A Comparison of Pollutant Emissions from a Traditional and an Improved Cookstove

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ABSTRACT

Traditional cookstoves are typically both fuel-inefficient and polluting. Emissions from such stoves have a profound impact on indoor air quality in homes around the world, causing major health problems. In response to Darfur's growing social and environmental issues, researchers developed the Berkeley-Darfur Stove (BDS), which is more fuel-efficient than the traditional three-stone fire (TSF). However, the reduced emissions benefit this improved stove could also provide is not yet known. This research, therefore, aimed to characterize the emissions profiles of both stoves, and to determine whether or not the BDS could reduce users' exposure to carbon monoxide (CO), fine particulate matter ($PM_{2.5}$), and black carbon (BC). I hypothesized that the greater fuel efficiency of the BDS would reduce the mass of these pollutant emitted compared to cooking with the TSF. Using a testing protocol that simulated local cooking practices, we conducted 10 tests for each stove. Pollutant concentrations were recorded at 1-second intervals (1-Hz), from which instantaneous and average fuel-based emission factors (g-pollutant/kg-wood burned) were calculated for each fire. I found considerable variability in pollutant emissions both within and between test fires for each stove. On average, emission factors were smaller for the BDS than the TSF for CO and $PM_{2.5}$, but not BC. After taking into account wood consumption, though, I found that the BDS emitted less total mass of all three hazardous pollutants. Thus, the BDS can potentially benefit users in terms of increased fuel efficiency and reduced adverse health effects.

KEYWORDS

Berkeley-Darfur Stove, three-stone fire, wood-burning cookstove, gas-phase pollutants, particulate-phase pollutants

INTRODUCTION

Simple stoves are used around the world for domestic cooking and household heating (Smith 2006a). Their presence in homes affects the daily lives of users in a multitude of ways, from the effort required to obtain fuel to the quality of air they breathe. Enhancing a cookstove's fuel efficiency reduces the amount of fuel required for cooking and heating and can lessen the amount of time spent gathering fuel, the cost of purchasing fuel, and the strain on the environment as a result of fuel consumption (Galitsky et al. 2006, Kammen 1995). Modified cookstoves with increased fuel efficiency can also improve indoor air quality if the amount of pollutants emitted by the combustion process is reduced (Jacobson and Kammen 2005). Exposure to particulate and gaseous pollutants emitted by cookstoves can lead to several health problems, particularly respiratory diseases that are frequently lethal (Smith 2006c). In addition to endangering health, the pollutants emitted can have regional and global impacts on climate that indirectly affect larger populations (Zhang et al. 2000, Jacobson 2002).

Currently, it is estimated that half of the global population uses coal or biomass fuels in traditional stoves, with around 60 percent of households burning wood (Kammen 1995, Smith 2008). Because women and children customarily spend a greater amount of time indoors with these basic cookstoves as compared to men, they are particularly susceptible to the health risks associated with exposure to several hazardous pollutants, including carbon monoxide and particulate matter (Smith 2008, Smith 2006a, Smith 2006c). Of striking concern, studies have shown that indoor concentrations of particulate matter from commonly used stoves can be between 10 to 100 times greater than the air quality standards set by the World Health Organization (Smith 2006a).

Exposure to such high levels of pollutants is associated with a range of health issues, including cataracts, tuberculosis, low birth weights, and cancer (Smith 2006a). The most established health effects of exposure to byproducts of biofuel combustion, though, are acute lower respiratory infections (ALRI) in children under the age of five and chronic obstructive pulmonary disease (COPD) in women (Dherani et al. 2008, Smith 2006b). Together, these diseases cause 1.6 million deaths annually around the world; women with COPD account for about 40 percent of these deaths and the remaining 60 percent occur mainly in the form of pneumonia in young children (Smith 2006c). Specifically, the particulate pollutants of wood smoke, including black carbonaceous soot, cause inflammation and are able to persist in high concentrations in the lungs once inhaled. Black carbon soot can also precipitate other health complications when absorbed into the bloodstream (Highwood and Kinnersley 2006). As such, besides poor water quality and inadequate sanitation, indoor air pollution from household fuels is considered the most influential environmental risk factor in the world (Ezzati et al. 2002).

As a result of both energy and health concerns, development and sustainability efforts have included a focus on improving cookstoves around the world. A current example can be seen in Darfur, where a fuelwood shortage in the war-torn region of Sudan has exacerbated stressed living conditions for the millions of displaced people. The areas surrounding the crowded refugee camps have been stripped of wood, so that women must travel increasingly longer distances in search of firewood, leaving the safety of the camps and risking violent attacks so as to secure fuel for their families (Amrose et al. 2008, LBNL 2006). In response to these daily hardships, the collaborative Darfur Stoves Project developed the Berkeley-Darfur Stove (BDS), which was designed with the dual goals of increased efficiency and cultural acceptance. Previous studies have found this improved stove to be significantly more fuel-efficient than the traditional three-stone-fire (TSF) (Darfur Stoves Project 2007). By requiring less fuelwood, the BDS thereby reduces the number of trips women must take to collect wood by 50 percent, appreciably decreasing their exposure to threats of attack (LBNL 2006).

