IN-HOME EMISSIONS OF GREENHOUSE POLLUTANTS FROM ROCKET AND TRADITIONAL BIOMASS COOKING STOVES IN UGANDA

APRIL 2011

This publication was produced for review by the United States Agency for International Development. It was prepared by Berkeley Air Monitoring Group.

IN-HOME EMISSIONS OF GREENHOUSE POLLUTANTS FROM ROCKET AND TRADITIONAL BIOMASS COOKING STOVES IN UGANDA

BERKELEY AIR MONITORING GROUP

EXECUTIVE SUMMARY

STUDY OVERVIEW

In July 2010, Berkeley Air Monitoring Group, in collaboration with Columbia University's Earth Institute and the University of Illinois at Urbana-Champaign, collected cookstove emissions data in Ruhiira, Uganda, one of the Millennium Village project sites. This project was a highly collaborative effort made possible by funding from the United States Agency for International Development, with the goal of better understanding the relationship between climate change and improved stoves. Climate change is a comparatively new consideration for stove dissemination programs, which to date have focused largely on natural resource and health outcomes. The resulting data provide the first field assessment in Africa of a stove intervention's impact on greenhouse gas and health damaging pollutant emissions, which are defined as the quantity or rate of pollutants emitted directly from the stove as a result of combusting fuels. It is important to distinguish this type of field-based emissions study from health-focused assessments of household air pollution concentrations, which previously have been conducted in Africa, albeit not extensively.

A total of 35 cooking events were sampled in 10 homes. Each home was sampled when the cook was using a traditional openfire (hereafter referred to as a traditional stove) and again when she was using a StoveTec rocket stove to allow direct comparison of samples. Cooking events were uncontrolled, with the participants asked to cook their regular meals and use their normal fuelwood and fire tending practices. The StoveTec rocket stove is a well characterized, mass-manufactured stove that was disseminated in this Millennium Village 5-12 months prior to the emissions study.

Fuel consumption was measured for each cooking event, with the number of people and foods prepared recorded. Emissions were measured directly above the stove and analyzed for carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), total non-methane hydrocarbons (TNMHCs), and particulate matter ($PM_{4.0}$). PM samples were analyzed for the relative compositions of black carbon (BC) and organic matter (OM). Estimates for BC emissions are of special interest, as reduction of global BC emissions is being promoted by some parties as a potentially cost-effective and immediate means to mitigate climate change. However, the development of rocket-style design principles and the StoveTec pre-date the emergence of BC as a potential policy driver, and the stove was not designed with BC reduction as an explicit objective.

While the results from this study help fill a critical data gap, it is important to interpret them with caution. The sample sizes here were relatively small (but consistent with other stove assessments)[1], and were collected in one cluster of villages in southwestern Uganda. Thus,

[1] Johnson et al. (2008) reported in-home GHG emissions for a cross-sectional study of 8 traditional and 13 improved stove users in Mexico. Roden et al. (2009) reported in-home emissions of carbon monoxide and particulate matter of 13 traditional and 19 improved stoves in Honduras. Laboratory based evaluations of GHG emissions from stoves have typically relied on a sample size of three for each stove/fuel combination (Smith et al. 2000; Zhang et al. 2000; McCarty et al. 2008; Bhattacharya et al. 2002).

these results should not be assumed as a definitive indicator of the StoveTec's performance, nor should they be directly extrapolated to other areas where fuel types, stove types, cooking practices, or other factors that impact stove emissions may differ substantively. Moreover, there is still much uncertainty regarding the relative climate forcing impact of BC.

SPECIFIC KEY RESULTS AND CONCLUSIONS

- **Fuel efficiency:** The StoveTec used less wood in comparison to the traditional stove as more energy released during the combustion of the fuel was transferred into useful cooking energy. Specifically, the StoveTec demonstrated a significant fuel savings of 42% on a per person-meal basis, which was in-line with previous estimates of 38-54% fuel savings reported for the StoveTec. This suggests that the StoveTec's fuel consumption performance is robust. A kitchen performance test would be a valuable follow-up to further verify the fuel savings results.

- **Combustion efficiency:** Although the StoveTec was more efficient in terms of fuel consumption, the combustion process was comparable to the traditional stove, with both stoves having combustion efficiencies of approximately 90-91%. In other words, for every kilogram of wood that was combusted, similar quantities of CO_2, CO, CH_4, TNMHCs, and PM were emitted. Thus the StoveTec emitted less pollutants overall, but this was due to the StoveTec using less fuel per person-meal, not because the fuel burned more cleanly.

- **Health-related emissions:** Exposure to PM has been shown to have negative health impacts, contributing to such diseases as pneumonia and chronic obstructive pulmonary disease (COPD). $PM_{4.0}$ emissions from the StoveTec were 31% higher per kilogram of fuel and 26% lower per person-meal than the traditional stove, although these differences were not statistically significant. The lower emissions per person-meal suggest the stove might have the potential to reduce household and regional particulate pollution, although more study would be required to evaluate this possibility and its corresponding health impacts. Emissions of CO, which has both acute and chronic health impacts, were similar per kg of fuel, but 42% less per meal for the StoveTec ($p=0.04$) compared to the traditional stove.

- **Climate impact from greenhouse gases:** The combined climate impact of the measured gases sanctioned under the Kyoto Protocol (CO_2 and CH_4), expressed as CO_2-equivalent (CO_2e), was that the StoveTec had an estimated 41% lower CO_2e emissions per person-meal than the traditional stove ($p=0.02$)[2]. Counting all the measured gases (CO_2, CO, CH_4, and TNMHC) also resulted in a 42% reduction in CO_2e ($p=0.02$), although the magnitude of the difference was slightly larger as the CO_2e savings associated with CO and TNMHC were also included.

- **Climate impact from particulate matter:** The StoveTec had more than twice the fractional BC content in its PM emissions (15.5%) compared to the traditional stove (7.2%) ($p<0.01$). The net impact of the StoveTec's PM emissions was estimated to be more climate-warming than that of the traditional stoves. While this result cannot be generalized to other improved

[2] These reductions assume that the fuel was harvested non-renewably, and therefore CO_2 is included in the estimate of CO_2e. If the fuel was harvested sustainably or semi-sustainably, both stoves' CO_2e emissions would be lower than reported here.

stoves (or even to the StoveTec without further study), it demonstrates that improved stoves should not be universally assumed to reduce BC emissions.

- **Emissions testing:** More field-based emissions studies are needed to better characterize the emissions from stoves, especially particulate emissions and their impact on overall CO_2e. While measurement of every stove program across Africa and/or every improved stove model would be difficult, targeting major improved stove dissemination efforts could provide a global database of emissions factors for common stove/fuel combinations in the main relevant geographies. More comprehensive field and laboratory emission assessments of a variety of stove/fuel combinations would also help identify the most promising and/or effective technologies for mitigation of climate-warming and health-damaging pollutant emissions.
- **Key parameters for reducing stove emissions:** Stoves that substantially decrease fuel consumption as well as increase combustion efficiency likely will provide the greatest health and climate benefits. It is therefore important to highlight combustion efficiency during a stove's design stage to ensure it achieves maximum efficiencies during normal daily stove use. Assessing emissions from stoves with advanced technologies (e.g. forced air, gasification, liquid fuels, etc.) would also be useful in order to test the hypothesis that these stoves could provide large reductions in CO_2e and health damaging pollutants.

