operation. The uncharacterized ventilation in this study may best explain why the tests results were similar in efficiency to lab-based results, but did not achieve the same pollutant concentration reductions suggested by lab results. If we assume the ventilation conditions to be typical of a traditional household, these findings suggest that ICS will generally perform worse in a field-based setting where ventilation conditions are uncontrolled. This is one of the reasons why field-based ICS measurements do not show the ability to reduce emissions to levels that may have positive health benefits as suggested by lab based measurements (Muralidharan et al., 2015).

Field-based WBT and CCT tests may help policy makers reliably benchmark fuel use savings and other efficiency related metrics, without over-promising health benefits that are suggested from lab based tests. Nonetheless, it is important to keep in mind that WBT and CCT trials are not representative of actual cooking events therefore nor are their related emissions. Despite this, the relative simplicity of conducting field-based WBTs and CCTs, compared to conducting field-based measurements of real household cooking events, may make comparing stoves more accessible for policy-makers where resources are limited. Field-based WBTs or CCTs may provide policymakers with quick feedback on the relative benefits and drawbacks of various ICS on-site, particularly when there are limited resources, in sites planning to or currently implementing ICS intervention studies.

Given the design of the CM, health benefits are expected to be minimal based on the findings of this on-site WBT test, but fuel efficiency and time use savings are expected to increase, thus improving the overall quality of life for rural populations where expensive gasifying stoves and fuels such as liquefied petroleum gas (LPG) are not yet feasible to deploy. Although the CM (and other ICS) may not provide immediate health benefits as suggested from lab measurements, given the scale of the ICS intervention operation in Malawi (50% of homes are expected to have ICS by 2020 and an estimated 13.7% already have ICS), it could have a significant effect on ambient air quality in the community. This is supported by our hypothetical analysis that suggests there may be community-wide benefits when a larger number of households switches to ICS.

Expensive high-quality ICS, such as the Philips stove, are currently not feasible for many sites to implement on such a large scale. Furthermore, field-based measurements suggest health benefits may not actually be as significant as those suggested from lab-based measurements (Muralidharan et al., 2015; Roden et al., 2009; Wathore et al., 2017), therefore expending more money for higher quality, yet still underperforming stoves, may not be the best first step toward. Fuel efficiency, along with time savings, is cited by the MBAULA Network (2017b) to be one of the main advantages of ICS in Malawi, and our on-site findings and hypothetical analysis support this. Locally produced stoves have been shown to provide benefits to the local economy and community, e.g., the time savings allow children to spend more time in school instead of collecting firewood and the sale of the CM stoves provides income for programs that support orphanages, schools, and HIV patient care (MBAULA, 2016). Further, given that lack of demand is an obstacle for intervention, preparing communities and educating them on the benefits of ICS may make future interventions run more smoothly when more costly improvements are possible.

Conclusion

In this study, we evaluated the performance of three stoves (one traditional stove, two ICS) using the Water Boiling Test in a simulated kitchen setting, and from this data we estimated the potential benefit or cost of widespread adoption of either ICS. The benefits in using ICS compared to the traditional TSF are many; we highlight potential fuel use reductions of 47% and 69%, CO emissions reductions of 41% and 62%, and $PM_{2.5}$ reductions of 50% and 78% for the Chitetezo Mbaula and the Philips stove, respectively.

We directly compared two scenarios: (1) high adoption rate of an intermediate performance stove and (2) low adoption rate of a high performance stove on a village-level scale. Our findings suggest that widespread adoption of intermediate ICS is more likely to have a community-level impact than irregular and individual adoption of high quality cookstoves. Recent studies suggest results that support our findings. Johnson and Chiang (2015) found that lower performing stoves may have similar or greater benefits than higher performing stoves if the displacement of the baseline stove is higher. Wathore et al. (2017) promote the idea of clean cooking systems, given that factors such as high levels of ambient air pollution in a study region may limit the potential reductions achievable through individual ICS intervention. Furthermore, since neither stove demonstrated in-field performance capable of reducing air pollutant concentrations below levels that would have an immediate impact on health, we emphasize that the economical Chitetezo Mbaula is a preferable alternative to the more expensive Philips stove.

We note several important caveats to our hypothetical analysis. We assume that households are using only one type of stove in the household and using it exclusively – in our hypothetical village there is no stove stacking or parallel usage of the three-stone fire with either the *Chitetezo mbaula* or the Philips stove. We also assume no suppressed demand (i.e., people cook more because they have a more efficient technology). Finally, we have not addressed the issue of the lifespan of stoves. Chitetezo mbaula stoves generally have a 2 to 4-year lifespan. Philips stoves can last for much longer, though often require repair and servicing.

The adoption and sustained use of improved cookstoves is a widely promoted strategy for reducing emissions of climate forcing pollutants, human exposure to household air pollution, and fuel consumption. Constraints on the supply of improved or clean cooking technologies in many developing countries, in tandem with limited capacity for consumers to allocate a significant share of expenditures to modern fuels or clean cookstoves raises questions about the efficacy of certain types of stoves for successful interventions. We highlight the capability of field-based WBT and CCT tests to provide reliable fuel efficiency and concentration reductions information for various ICS in a resource-deficient setting where more expensive testing is not practical. It may be that not all three goals can be achieved from one intervention or one improved cookstove but we emphasize the importance of affordable and accessible improved cookstoves as an intermediate step.

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