Although the efficiency benefits of the BDS are known, studies have not yet considered the stove’s potential to reduce pollutant emissions. Given the significant health impacts of indoor air pollution from biomass fuel use, it is vital to understand the potential improvements to environmental health that the BDS can provide for users in Darfur. Moreover, characterizing pollutant emissions from improved cookstoves is generally important since there are similar projects underway in numerous regions throughout the developing world. As such, this study aimed to compare major hazardous pollutant emissions in the wood smoke from the newly designed BDS to those from the traditional TSF. Specifically, this research evaluated whether or not the BDS lowers users’ exposure to carbon monoxide (CO), fine particulate matter ($PM_{2.5}$), and black carbon (BC). $PM_{2.5}$ is particulate matter smaller than 2.5 micrometers in diameter, which is small enough to enter deep into the lungs when inhaled, causing the most significant respiratory health problems (Morawska and Zhang 2002). Most freshly emitted soot particles are found in this size fraction of PM (Highwood and Kinnersley 2006). BC is the black—or strongly light-absorbing—portion of $PM_{2.5}$. In addition to representing a major portion of the particulate mass, the emitted BC is transported in the atmosphere where it absorbs solar radiation and contributes to regional and global climate change (Ramanathan 2007).

I hypothesized that since the BDS is more fuel-efficient than the TSF, the BDS will emit less CO, $PM_{2.5}$, and BC. Alternatively, the mass of these pollutants emitted could be amplified by the improved combustion efficiency of the BDS. This research, which I conducted with scientists at Lawrence Berkeley National Laboratory (LBNL), characterizes and compares the emissions from both stoves. The data presented tests my hypothesis, and, moreover, augments the currently incomplete understanding of the potential for improving the health conditions of users of simple cookstoves.

METHODS

Study stoves

The traditional TSF (Fig. 1) is a fire in the center of a triangular configuration of three stones, upon which a pot is balanced. A ceramic base separated the fire from the metal platform where the tests were conducted because the metal surface might otherwise have drawn away heat and affected the efficiency of the TSF. The ceramic base was believed to better replicate a natural earthen surface encountered in Darfur, compared to the metal platform.

Figure 1. Traditional three-stone fire. Note the ceramic base that separates the fire from the metal platform.

The BDS (Fig. 2) is a metal, cylindrically shaped stove that fans out to support a pot. An opening on the side gives users access to a raised horizontal grate, upon which the fire is built. Testing with the BDS was conducted on the same metal platform as the TSF, but the BDS separated the fire from the metal surface, so the ceramic base was not needed.

Figure 2. Berkeley-Darfur Stove. Note that the fire is raised above the metal platform by a horizontal grate, which made the ceramic base unnecessary for conducting tests.

Testing facility

The cookstove testing facility at LBNL consisted of a fume hood above the burning platform, into which all emitted smoke was drawn (Fig. 3). The fume hood was connected to a duct system and mechanical blowers (i.e., fans). In addition to capturing the smoke, this duct system cooled the smoke by diluting it with room air. The diluted smoke was sampled by various air pollution monitoring instruments from a point along the duct system (point D in Fig. 3). The air to be sampled was first passed through a cyclone to remove particulate matter larger than $PM_{2.5}$. The sampling flow was then diverted into two branches: one for sampling gas-phase pollutants and the other for sampling particle-phase pollutants. The particle-phase pollutants were further diluted beyond the initial dilution of the fume hood so as to ensure that the monitoring instruments would not be overwhelmed by the high concentrations of $PM_{2.5}$ and BC (Fig. 4). In order to account for this dilution when comparing concentrations of particulate and gaseous pollutants, we calculated a dilution factor for each test, which ranged between 7.5 and 12.0. It was not necessary to do the same for the gas-phase pollutants because the intrinsic dilution resulting from the fume hood was sufficient for our gas analyzers.

Figure 3. The cookstove testing facility at LBNL. Note the (A) burning platform, (B) fume hood, (C) duct system, (D) sampling point, and (E) mechanical blowers.