AUTHORS AND ACKNOWLEDGEMENTS

REPORT AUTHORS:

Berkeley Air Monitoring Group
Michael Johnson, Nicholas Lam, David Pennise, Dana Charron

University of Illinois, Champaign-Urbana
Tami Bond

Columbia University
Vijay Modi

Center for Integrated Research and Community Development Uganda
Joseph Arineitwe Ndemere

FIELD TEAM:

Berkeley Air Monitoring Group
Nicholas Lam

University of Illinois, Champaign-Urbana
Justin Ellis

Center for Integrated Research and Community Development Uganda
Joseph Arineitwe Ndemere, Godfrey Isabirye, Fred Muhwezi

Alexander Torres, Erin Milner, and Nhan Duong assisted with sample analysis and data management. Kate Kennedy Freemen, Michael Turner, and David Siriri helped facilitate participant recruitment and field logistics.

We would like to thank the following for reviewing and providing valuable feedback on this report:

United States Agency for International Development
Pamela Baldinger, Jennifer Leisch

University of California, Berkeley
Professor Kirk R. Smith

United States Environmental Protection Agency
Pete DeCarlo, Brenda Doroski, Jim Jetter, John Mitchell, Jacob Moss, Carlos Nunez, Erika Sasser

We also thank the participating women and families, who graciously opened their homes for this study.

ABBREVIATIONS AND ACRONYMS

BC	black carbon
CCT	controlled cooking test
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
EC	elemental carbon
g	gram
GHG	greenhouse gas
GWP	global warming potential
kg	kilogram
KPT	Kitchen Performance Test
N	sample size
NCE	nominal combustion efficiency
NO	nitrogen oxide
OC	organic carbon
OM	organic matter
PICs	products of incomplete combustion
PM	particulate matter
$PM_{4.0}$	particulate matter less than 4.0 microns in diameter
SA	standard adult
TNMHC	total non-methane hydrocarbons
USAID	United States Agency for International Development
WBT	water boiling test

TABLE OF CONTENTS

1.0 INTRODUCTION

The goal of this project was to make a rapid assessment of greenhouse gases (GHGs) and particulate matter (PM)−including black carbon (BC)−emitted from a traditional and an improved biomass cookstove in Africa, in order to better understand the relationship between household energy practices and climate change. This project was a collaborative effort led by Berkeley Air Monitoring Group, involving Columbia University's Earth Institute and the University of Illinois at Urbana-Champaign. Cookstove emissions were collected in Ruhiira, Uganda, one of the Millennium Village project sites. This project was made possible by funding from the United States Agency for International Development (USAID).

The resulting data provide the first field assessment in Africa of a stove intervention's impact on a comprehensive set of GHG and PM emissions. It is important to distinguish this type of emissions study from health-focused assessments of household air pollution, which have been conducted previously in Africa (Ezzati et al. 2000; Pennise et al. 2009). Air pollution studies evaluate the concentrations of particulate matter, carbon monoxide, or other pollutants in a kitchen, room, or other area where people are exposed. Emissions studies assess the quantity or rate of pollutants directly emitted from the stove.

The contributions from residential cookstoves to global GHG emissions are not well known, even though nearly half the world's population still relies on solid fuels for their primary energy needs (Rehfuess et al. 2006). Solid fuel use is most prevalent in developing regions, with three-quarters of the population in South Asia and sub-Saharan Africa using biomass (WHO 2002). Combustion of solid fuels in traditional cookstoves and other small-scale devices is characterized by relatively poor energy efficiencies, resulting in high emissions of pollutants relative to the amount of energy that is actually used (Smith et al. 2000).

Emissions data from household stoves collected during normal daily cooking are generally sparse, and data from Africa are especially limited. Bertschi et al. (2003) reported a broad range of gaseous emission factors (including CO_2, CO, and CH_4) in Zambia, but from only three open-fire "traditional stoves." Kituyi et al. (2001) and Ludwig et al. (2003) assessed only CO_2, CO, and NO in Kenya, Zimbabwe, and Nigeria. None of these studies evaluated the impact of an improved stove on GHG emissions, nor did they assess particulate matter or black carbon emissions.

Accurate estimation of emissions from cookstoves is critical for evaluating the potential climate benefits of improved stoves, as well as modeling atmospheric GHG concentrations (Kasibhatla et al. 2002; Tan et al. 2004). The majority of emissions data that does exist, however, has been derived from water boiling tests conducted in a laboratory setting (Smith et al. 2000; Zhang et al. 2000; Venkataraman and Rao 2001; Bhattacharya et al. 2002), which are important for providing stove design feedback, but have been demonstrated to not reflect emissions measured during normal daily stove use (Johnson et al. 2008; Johnson et al. 2009a; Roden et al. 2009).

Of recent interest has been the potential for improved stoves to reduce BC emissions, as household use of biofuels is thought to produce approximately one-fourth of total anthropogenic BC emissions (Bond et al. 2004). BC in particulate emissions produces a warming effect by absorbing light and is estimated by some to be second only to CO_2 in its warming impact

(Ramanathan and Carmichael 2008). Reduction of particulate emissions with high BC content has been proposed as a means to immediately slow global warming, as the atmospheric life of black carbon is measured in weeks, in contrast to other GHG species which can persist for decades or centuries (Hansen et al. 2000; Bond and Sun 2005). Thus, reducing BC emissions would have an immediate impact, as atmospheric concentrations would decrease within weeks instead of decades, as is the case with CO_2 and methane.

The net warming or cooling impact of particulate emissions from cookstoves, however, is not well known since particulate emissions from stoves include organic matter − which has a cooling impact (Jacobson et al. 2000) – in addition to BC. The ratios of BC to organic matter are not well characterized, with only two in-field studies having reported these ratios from domestic wood-burning stoves (Roden et al. 2006; Johnson et al. 2008).

This report aims to begin filling these gaps by assessing the emissions impact of an improved stove program in Ruhiira, a Millennium Village site in southwestern Uganda. Emissions data for CO_2, CO, CH_4, total non-methane hydrocarbons (TNMHC), and particulate matter, characterized by black and organic fractions, are presented as emission factors (grams emitted per kilogram fuel consumed), which are critical for emission inventories and climate models. Potential emission reductions, estimated by combining fuel consumption per cooking event and emission factors, are also presented.

2.0 METHODS

2.1 STUDY SITE AND STOVE TYPES

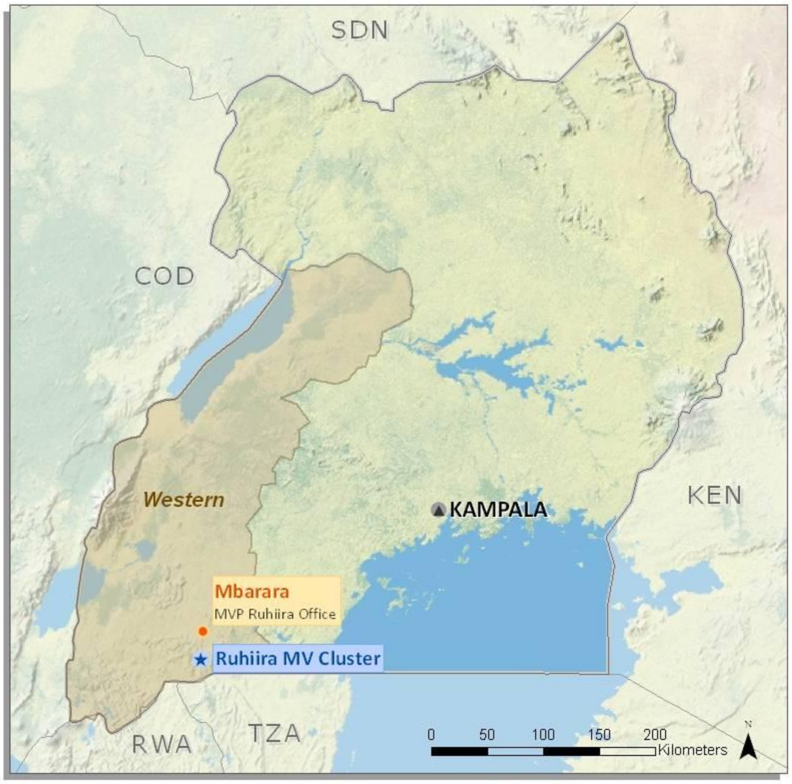
The study was conducted in the Ruhiira District, located in southwestern Uganda (see Figure 1), which is one of the 14 Millennium Village sites spread across Africa. The Millennium Village project is designed to bring people out of poverty by increasing access to proven, community-level interventions that can enhance farm productivity, health, education, business development, and access to markets (please see http://www.millenniumvillages.org for more information). A rocket-style wood-burning stove produced by StoveTec (Oregon, USA) is one of the interventions that has been deployed in Ruhiira, which provided the opportunity to evaluate the impact of an engineered stove on emissions in an African context.

The Ruhiira District is a cluster of eight villages, with a total population of approximately 40,000. Farming and agriculture form the base of the economy. Elevation ranges from 1,350-1,850 meters, and there are two rainy seasons from March-May and August-December. This study was conducted in July 2010, during the dry season.

Given the compressed timeframe of this study, the Ruhiira site presented an excellent opportunity to make a rapid assessment in Africa. As a Millennium Village actively being studied by Columbia University's Earth Institute, preexisting infrastructure was in place for carrying out the study. Berkeley Air Monitoring Group's strong relationship and past experience with the Center for Integrated Research and Community Development Uganda (CIRCODU) also provided us with confidence in a local partner to help with the fieldwork. We were also able to incorporate Dr. Tami Bond's Research Group from the University of Illinois at Urbana-Champaign in the study, which provided filter analysis for black and organic carbon. The use of StoveTec stoves in Ruhiira was also valuable, as this is a well known, mass-manufactured stove with a successful track record. It is important to note that Berkeley Air Monitoring Group is an independent evaluator, with no investment in the performance of the StoveTec stove or any other stoves, fuels, or cooking technologies.

Access to the community was facilitated by Columbia University and Millennium Promise, an NGO that has been working in Ruhiira for several years as part of the Millennium Villages project. They coordinated participant recruitment and assisted with the logistics required for a field study. Participants were compensated with a solar-powered LED light at the conclusion of the study. Institutional Review Board approval was granted by Columbia University.

Figure 1. Map of field location within Uganda.



This study evaluated traditional open-fire stoves and the StoveTec rocket stove (see Figure 2). The traditional stoves were three-stone fires as pictured below, with the exception of one mud stove with a non-functional chimney. None of the stoves had forced drafts (e.g., used fans). Additional information on the StoveTec rocket stove is available from the StoveTec website (http://www.stovetec.net) and from a recent USAID report of comparative stove testing, *Evaluation of Manufactured Wood-Burning Stoves in Dadaab Refugee Camps, Kenya* (http://www.usaid.gov/our_work/economic_growth_and_trade/energy/pubs/).

Figure 2. A typical traditional 3-stone fire (a), and the (b) StoveTec rocket stove.

a)

b)

2.2 STUDY DESIGN AND TESTING PROCEDURE

The criteria for participating homes was that they have a traditional stove and a StoveTec stove, which was being actively used, and that cooking took place primarily indoors (important for logistics of sampling emissions). Participants reported having the StoveTec stove for approximately 5-12 months. The use of an improved and traditional stove in a single home, as was commonly the case in Ruhiira, is a common kitchen setup, as families tend to retain a traditional stove for various tasks, especially those for which large pots and/or batches of food are required.

Sampling was conducted in homes during normal daily cooking events. Cooking events were uncontrolled, with the participants asked to cook their regular meals and use their normal fuelwood and fire tending practices. No fuel was provided. Each home was sampled when using a traditional stove, and again with the StoveTec rocket stove to allow direct comparison of samples. Before each cooking event, all fuels, including materials used to start the fire, such as agricultural residues and dried banana leaves, were weighed. At the end of the cooking event, the remaining fuel, char, and ash were weighed on a calibrated, one-gram resolution digital scale. Wood moisture content readings were made with a Delmhorst BD-2100 (USA) moisture meter at three points on three randomly selected sticks from the fuel pile. Active emission sampling periods corresponded to the entire duration of the cooking events, which were defined as any stove-use activity, including preparation of meals, tea, milk, or other activities. The food used was recorded for each cooking event as was the number and age of persons for which the food was intended. To account for differences in the amount of food cooked for more or fewer people per event, an equivalence factor called a “standard adult” was used. This factor converts the food requirements of each meal participant to an adult male of reproductive age, using the following ratios: Child: 0-14 years, 0.5; Female: over 14 years, 0.8; Male: 15-59 years, 1.0; Male: over 59 years, 0.8 (FAO 1983). One or two events in each of two homes were sampled per day, depending on when and how many cooking events occurred.

Emissions were collected directly above the stove using a three-pronged probe and analyzed for carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), total non-methane hydrocarbons (TNMHCs), and particulate matter ($PM_{4.0}$)[3]. $PM_{4.0}$ samples were analyzed for the relative compositions of black and organic carbon. While there is currently no standard method approved by a recognized standard-setting body for in-field emissions monitoring of stoves, the general approach used here is based on the "carbon balance," for which the ratio of emitted species is applied to the total carbon emitted to determine emission factors (Smith et al. 2000; Zhang et al. 2000; Pennise et al. 2001; Bhattacharya et al. 2002; Roden et al. 2006; Johnson et al. 2008). The main benefit of using emission ratios rather than attempting to measure the total emissions is that this method does not require cumbersome exhaust hoods with precise flow monitoring, which are impractical for work in remote rural homes. Instead, a probe designed to collect a representative sample from the emissions plume can be used to determine the emissions ratios required for the carbon balance. The multi-prong, aluminum probe used here has been systematically evaluated against an emissions hood with the probe method resulting in the same measured combustion efficiencies as with the hood (Johnson et al. 2009b). The carbon balance has also been used for several stove emission studies (Smith et al. 2000; Zhang et al. 2000; Pennise et al. 2001; Bhattacharya et al. 2002; Roden et al. 2006; Johnson et al. 2008). A detailed description of the emissions sampling train and analytical methods used is presented in Appendix A.

Each of the GHGs measured here causes a specific amount of atmospheric warming per unit (gram or mole) of emissions over the course of its lifetime in the atmosphere. This pollutant-specific warming, often called the "global warming potential" (GWP), is calculated in relation to the atmospheric warming caused by one gram or one mole of CO_2, called the "CO_2 equivalent" (CO_2e). The CO_2e of each emitted GHG can be added together to yield the combined warming of a set of emissions. The CO_2e emissions in this study were calculated using the following equation:

$$\mathrm{CO_2e} = \sum \mathrm{GWP_i} \times \mathrm{GHG_i}$$

where GWP_i[4] is the 100 year GWP for each gas and GHG_i is the quantity of each GHG. The GWPs used for CO_2 and CH_4 (1 and 25, respectively) were those published in the IPCC's 2007

---

[3]Emissions of particulate matter are typically collected as total-suspended particulate matter (TSP) or $PM_{4.0}$. $PM_{4.0}$ was monitored here to remove dust particles, which are generally larger than 4.0 microns in diameter, while capturing emissions particles, which are generally smaller than 4.0 microns.

[4] The warming potential of a greenhouse gas can be impacted by the degree to which the fuel is harvested renewably. When fuel is harvested renewably, CO_2 is reintegrated into vegetation and thus not included in the CO_2e emissions. For simplicity, this calculation assumes non-renewable harvesting, as is the case in many areas of Africa.

report (Solomon 2007), and the GWP for TNMHC (11) is from the IPCC's 1990 report (IPCC 1990)[5]. CO is an indirect GHG, which extends the life of other GHGs by providing the primary atmospheric sink for the hydroxyl radical (OH). The IPCC reports a range of 100-year GWPs for CO from 1.0 to 3.0 with a mean of 1.9 (Solomon 2007), which was used here.