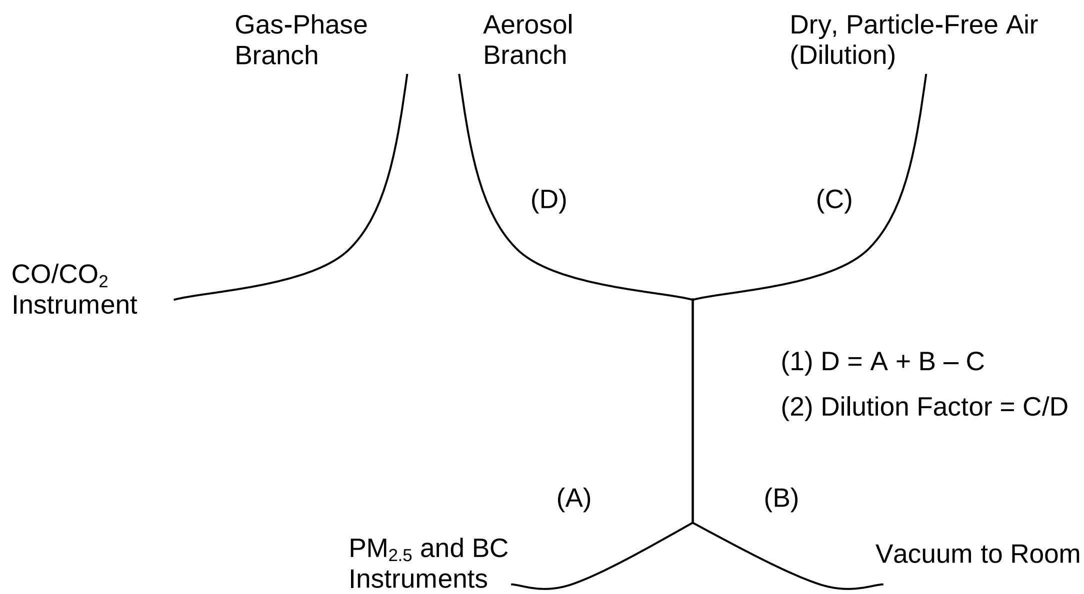


Figure 4. Schematic of sampling and dilution system flows. Note that A, B, C, and D represent the measured flow rates (liters per minute), while (1) and (2) give the equations used to determine the dilution factors that were applied to measured $PM_{2.5}$ and BC concentrations when comparing them to the concentrations of gas-phase pollutants.

Measurements and instruments

Pollutant concentrations were measured at 1-second intervals (1-Hz) over each test fire, from the moment the fire was lit until the test was complete. Concentrations of CO and CO_2 were measured with an infrared gas analyzer. BC concentrations were measured with an Aethalometer (Magee Scientific, Berkeley), which determined BC concentration by continuously analyzing changes in the amount of light transmitted through particles collected on a filter. $PM_{2.5}$ concentrations were measured with a DustTrak (TSI Inc., St. Paul), which estimated the concentration of $PM_{2.5}$ based on the amount of light scattering by the sampled particles. Since the relationship between particle light scattering and particle mass depends on the type of particles sampled, we calibrated the instrument's response specifically for wood smoke. We did this using a traditional filter-based method, in which $PM_{2.5}$ was collected on several filters throughout each test fire. By finding the mass differential of these filters from before and after a test, we determined the actual particulate concentrations. Through a comparison of these concentrations with those recorded by the DustTrak, we calculated a calibration factor that was then incorporated in our analysis of $PM_{2.5}$ measurements.

Testing procedure

Our stove tests followed a cooking protocol known as the Assida test, which was derived from field observations and simulated cooking methods practiced by refugees in Darfur (Galitsky et al. 2005). During this Assida test, 2.5 liters of water were brought to a boil (100 °C), and then were maintained at a temperature between 94-100 °C for 15 minutes. We used mixed softwoods as fuel with an average size of approximately 15 centimeters long, 2 centimeters wide, and 2 centimeters tall. Fires were lit using slivers of wood and two half-sheets of crumpled newspaper, and then maintained with an average of 5 pieces of wood in the stove at any time. As a test progressed, notes were recorded about how the fire was managed, including the moisture content and mass of each piece of wood added, as well as the time at which it was placed in the fire. In order to keep the fire from going out, the tester could shift the wood or use a bellows to blow on the fire. These actions were also recorded so as to correlate these events with variations in emissions. For this study, we conducted 10 Assida tests for each stove type, for a total of 20 test fires. All 10 tests for each stove design included measurements of CO, CO_2, and BC concentrations, while 5 tests for each type included $PM_{2.5}$ measurements.

Data analysis

We plotted the continuously measured pollutant concentrations from each burn to show the variability within and between fires. I also calculated the 1-Hz fuel-based pollutant emission factors for each cooking event (Eq.1A-C), which relates the amount of pollutant emitted per amount of fuel used (g-pollutant/kg-wood burned).

(A)

$$\mathrm{EF}_{\mathrm{CO}} = \left[\frac{Y_{CO}}{Y_{CO} + \Delta Y_{CO_2}}\right]\left[\frac{MW_{CO}}{MW_C}\right] w_c$$

(B)

$$\mathrm{EF}_{\mathrm{PM}_{2.5}} = \left[\frac{X_{\mathrm{PM}_{2.5}}}{Y_{CO} + \Delta Y_{CO_2}}\right]\left[\frac{L}{0.0409\ \mathrm{mol}}\right]\left[\frac{w_c}{MW_C}\right]$$

(C)

$$\mathrm{EF}_{\mathrm{BC}} = \left[\frac{X_{\mathrm{BC}}}{Y_{CO} + \Delta Y_{CO_2}}\right]\left[\frac{\mathrm{L}}{0.0409\ \mathrm{mol}}\right]\left[\frac{w_c}{MW_C}\right]$$

Equation 1. Fuel-based emission factors (EF) for CO, $PM_{2.5}$, and BC. In these equations, Y_i is the mole fraction of species *i* in the air, MW_i is the molecular weight of *i*, MW_C is the molecular weight of carbon, X_i is the mass concentration of species *i*, and w_c is the weight fraction of carbon in the fuel wood.

These calculations are based on the method of carbon mass balance, comparing carbon in the air to carbon emitted during combustion. I assumed that the sum of the mole fractions of CO and above-background CO_2 comprised all the carbon emissions from the fire, and that the weight fraction of carbon in the fuelwood was 0.5 (Roden and Bond 2006).