GWPs were also applied to the BC and organic matter (OM)[6] in the particulate emissions. The range of 100-year GWPs for BC in current literature is 460 to 2020 (Bond and Sun 2005; Hansen et al. 2007; Reddy and Boucher 2007; Fuglestvedt et al. 2010; Jacobson 2010; Bond et al. 2011)[7] and the range for OM is -36[8] to -30 (the figures are negative as OM has a cooling impact) (Bond and Sun 2005; Fuglestvedt et al. 2010). There is considerable uncertainty in the reported GWPs and estimating climate impacts is difficult as the radiative forcing of aerosol emissions is affected by several factors, including emissions location, meteorological conditions, cloud interactions, and atmospheric reactions. Here we apply the 100-year GWPs from the Bond Research Group (BC: 660 and OM: -30) (Bond and Sun 2005; Bond et al. 2011), as these estimates are reasonably reflective of the published range of GWPs. Given the variability and uncertainty in the impact of aerosol emissions on climate, the resulting CO_2e contributions from particulate emissions presented here are intended to be illustrative.

[5] GWPs for TNMHC are not presented in later IPCC assessments.

[6] Organic matter is defined as organic carbon and its associated elements (oxygen and hydrogen).

[7] The upper estimate of 2020 is from Jacobson (2010), who reports a 100-Year Surface Temperature Response per Unit Emission rather than a GWP. Jacobson (2010) reports that the GWP and STRE are similar and the author reported a range of 1500-2240 for BC 100-yr GWPs in his testimony to the United States Congress http://www.stanford.edu/group/efmh/jacobson/0710LetHouseBC%201.pdf.

[8] Fuglesvedt et al. (2010) present a 100-yr GWP of -69 for organic carbon. Assuming a OM:OC ratio of 1.9, as was assumed for this report, results in a GWP of -36 for OM.

3.0 RESULTS

3.1 FUEL CONSUMPTION

A total of 35 emission samples were successfully collected from 10 homes, which each used a traditional (n=17) and StoveTec stove (n=18). The sampled cooking events were typically breakfast and lunch, and ranged from 17-116 minutes in duration with a mean of 61 minutes. The most common dish was matoke, which consists of steamed, mashed bananas. Tea, milk, porridge, and beans were also commonly cooked. The dominant fuelwood was eucalyptus, and starter fuels were typically crop residues or dried banana leaves. Cooking fires were generally started by lighting a small piece of brush or banana leaves with a match and inserting it into the starter fuels. Starter fuels were included in the calculation of fuel consumption by using an energy equivalence conversion.

As shown in Table 1, the number of standard adults[9] and moisture contents were slightly lower for StoveTec cooking events, but the differences were small and not significant. Fuel consumption per person-meal[10], however, was 42% lower, which was statistically significant. It is important to note that this is a relative measure during a single cooking event which may not represent the overall household fuel-use reductions over a year, as families typically use multiple fuels and stoves to meet their total household energy needs.

Table 1. Mean fuelwood consumption metrics. Fuel consumption is presented as kilograms per person-meal. Variability is expressed as ±1 standard deviation.

	N	Standard Adults	Moisture Content (%)	Fuel Consumption (kg per person-meal)
Traditional	17	6.9±3.4	17±6	0.40±0.25
StoveTec	18	6.0±2.9	16±5	0.23±0.17
Difference	-	-13% (p=0.42)	-7% (p=0.52)	-42% (p=0.03)

Red denotes statistical significance at the p<0.05 level use a paired-samples student's t-test[11].

[9] A "standard adult" converts the food requirements of a person to an adult male of reproductive age, using following ratios: Child: 0-14 years, 0.5; Female: over 14 years, 0.8; Male: 15-59 years, 1.0; Male: over 59 years, 0.8.

[10] A person-meal is defined here as a standard-adult meal.

[11] A paired samples t-test evaluates the likelihood that the differences between paired samples are significant (in this case differences in the outcome variable between using the traditional and improved stove in each home).

3.2 EMISSIONS

3.2.1 Combustion Performance

Table 2 presents nominal combustion efficiencies (NCEs) across stove types. NCE is presented as it provides a single, overall indication of how cleanly fuel is being combusted. NCE is defined as the percentage of carbon converted to CO_2 during combustion. In perfect combustion (NCE of 100%), all of the carbon in a fuel is converted to CO_2. When combustion is not complete, some of the carbon in the fuel is converted to products of incomplete combustion (PICs), which include carbon monoxide, methane, hydrocarbons, and particulate matter. Thus, higher combustion efficiencies result in lower emissions of PICs, and lower combustion efficiencies result in higher emissions of PICs, which are almost all unhealthful and have large relative climate impacts. Here we found that the combustion efficiencies were similar (NCE~90-91%) for both stove types, indicating that the StoveTec was not combusting fuel more efficiently than the traditional stove.

It is important to note that combustion efficiency is different from fuel efficiency. For example, a large, heavy new car with a big engine may combust gasoline very cleanly (high NCE) but only achieve 15 miles per gallon (low fuel efficiency). Conversely, an old, lightweight compact car may emit much more carbon monoxide and particulate matter per gallon gasoline (low NCE), but achieve 30 miles per gallon (high fuel efficiency). In the case of these stoves, the traditional and StoveTec stoves converted the fuel carbon to CO_2 with about the same combustion efficiency (NCE~90-91%), but the StoveTec was much more fuel efficient in how much wood was needed per cooking event. The StoveTec's lower fuel consumption indicates that it did a better job of transferring the heat released from burning wood into cooking energy.

Table 2. Mean nominal combustion efficiencies across stove types. Variability is presented as ±1 standard deviation.

Stove	N	Nominal combustion efficiency	Fraction of carbon emitted as products of incomplete combustion
Traditional	17	91.2±2.0%	8.8±2.2%
StoveTec	18	90.3±2.5%	9.7±2.5%
Difference		-0.9% (p=0.36)	9.5% (p=0.36)

Note: No differences were statistically significant at the p<0.05 level using a paired-samples student's t-test.

3.2.2 Emission Factors

Two types of emission factors are presented in this report. Emission factors on a fuel basis (per kilogram fuel consumed) are the most relevant for emissions inventories. These emission factors can be applied to fuel consumption estimates for a given source (e.g. country or region-wide domestic biomass consumption) to estimate the source's emissions contributions, which is useful in modeling atmospheric concentrations of gases and climate. Fuel-based emission factors must be applied with great care as large errors can arise if the emission factors are not representative of the source. Emission factors on a person-meal basis are presented as the most relevant metric for this specific study as they provide a relative evaluation of the StoveTec in comparison to the traditional stove.

Emission factors on a fuel-basis and person-meal basis are presented in Table 3. Due to similar combustion efficiencies, the StoveTec did not show any significant reductions in gas emissions per kilogram fuel consumed (fuel basis section of Table 3). The StoveTec used 42% less fuel per person-meal and released 42% less carbon overall, which translated into lower gaseous emissions per person-meal for all pollutants except for TNMHC (see person-meal section of Table 3). The StoveTec's larger TNMHC emissions, however, were not statistically significant as the variability in TNMHC was high. The magnitude of the difference in TNMHC emissions was also small (<2 g per kg fuel and <1 g per person-meal.) The StoveTec's lower CO_2 and CO emission factors per person-meal were statistically significant.

Table 3. Mean gaseous emission factors. Variability is presented as ±1 standard deviation.

Fuel basis (grams emitted per kilogram fuelwood consumed)					
	N	**CO_2**	**CO**	**CH_4**	**TNMHC**
Traditional	17	1533±36	69±14	4.5±3.4	2.4±2.2
StoveTec	18	1519±32	70±20	5.1±4.1	3.9±4.3
Difference	-	-1% (p=0.36)	1% (p=0.87)	14% (p=0.53)	64% (p=0.36)
Per person-meal basis (grams emitted per standard adult-meal)					
	N	**CO_2**	**CO**	**CH_4**	**TNMHC**
Traditional	17	606±378	29±23	1.8±2.0	0.8±0.8
StoveTec	18	347±199	17±12	1.3±1.4	1.1±2.6
Difference	-	-43% (p=0.02)	-42% (p=0.04)	-28% (p=0.27)	30% (p=0.67)

Red denotes statistical significance at the p<0.05 level use a paired-samples student's t-test.

Table 4 presents the particulate matter emission factors. The StoveTec had a slightly higher $PM_{4.0}$ emission factor than the traditional stove on the basis of kilogram of fuel consumed, although this difference was not statistically significant. The BC content in the particulate emissions from the StoveTec was significantly higher, constituting 15.5% of the $PM_{4.0}$ compared to only 7.2% for the open-fire. This translated into the BC emissions per kilogram of wood being 182% greater for the StoveTec than the traditional stove. The BC emissions per cooking event were also higher for the StoveTec than the traditional fire, although the StoveTec's lower fuel consumption per event translated into a smaller and not statistically significant increase of 60%. The implications of these particulate emissions are discussed more fully in the following sections.

Table 4. Mean particulate emission factors and $BC/PM_{4.0}$ ratios. Variability is presented as ±1 standard deviation.

Fuel basis (grams emitted per kilogram fuelwood consumed)					
	N	**$PM_{4.0}$**	**Black Carbon**	**Organic Matter**	**$BC/PM_{4.0}$**
Traditional	16	9.5±3.2	0.7±0.4	10.8±4.1	7.2%±4.2%
StoveTec	17	12.4±5.7	1.9±1.4	12.5±6.7	15.5%±9.8%
Difference	-	31% (p=0.10)	182% (p<0.01)	15% (p=0.50)	115% (p=0.01)
Per person meal (grams emitted per standard adult-meal)					
	N	**$PM_{4.0}$**	**Black Carbon**	**Organic Matter**	
Traditional	16	3.8±2.7	0.3±0.4	4.4±3.5	
StoveTec	17	2.8±1.9	0.5±0.6	3.2±2.8	
Difference	-	-26% (p=0.13)	60% (p=0.35)	-27% (p=0.28)	

Red denotes statistical significance at the p<0.05 level use a paired-sample student's t-test.

The StoveTec's $PM_{4.0}$ and CO emissions suggest the potential for reducing exposure to these health-damaging pollutants. On a person-meal basis, the StoveTec had slightly lower $PM_{4.0}$ and CO emissions than the traditional stoves, although only the CO reduction was statistically significant (p=0.04). These emission estimates provide evidence that overall CO emissions were reduced, but more study would be required to determine if the StoveTec's $PM_{4.0}$ emissions resulted in reduced contributions to household and/or regional air pollution.

3.2.3 Particulate Emissions

In addition to their link to health effects, particulate matter (PM) emissions have implications for climate change. PM from combustion sources is primarily made up of BCand OM[12]. BC warms the atmosphere as it strongly absorbs sunlight and has a large relative warming impact, estimated at 460-2020[13] times greater per gram emitted than that of CO_2 (Bond and Sun 2005; Hansen et al. 2007; Reddy and Boucher 2007; Fuglestvedt et al. 2010; Jacobson 2010; Bond et al. 2011). OM, conversely, is lighter in color and thus scatters and reflects light, resulting in a cooling impact (estimated GWP of -30 (Bond and Sun 2005; Bond et al. 2011). Thus while reducing overall PM emissions is critical for mitigating both health and climate impacts, reducing the ratio of BC in PM would provide additional climate benefits.

Here we found the percentage of BC which made up the $PM_{4.0}$ was significantly lower for the traditional stove (7.2%) than the StoveTec (15.5%) (p<0.01). Thus, even though the overall

[12] Habib et al. 2008 reported that inorganics, including nitrates, sulfates, chlorine, ammonium, and potassium made up less than 7% of $PM_{2.5}$ mass from aerosols emitted from wood-burning cookstoves.

[13] The upper estimate of 2020 is from Jacobson (2010), who reports a 100-Year Surface Temperature Response per Unit Emission rather than a GWP. Jacobson (2010) reports that the GWP and STRE are similar and the author reported a range of 1500-2240 for BC 100-yr GWPs in his testimony to the United States Congress http://www.stanford.edu/group/efmh/jacobson/0710LetHouseBC%201.pdf.

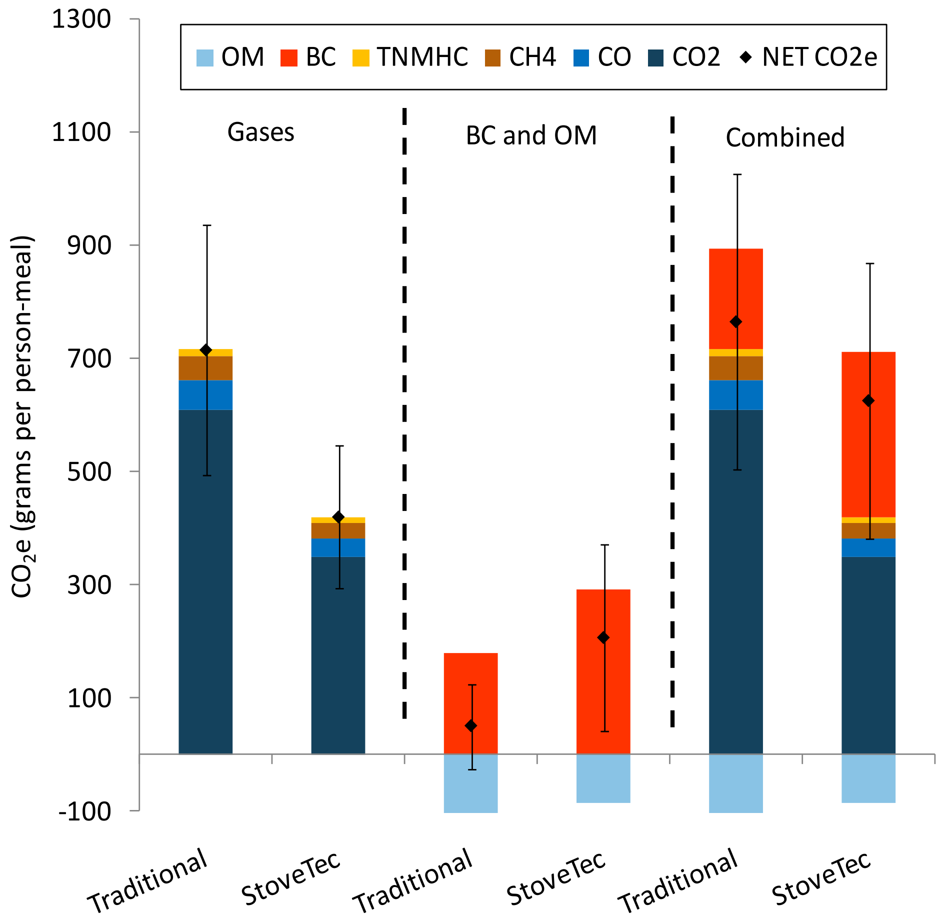
$PM_{4.0}$ emissions were lower for the StoveTec per person-meal, the higher BC content in the StoveTec's $PM_{4.0}$ emissions meant that the $PM_{4.0}$ had a net warming impact greater than the traditional stove's $PM_{4.0}$ emissions.