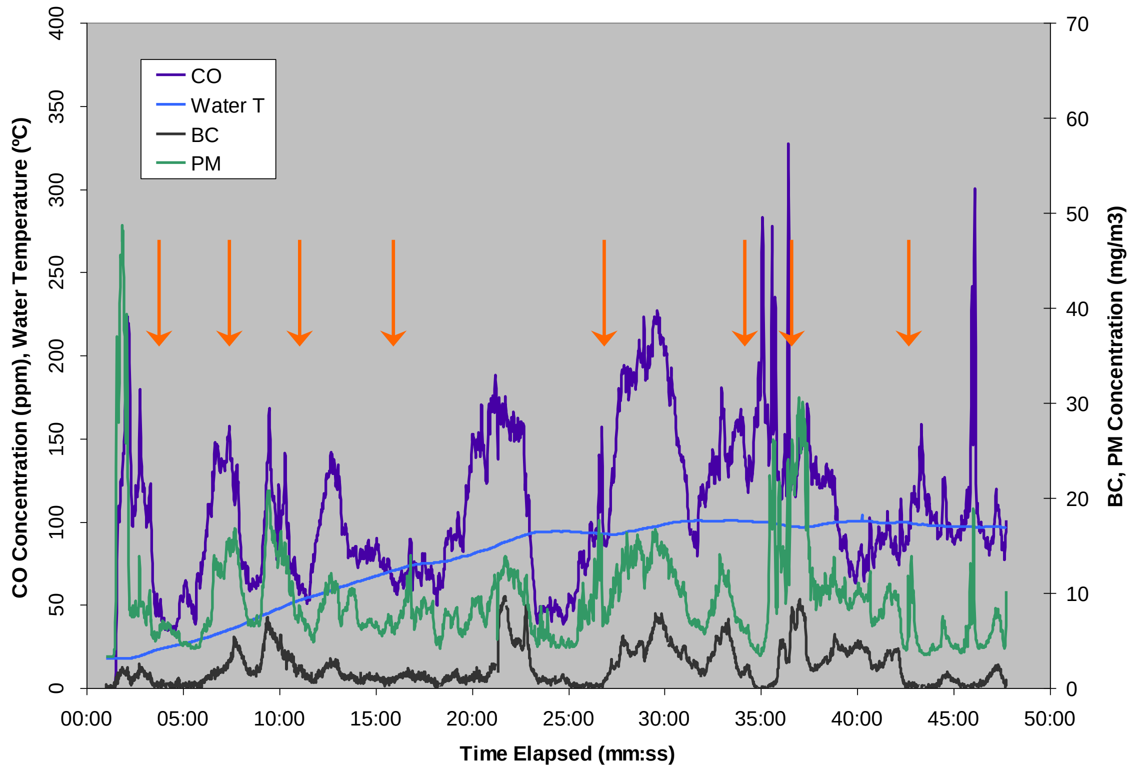
I then performed several analyses to compare the two stoves. First, I found the frequency distributions for the three pollutants' 1-Hz emission factors. Second, I determined the mean emission factors for each test, which were then averaged over all tests conducted (10 for CO and BC, 5 for $PM_{2.5}$) to derive a single average value of each pollutant emission factor for both stoves. Finally, I multiplied the mean emission factors (g-pollutant/kg-wood) and the wood consumption (kg-wood) from each test to calculate the mass (g-pollutant) of CO, $PM_{2.5}$, and BC emitted. These three analyses enabled an evaluation of emissions in terms of both fuel mass and as a total mass per cooking event.

RESULTS

Variability of emissions

Time series of pollutant concentrations recorded during two tests on the same day with the TSF and BDS are presented in Fig. 5A and B. As shown, pollutant concentrations were highly variable throughout each fire and different for the two stove designs. Over all 10 tests with the TSF, the concentration of CO_2 varied between the average background level of 510 ppm to as high as 11,000 ppm, while CO varied between 0 and 1300 ppm. The concentration of $PM_{2.5}$ had a range between 0 and 157 mg/m^3, and as much as 73 mg/m^3 of BC was emitted. Over all of the test fires with the TSF, we collected an average of 3590 ppm CO_2, 169 ppm CO, 19.4 mg/m^3 $PM_{2.5}$, and 1.1 mg/m^3 BC. Over all 10 tests with the BDS, on the other hand, the concentration of CO_2 varied between ambient levels and 15,800 ppm, while CO varied between 0 and 1590 ppm. $PM_{2.5}$ concentrations ranged between 0 and 405 mg/m^3, whereas BC emissions were as high as 119 mg/m^3. Over all of the test fires with the BDS, we collected an average of 4480 ppm CO_2, 171 ppm CO, 34.4 mg/m^3 $PM_{2.5}$, and 1.6 mg/m^3 BC. Thus, the range, maximum values, and average values of pollutant concentrations were larger for the BDS than for the TSF.