3.2.4 CO_2-equivalent Emissions

CO_2e emission factors per person-meal are presented in Figure 3, which are the combined impact of the gaseous emissions (CO_2, CO, CH_4, and TNMHC), as well as the $PM_{4.0}$ emissions (BC and OM). When all measured gas emissions are considered, the StoveTec had net CO_2e (indicated by black diamonds) emissions that were 41% lower than the traditional stove ($p=0.02$). CO and TNMHC were important contributors, accounting for ~10% of the CO_2e for both stove types. In current carbon trading markets, however, CO and TNMHC are not included in CO_2e calculations as they are not covered by the Kyoto Protocol. If only the measured Kyoto Protocol gases (CO_2 and CH_4) are considered, the StoveTec's CO_2e emissions were still 42% lower than the traditional stove ($p=0.02$), but the magnitude of the savings was ~20 g CO_2e per person-meal less.

The relative warming/cooling impacts of the PM emissions are shown in the center of Figure 3. The net CO_2e from PM for the StoveTec was 210 g CO_2e per person-meal, compared to 50 g CO_2e per person-meal for the traditional stove, with the difference due primarily to the StoveTec's higher BC emissions. When all gases and particulate emissions are considered, as shown on the right side of Figure 3, CO_2e emissions were 770 and 630 g per person-meal for the traditional stove and StoveTec, respectively. BC was the largest non-CO_2 contributor, accounting for 17% and 37% of the CO_2e, respectively, for the traditional stove and StoveTec.

Figure 3. Mean CO_2e emission factors. CO_2e from all measured gases is presented to the left of the dashed line and only the CO_2e from particulate matter emissions is presented to the right.



Notes: Error bars represent ±95% confidence intervals based on the measured emission factors.

The results presented here assume for simplicity's sake that the fuelwood is not harvested renewably, and thus all CO_2 emissions are included in CO_2e. This is the case for both stove types. When the harvesting of fuelwood is not fully renewable the emitted CO_2 is not entirely reincorporated into the regrowth of trees. In areas where fuelwood is harvested at least in part renewably, the relative importance of the non-CO_2 emissions would increase, as CO_2 would not be included in CO_2e from renewably harvested fuelwood. The PICs (CO, CH_4, TNMHC, BC, and OM), however, are not used in photosynthesis and are thus not affected by the renewability of biomass harvesting.

Using country-wide figures for growing stock and wood harvesting from the Food and Agriculture Organization, and assuming a generic regrowth rate of 2.5%, results in an estimate of ~90% non-renewable wood harvesting for Uganda[14]. Given 90% non-renewable harvesting, the net CO_2e emissions including all measured gases and particulate matter would be ~720 and 610 g per person-meal for the traditional stove and StoveTec, respectively, compared to ~770 and 630 g per person-meal when the biomass fuel is assumed to be 100% non-renewable. In contrast, if the fuel is harvested 100% renewably, the net CO_2e emissions would be only ~150 and 280 g per person meal for the traditional stove and StoveTec, respectively[15]. The large difference in CO_2e emissions between the two scenarios demonstrates the importance of the degree of non-renewable harvesting, with the implication that targeting improved stove efforts in areas with greater deforestation rates and high non-renewability may reap greater climate and ecological benefits.

[14] See ftp://ftp.fao.org/docrep/fao/011/i0350e/i0350e04c.pdf, and ftp://ftp.fao.org/docrep/fao/011/i0350e/i0350e04d.pdf.

[15] The change in relative CO_2e contributions of the traditional and StoveTec between the two scenarios arises from the differences in emissions of non-CO_2 species. The StoveTec produced more non-CO_2e emissions than the traditional stove, which unlike CO_2, are counted towards CO_2e in the 100% renewable scenario.

4.0 DISCUSSION OF RESULTS

4.1 STUDY LIMITATIONS

This study presents the first field-based evaluation of a rocket stove's impact on GHG emissions in Africa, including the impacts of both gaseous and particulate emissions. While the results from this study help in filling a data gap, it is important to interpret the results with caution. The sample sizes here were relatively small (10 homes and 35 total cooking events), and were collected in one cluster of villages in southwestern Uganda. This study also evaluated only the StoveTec rocket stove in comparison to a traditional fire. The StoveTec is a well-known, mass produced stove, but there are many other types of engineered stoves being disseminated. Moreover, the StoveTec was not specifically designed to reduce BC, which has only recently become a consideration for stove programs. Finally, since there are few similar field-based studies, drawing comparisons with other research is difficult. Thus these results should be interpreted with care, and not directly extrapolated to other areas where fuel types, stove types, cooking practices, or other factors that impact stove emissions may differ substantively, even for the StoveTec.

4.2 FUEL CONSUMPTION

The 42% fuel consumption savings per person-meal measured during this study compares well with previous estimates for the StoveTec rocket stove. The study *Evaluation of Manufactured Wood Stoves in Dadaab Refugee Camps, Kenya* prepared by Berkeley Air Monitoring Group for USAID reports the StoveTec saved 54% on fuel wood during Controlled Cooking Tests of rice and vegetables (Pennise et al. 2010). A study of Controlled Cooking Tests of matoke conducted with the StoveTec stove in Ruhiira by Columbia University found that it saved 38% on fuelwood compared to a three-stone fire (Adkins et al. 2010). The 42% savings measured here during normal daily cooking falls between these estimates, which is promising, as fuel savings from daily cooking often do not live up to the fuel savings estimated from controlled testing (Smith 1989; Bailis et al. 2007). Given the consistency across these studies, the StoveTec appears to perform well from a fuel consumption perspective, with robust savings of approximately 35-55% per person-meal. Fuel savings per household, however, are likely to be more modest, as many improved stoves are used as a partial replacement for traditional stoves, with most homes using a combination of fuels and stoves to meet their overall energy needs.

4.3 ROLE OF FIELD-BASED EMISSIONS MONITORING

The majority of stove testing is conducted in the laboratory, most often with a version of the Water Boiling Test (WBT)[16]. The WBT and other controlled laboratory tests are important components of stove development and testing. The WBT provides rapid feedback to designers and can be used as a common, replicable protocol for comparing important performance metrics across different stove technologies. However, the WBT protocols explicitly state that

[16] The Water Boiling Test is a standardized test in which a trained stove operator conducts a series of boiling and simmering phases designed to represent cooking legumes. It is the most commonly applied stove design test and is often employed for emissions testing. Protocols for WBT 3.0 can be found online at http://www.pciaonline.org/testing.

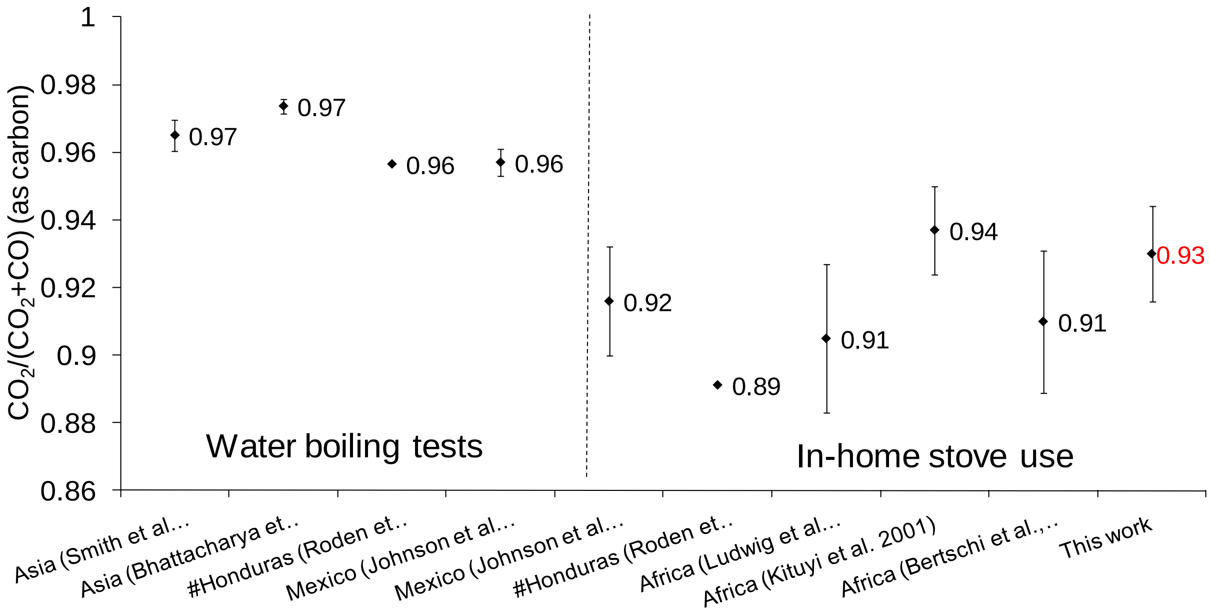
results should be considered only as preliminary indicators of stove performance and are not intended to predict field performance.