(A)



(B)

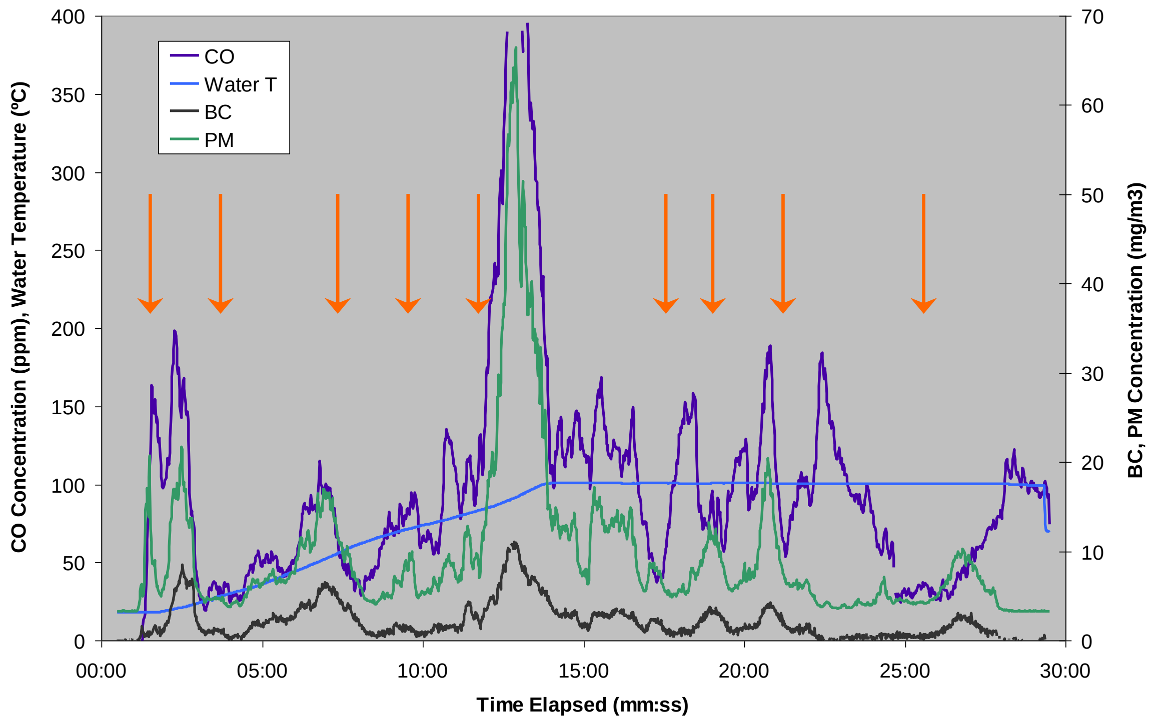
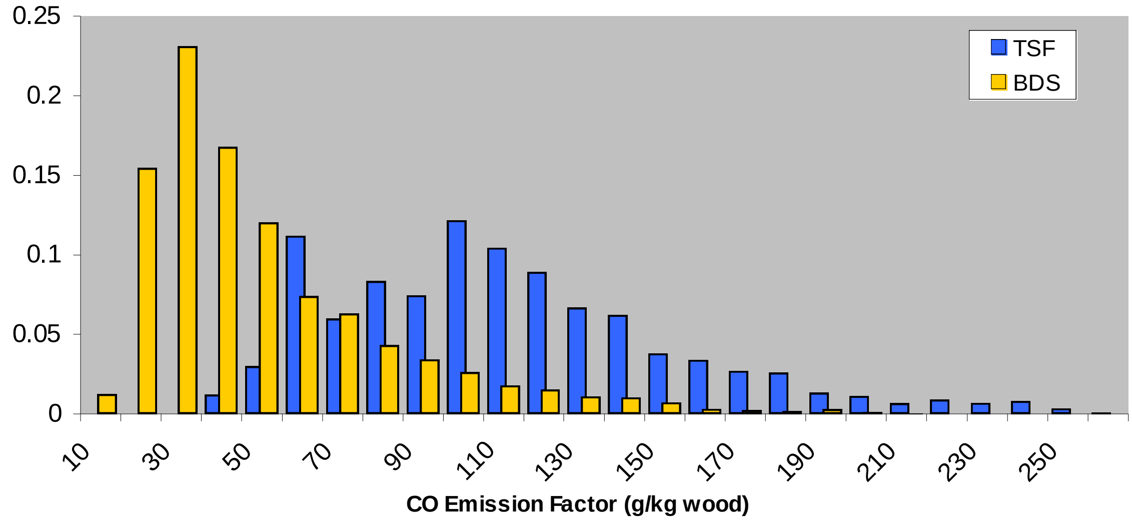


Figure 5. 1-Hz measurements of CO, $PM_{2.5}$, BC, and water temperature. The emission profiles for tests with the TSF (A) and BDS (B) conducted on the same day under identical conditions. The orange arrows indicate times when wood was added.

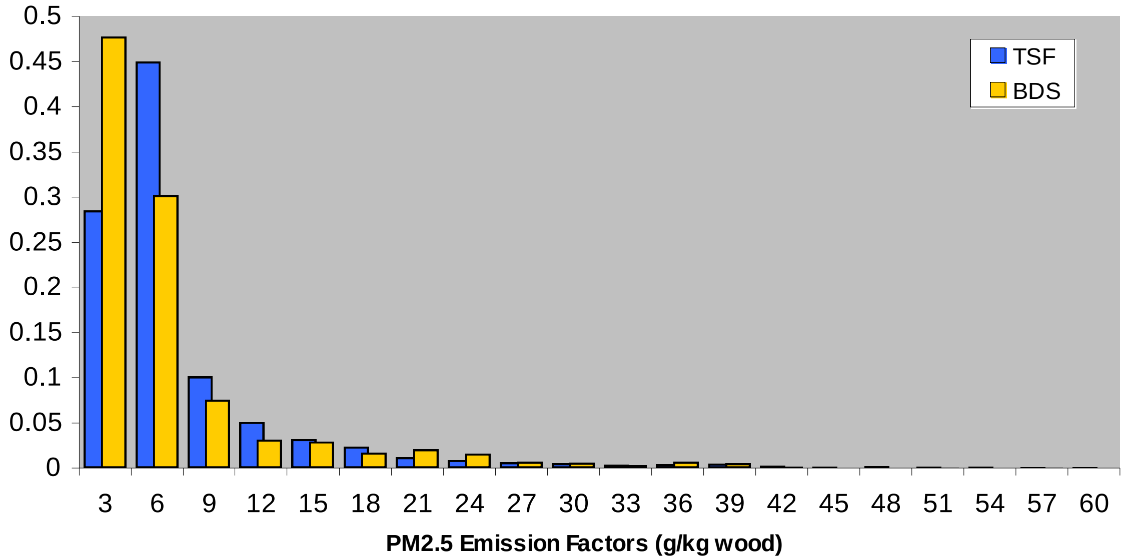
1-Hz emission factors

Emission factors for CO, $PM_{2.5}$, and BC were calculated from pollutant concentrations with a time resolution of 1-Hz. The frequency distributions of all of these 1-Hz emission factors are right-skewed for all three pollutants and for both stoves (Fig. 6A-C). For the TSF, the average values were 71.2 g CO/kg wood, 6.6 g $PM_{2.5}$/kg wood, and 1.0 g BC/kg of wood. The average values for the BDS, on the other hand, were 45.7 g CO/kg wood, 5.8 g $PM_{2.5}$/kg wood, and 1.1 g BC/kg wood.

(A)



(B)



(C)

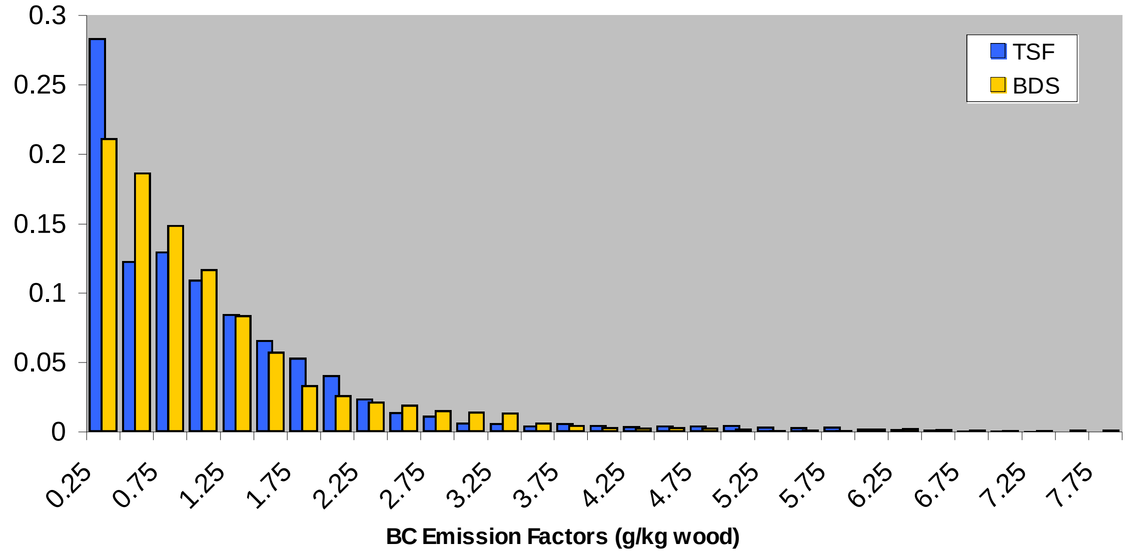


Figure 6. Distributions of 1-Hz emission factors over all TSF and BDS tests. Note that the distributions are right-skewed for (A) CO, (B) $PM_{2.5}$, and (C) BC for both stove types.

Average emission factors and cumulative emissions

The mean emission factors for each test fire were calculated from the continuous data. These were averaged over all tests to calculate the average emission factor for each stove design (Table 1). Relative to the mass of fuelwood burned, the BDS emitted 30 percent less CO and 7 percent less $PM_{2.5}$, but 9 percent more BC than the TSF (Table 1). However, compared to the BDS, the TSF required an average of 36 percent more fuelwood and took an average of 35 percent more time to complete a test. When the amount of wood consumed during each test was taken into account, the BDS emitted 55 percent less CO, 39 percent less $PM_{2.5}$, and 31 percent less BC (Table 2).

Table 1. Average CO, $PM_{2.5}$, and BC emission factors for each stove. These average values (g-pollutant/kg-wood burned) and their standard deviations were determined by averaging the mean 1-Hz emission factors from each test.

Stove	EF_{CO}	EF_{PM}	EF_{BC}
TSF	67.2 ± 19.2	6.2 ± 2.0	1.0 ± 0.6
BDS	46.9 ± 22.1	5.8 ± 2.5	1.1 ± 0.6

Table 2. Cumulative emissions of CO, $PM_{2.5}$, and BC from each test for both stoves. These total values (g-pollutant) were calculated from the mean 1-Hz emission factors (g-pollutant/kg-wood) and dry weight of consumed wood (kg-wood) from each test. The average masses emitted for each stove and their standard deviations were then derived by averaging these mean values from each test.