Field-based evaluations of stove emissions during normal daily conditions are, therefore, critical to understanding actual impacts. Substantial differences in emission factors and fuel consumption between laboratory and field testing, for example, have been reported (Bailis et al. 2007; Johnson et al. 2008; Johnson et al. 2009a; Roden et al. 2009). For example, Figure 4 shows a comparison of proxy combustion efficiencies[17] for traditional open-fire stoves during laboratory-based WBTs and normal daily cooking in homes. The overall trend demonstrates that WBTs result in higher combustion efficiencies for traditional stoves than those measured during normal daily cooking. This overestimation of combustion efficiencies during WBTs, and thus underestimation of CO, PM, and other PICs, is not surprising given that fire tending and fuel conditions outlined in the test protocols are likely more ideal than those used in homes[18]. This overestimation does not diminish the primary utility of the WBT as a practical stove design tool, rather it suggests that data derived from WBTs should not be extrapolated to actual performance in homes.

[17] The ratio of $CO_2/(CO_2+CO)$ is used as a proxy for combustion efficiency since it has shown strong agreement with simultaneously measured NCE (Johnson et al. 2009a), and often CO_2 and CO are common emissions data available from other studies.

[18] The WBT protocols recommend that fuelwood be “well-dried and uniform in size” (2-5cm in diameter). During the high-power phase the stove operator is instructed to “control the fire with the means commonly used locally to bring the first pot rapidly to a boil without being excessively wasteful of fuel.” For the low power phase the operator “must vigilantly try to keep the simmering water as close as possible to 3 degrees C below the local boiling point” for 45 minutes.

Figure 4. Proxy combustion efficiencies ($CO_2/[CO_2+CO]$) for traditional open-fire stoves. Results from this study are highlighted in red.



Notes: Error bars represent ±1 standard deviation.

Figure 4 shows that the 93.4% proxy combustion efficiency measured here for traditional open-fire stoves during normal daily cooking is significantly lower[19] than the 96-97% reported during laboratory tests using WBTs reported from several studies (Smith et al. 2000; Zhang et al. 2000; Bhattacharya et al. 2002; Johnson et al. 2008; Roden et al. 2009). *Importantly, a few percent decrease in combustion efficiency translates into a large increase in the amount of carbon emitted as products of incomplete combustion.* This discrepancy reinforces the need to study and report emission factors measured during normal daily cooking as those derived from WBTs are likely to produce errors in emission inventories used for climate models, as well as emission factors used for carbon offset calculations. For example, there has been a consistent underestimation of CO concentrations predicted by atmospheric models for Asia (Carmichael et al. 2003; Tan et al. 2004). These models use emissions inventories with CO emission factors derived from WBTs (Streets et al. 2003). Tan et al. (2004) suggested that a three-fold increase in the CO emissions from domestic and small-scale coal combustion would account for this difference, which is approximately the difference between the CO emission factors derived from WBTs and those measured during normal daily stove use.

The results found here fit this pattern of the WBT producing unrealistically high combustion efficiencies, and thus underestimating emissions of CO, PM, and other PICs. A recent study reported the emissions of CO and PM from 50 different stoves including a three-stone fire and StoveTec measured during WBTs (MacCarty et al. 2010) (BC and other GHGs were not reported for this study). The CO emission factors reported in this study (see section 3.2.2) were

[19] $p<0.01$ using an independent samples student's t-test.

1.3 and 2.9 times greater than those reported by McCarty et al. (2010) for the traditional stoves and StoveTec, respectively. Differences in PM emission factors were more pronounced, with those reported here 7 and 12-fold greater than those found during the WBT-based study for the traditional stoves and StoveTec, respectively. The reasons for these discrepancies likely arise from differences in fuel conditions and tending practices. Fuelwood is often more irregular, larger, and higher in moisture content in homes than that used for WBTs. Fires are also often left unattended while users conduct other tasks. Fuel loading is also generally higher during normal use than during WBTs, which can reduce combustion efficiency, especially for stoves designed to take smaller amounts of fuel.

4.4 IMPLICATIONS FOR IMPROVED STOVES REDUCING BLACK CARBON EMISSIONS

The StoveTec did not demonstrate lower BC emissions than the traditional stove during this study. Although we can only speculate about the possible causes for the higher BC content in the StoveTec's $PM_{4.0}$ emissions, the rocket design and insulated combustion chamber may have been more conducive to high temperature flaming combustion, which produces more BC than cool, smoldering combustion. This trend was observed under laboratory conditions for a similar prototype rocket stove, for which the BC content of PM from the rocket stove was also approximately double (68%) that of a traditional three-stone fire (38%) (MacCarty et al. 2008). A field study by Roden et al. (2009) also reported a rocket-style stove (Eco-Lenka) had a higher BC content in the PM (21%) compared to traditional stoves (13%). These studies, combined with the results presented here, suggest a trend of rocket-style stoves producing higher BC content in PM, although more studies are clearly needed to draw more definitive conclusions.

While the StoveTec's BC emissions almost certainly will differ where fuel types and cooking practices are different from those in Ruhiira, the results found here demonstrate the danger in making assumptions about a stove's impact on emissions without evaluating its performance during normal daily cooking. The StoveTec has demonstrated strong fuel savings in the field as well as reduced PM and CO emissions in the lab, yet still emitted more BC overall during this study. These highlight the need for more emissions assessments. Identifying and assessing stove technologies which do result in substantial BC emission reductions would be aided by comprehensive and coordinated laboratory and field efforts.

4.5 IMPACT ON GREENHOUSE GASES

The StoveTec emitted 42% less CO_2e emissions than the traditional stove when only the measured gases are considered (CO_2, CO, CH_4, and TNMHC). The StoveTec's lower measured CO_2e emissions resulted from relative gains in fuel efficiency, as it used 42% less wood than the traditional stove. However, as the StoveTec and traditional stove had similar combustion efficiencies (~90-91%), the StoveTec did not achieve greater CO_2e reductions by emitting less CO, CH_4, or TNMHC per kg fuel consumed. Similarly, its overall particulate emissions did not differ significantly from the traditional stove.

The CO_2e emissions reductions by the StoveTec are reported on a per person-meal basis. This reduction is only a relative indication of the potential CO_2e savings when the StoveTec is used for cooking a meal instead of a traditional stove. In many homes, multiple stoves, including traditional and improved, are often used in various combinations to meet total energy needs. Thus the CO_2e savings per household with a StoveTec stove may be less than 42%, as the StoveTec is likely not used exclusively. Higher combustion efficiency relative to the traditional stoves would have resulted in lower emission factors of PICs, which in turn would have yielded greater potential CO_2e reductions.