Stove	Test	Wood Used (kg)	CO (g)	$PM_{2.5}$ (g)	BC (g)
TSF	1	0.8114	86.0	-	0.7
	2	0.5997	45.9	-	0.1
	3	0.6375	46.7	-	0.1
	4	0.4474	14.2	-	0.9
	5	0.7613	44.4	7.4	1.3
	6	0.5930	39.5	3.1	0.6
	7	0.5885	44.5	2.6	0.6
	8	0.7863	52.7	4.6	1.0
	9	0.5018	33.1	-	0.7
	10	0.5384	27.4	3.2	0.5
	Average:		**43.4 ± 18.7**	**4.2 ± 1.9**	**0.6 ± 0.4**
BDS	1	0.4235	21.9	-	0.4
	2	0.3277	10.3	-	0.1
	3	0.4123	13.0	-	0.3
	4	0.3773	11.0	-	0.6
	5	0.3999	18.9	3.0	0.7
	6	0.3682	16.3	1.4	0.3
	7	0.4591	34.1	2.1	0.4
	8	0.5085	48.2	4.7	0.8
	9	0.3580	9.1	-	0.7
	10	0.3559	14.0	1.5	0.3
	Average:		**19.7 ± 12.4**	**2.5 ± 1.4**	**0.4 ± 0.2**

DISCUSSION

Pollutant emissions from traditional cookstoves negatively affect the health of billions of people throughout the developing world. Enhanced stove designs, however, can offer not only increased fuel-efficiency, but also reduced pollutant emissions. While the efficiency benefits of the improved BDS as compared to a traditional TSF have previously been studied, there has yet to be any examination of the impact on emissions. As such, this study aimed to describe the emission profiles for the TSF and BDS, as well as to determine whether or not the more fuel-efficient BDS would reduce users' exposure to carbon monoxide (CO), fine particulate matter ($PM_{2.5}$), and black carbon (BC). Our results showed a large amount of variability for both stoves. Ultimately, the improved efficiency of the BDS reduced the overall amount of fuelwood burned during cooking events, which decreased the total amount of hazardous pollutants emitted.

Variability of emissions

We found considerable variability of emissions within and between each test for both stove types. There tended to be greater variability within a test with a TSF, as the fire was more unpredictable and required the rapid addition of several pieces of wood as the fire repeatedly began to quickly die. This cycle is reflected in Fig. 5A, where there are repeating peaks and then drops in the emissions of all three pollutants. Tests conducted with the BDS, on the other hand, were steadier, as indicated by the relatively constant temperature once the water reached its boiling point (Fig. 5B).

Generally, these differences were caused by fluctuations in the combustion process as wood was added to the stove, as embers were blown on to maintain the fire, and as the woodpile shifted. By noting these external and internal changes, we were able to associate these events with various peaks and plateaus in the emission profiles, thereby identifying which parts of the cooking process are most important in terms of emissions. The bulk of emissions tended to occur when the fire was lit, which can be attributed mostly to the newspaper used to start the fire. After that initial spike, as a newly introduced piece of wood caught fire, there was soon after a sudden increase in CO, $PM_{2.5}$, and BC concentrations, an effect also found in previous work (Roden et al 2006). This relationship is clearly seen in Fig. 5B, where several pieces of wood were added within a short period of time and created a significant peak in emissions. Conversely, we found that periods of smoldering, as when the fire was dying and only embers remained, were distinguished with modest particulate and soot levels and elevated CO concentrations. This, too, is found in Fig. 5B during the last three minutes of the BDS test. Importantly, we noticed that the fires are not uniform within a stove. At any one time, there could be both an area where flames emitted large amounts of particulates and soot and a region of embers that contributed to increasingly high levels of CO. Since the TSF did not efficiently consume wood, a growing bed of coals would emit gradually more CO as the test progressed.

Previous research has discovered a wide range of concentrations for the emissions from wood-burning cookstoves (Smith et al. 1993, Naeher et al. 2001, Oanh et al. 2005). This variability within the literature supports our conclusion that different stove designs emit varying levels of pollutants. This comparison thereby encourages the need for stove-specific emissions studies like this one, given that there is no ubiquitous cookstove emissions profile.

1-Hz emission factors

The right-skewed distributions of emission factors for CO, $PM_{2.5}$, and BC for both stoves suggest that some aspects of a cooking event are more significant for the release of these pollutants than others. Because the emission of CO, particulates, and soot is not normally distributed, half of the cumulative mass of each is emitted during a small portion of the test fire. As a result, a few major emission events contribute the most to a cooking event's total emissions. While the distributions for $PM_{2.5}$ and BC are relatively similar in shape and spread for both stoves, the TSF distribution of CO emission factors is shifted towards values higher in magnitude. This reflects the trend of a coal bed emitting slightly more CO for the traditional fire. If those moments within a cooking event that skew these distributions can be prevented, one's personal exposure to these hazardous pollutant could be drastically reduced by cutting out the most substantial contributions to total emissions.

Average emission factors and cumulative emissions

The range of emission factors for CO, fine particulates, and soot (Table 1) follow those found in previous studies of wood-burning cookstoves (Habib et al. 2008, Roden et al. 2006, Zhang et al. 2000). The average emission factors that I calculated for each stove, however, suggest that a differential exists in emission benefits between the TSF and the BDS. While the BDS emits less CO and $PM_{2.5}$ per amount of fuel consumed than the TSF, it emits slightly more BC. While this result is unexpected, it is not unprecedented. In particular, Ahuja et al. (1987) found that these goals are mutually dependent, so that maximal efficiency and minimal emissions are not concurrently achievable. It is likely that since the BDS better isolates the thermal energy of the fire, as opposed to allowing heat to escape to the surrounding environment like the TSF does, its flame emits more BC than that of the TSF. Nonetheless, the range of values around the three averages for each stove overlap with one another. While these averages indicate that it is most likely that the BDS will emit less CO and $PM_{2.5}$ but more BC than the TSF, the coinciding ranges mean that it is possible for the results to be the reverse at times (i.e., the TSF could emit more BC than the BDS). As the Ahuja et al. (1987) study also determined, even though greater efficiency can be correlated with larger emission factors (g-pollutant/kg-wood burned), overall emissions per cooking event can be reduced by a more efficient stove because it consumes less wood. The average cumulative emissions (Table 2) support this conclusion, with the BDS emitting less total CO, $PM_{2.5}$, and BC than the TSF.

Methodological issues and future research

User variability can have a significant influence on the performance of a stove both in terms of efficiency and emissions (MacCarty et al. 2008, Roden et al. 2009). In order to address this confounding issue, I conducted every test fire in this study. Nevertheless, the manner in which a stove is used and a fire is maintained by either a researcher or a real-life user could skew results in either direction. These results should not be considered as absolute, therefore, but as an indication of the potential improvement that the BDS can offer over the TSF in terms of fuel consumption and pollutant exposure.

A related obstacle for any cookstove project is the matter of laboratory versus field settings. The experimental setup and testing protocols that simulate cooking practices under the controlled and replicable conditions of the laboratory may not be realistic of the real world application of a stove. For instance, a recent study that compared cookstove performance under each setting found that field measurements of particulate emissions of an authentic cooking event were much greater than those found by imitating cooking in the laboratory (Roden et al. 2009). Such differences have been linked to the need for scientific reproducibility, in which laboratory testing uses standardized fuelwood and requires constantly and methodically managed fires. In reality, however, wood is more variable and users' must divide their attention between tending fires and other household needs (Ibid). In conjunction with the user variability problem, this quandary can thus limit the strength of laboratory-based results and conclusions about the efficiency and emissions benefits of an improved cookstove. In order to address this significant methodological issue, future research must conduct tests in the field in addition to continued testing in the laboratory. By comparing results found under controlled conditions by researchers to observational studies of actual cooking by users in Darfur, it would be possible to more reasonably and realistically quantify the difference between the TSF and BDS for both emissions and efficiency. Such future research should not be isolated to this specific study, however, but should be applied to every comparison of traditional and improved cookstoves.

Implications of this study

The reduction in total emission of CO, particulates, and soot by the BDS suggests that this more fuel-efficient stove would also improve the indoor environment of its users. By reducing the cumulative mass emitted for all three pollutants, the BDS would considerably improve indoor air quality for the refugees in Darfur, which would help alleviate health problems that are associated with exposure to wood smoke. The results of a previous study of Guatemalan improved cookstoves supports this conclusion, showing that those stoves reduced indoor air pollution and hence significantly reduced the occurrence of chronic respiratory symptoms (Smith-Siversten et al. 2009). Although there can be a tradeoff between efficiency and emissions, the greater efficiency of the BDS overcomes the potential differential of emission factors, thereby distinguishing it as the more beneficial cookstove for the people of Darfur than the traditional TSF.

In addition to the efficiency and health benefits of the BDS, this improved stove can also emit less CO_2 and black carbon soot that affects regional and global climate. The collective contribution of simple and improved cookstoves to the emission of greenhouse gases to the atmosphere can significantly impact climate (Zhang et al. 2000). Earlier studies have found that the CO_2-equivalent global warming potential of non-CO_2 emissions could potentially be as significant as that of CO_2 alone (Smith et al. 1993). As such, recent research has worked to quantify the carbon savings from improved biomass cookstove projects so that such stoves can be used as a carbon abatement mechanism (Johnson et al. 2009). Consequently, stoves could transition from not only being a technological solution to fuelwood scarcity and respiratory health issues, but also a policy option for carbon trading schemes. Soot emissions are significant for climate science as well, with research indicating that BC could be the second greatest contributor to climate change, behind CO_2 (Jacobson 2002). Moreover, the rapid atmospheric transport of BC means that the impacts of stove emissions are not constrained to the local climate, but affect surface albedos and solar radiation absorption worldwide (Ramanathan 2007).

Therefore, by reducing the total amount of greenhouse gases and soot emitted, improved stoves can become a noteworthy policy tool for mitigating climate change.

In conclusion, this study has shown how the emission profiles differ between the traditional TSF and improved BDS. The BDS has the potential to benefit environmental health conditions by reducing indoor air pollution. This appropriate technology can, therefore, not only improve the living conditions for the refugees of Darfur by reducing the need for fuelwood collection trips, but also by lessening the severity of respiratory health problems.

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