5.0 CONCLUSIONS AND FUTURE DIRECTIONS FOR STUDY

5.1 CONCLUSIONS

- This study contributes to the body of evidence that rocket stoves save fuel, with the 42% savings per person-meal lying within the range of previous research on the StoveTec.
- $PM_{4.0}$ and CO emissions from the StoveTec were 26% and 42% lower per person-meal than the traditional stove, although only the reduction in CO emissions was statistically significant. The lower emissions per person-meal suggest the potential the StoveTec has to reduce contributions to household and regional air pollution (and associated health impacts), although more study would be required to evaluate this possibility, especially for PM.
- The StoveTec's estimated CO_2e savings relative to the traditional stove were 41% on a per person-meal basis, considering only the measured gases. While these CO_2e emissions are clearly a positive step, larger reductions could be achieved by increasing combustion efficiency above that of the traditional stove (~90%), which would in turn further decrease the emissions of PICs.
- This study demonstrated an improved stove can increase BC emissions relative to traditional stoves. The StoveTec had higher BC content in its PM emissions and higher overall BC emissions than the traditional stove, even though it reduced fuel consumption compared to the traditional stove. While this result cannot be generalized to all improved stoves (or even to the StoveTec without further study), it demonstrates that improved stoves should not be assumed to reduce BC emissions.
- More broadly, this study serves as an example of the care that needs to be taken in promoting and using stoves as means to reduce BC emissions. Given that combustion of biomass contributes an estimated one-fourth of anthropogenic BC emissions, improved stoves do offer a unique and potentially cost-effective means to mitigate climate change. However, the stove technologies employed need to be carefully monitored to ensure that potential reductions in BC are real.

5.2 LESSONS AND CONSIDERATIONS FOR EMISSIONS STUDIES

- The specific methods and equipment used here require a level of technical expertise beyond what is needed for basic evaluations of a stove intervention's impact on household air pollution or fuel consumption. For example, assessing a comprehensive set of emissions from a stove, including methane and black carbon, required collecting multiple filters and a gas sample bag, with careful consideration of flow rates and the analytical limits of instrumentation. Filters and gas samples also needed to be analyzed in a laboratory with specialized equipment, which required additional time and resources.
- The measurement and reporting of in-field emissions tests is further complicated by the lack of a standard method. Reducing this complexity by facilitating recognition of accepted protocols and encouraging the development of user-friendly equipment would assist in making climate warming emissions monitoring more accessible to interested parties.
- In general, field evaluations are more expensive and logistically challenging than laboratory studies. At the same time, the enhanced value derived from field evaluations is complex and

may not be immediately discernable to a non-technical audience. As a result, funding agencies and carbon offset methodologies are reluctant to require that implementing partners spend resources on collecting project-specific data, allowing laboratory results and/or default values to be used instead, in hopes that the program's benefits can be maximized. However, as this work and other studies have demonstrated, the actual performance in the field can be much different from default or laboratory-based measures, and this difference can have critical implications for the long-term success of household energy interventions.

5.3 RESEARCH AND PROGRAMMATIC RECOMMENDATIONS

- More field-based emission studies are needed to better characterize the emissions from stoves, especially particulate emissions and their impact on overall CO_2e. A large-scale, global, independent field evaluation of a full range of solutions, including clean fuels (e.g. LPG, ethanol, biogas, kerosene, and plant oils), advanced stoves (e.g. forced air, gasifier, TLUD, and pyrolytic), rocket stoves, and others would provide a valuable database of emissions factors, as well as means to compare different stove technologies' performance under realistic conditions.

- Research on post-emission atmospheric processing of cookstove particulate emissions and subsequent climate impacts should also be considered to better understand the climate impacts of cookstoves.

- CO_2e emissions estimates often have a high degree of uncertainty as they incorporate variability from emission factors and fuel consumption. To estimate CO_2e savings of an improved stove program with a higher degree of certainty that the savings are real and significant, larger sample sizes than what was possible for this study would be required, preferably with a minimum sample size of 30 homes which are geographically and socioeconomically representative of the project area.

- There is now evidence from laboratory, controlled, and uncontrolled testing which indicates that the StoveTec uses significantly less fuelwood than traditional open-fires. The next logical, valuable step would be a fuel consumption study using the Kitchen Performance Test (KPT). The KPT provides fuel consumption estimates per home, for which fuel-based emission factors can be applied to estimate CO_2e savings on a per home basis as well. Estimates of a CO_2e savings per home can be applied to the number of homes using an improved stove for a given project and thus provide a project-wide CO_2e savings estimate.

- Stoves that substantially improve both fuel and combustion efficiency provide the greatest health and climate benefits. It is therefore essential to further incentivize the development and dissemination of stoves with demonstrably high combustion efficiencies during normal daily stove use (beyond those with fuel savings improvements alone). Carbon offset methodologies in both the voluntary and regulatory markets can incentivize this progression by promoting the use of project-specific emission factors measuring during normal daily cooking rather than relying on current default emission factors, which do not reward high-combustion efficiency stoves.

- Given the finding that the StoveTec had higher measured BC emissions during this study, it is clear more assessments of improved stoves are needed to determine if this is a common outcome. There is a timely imperative for this research, created by the growing enthusiasm for improved stoves as a cost-effective source of climate benefits. It will be far more effective to build realistic field-based emissions factors for stoves into the initial phases of BC mitigation models and programs than to discover retrospectively that the benefits of improved stoves may have been overstated in certain circumstances.

6.0 REFERENCES

Adkins E, Tyler E, Wang J, Siriri D, Modi V (2010) Field testing and survey evaluation of household biomass cookstoves in rural sub-Saharan Africa. Energy for Sustainable Development 14: 172-185

Bailis R, Berrueta V, Chengappa C, Dutta K, Edwards R, Masera O, Still D, Smith KR (2007) Performance testing for monitoring improved biomass stove interventions: experiences of the Household Energy and Health project. Energy for Sustainable Development 11: 57-70

Bertschi IT, Yokelson RJ, Ward DE, Christian TJ, Hao WM (2003) Trace gas emissions from the production and use of domestic biofuels in Zambia measured by open-path Fourier transform infrared spectroscopy. Journal of Geophysical Research-Atmospheres 108: -

Bhattacharya SC, Albina DO, Salam PA (2002) Emission factors of wood and charcoal-fired cookstoves. Biomass & Bioenergy 23: 453-469

Birch ME, Cary RA (1996) Elemental carbon-based method for monitoring occupational exposures to particulate diesel exhaust. Aerosol Science and Technology 25: 221-241

Bond TC, Streets DG, Yarber KF, Nelson SM, Woo JH, Klimont Z (2004) A technology-based global inventory of black and organic carbon emissions from combustion. Journal of Geophysical Research-Atmospheres 109: doi:10.1029/2003JD003697

Bond TC, Sun HL (2005) Can reducing black carbon emissions counteract global warming? Environmental Science & Technology 39: 5921-5926

Bond TC, Zarzycki C, Flanner MG, Koch DM (2011) Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse. Atmos. Chem. Phys. Discuss. 10: 15713-15753

Brocard D, Lacaux C, Lacaux JP, Kouadio G, Yoboue V (1996) Emissions from the combustion of biofuels in West Africa. In: Levine JS (ed) Biomass burning and global change. MIT Press, Cambridge, Mass., pp 350-360

Carmichael GR, Tang Y, Kurata G, Uno I, Streets DG, Thongboonchoo N, Woo JH, Guttikunda S, White A, Wang T, Blake DR, Atlas E, Fried A, Potter B, Avery MA, Sachse GW, Sandholm ST, Kondo Y, Talbot RW, Bandy A, Thorton D, Clarke AD (2003) Evaluating regional emission estimates using the TRACE-P observations. J. Geophys. Res. 108

Crutzen PJ, Heidt LE, Krasnec JP, Pollock WH, Seiler W (1979) Biomass Burning as a Source of Atmospheric Gases CO, H-2, N2O, NO, CH3Cl and COS. Nature 282: 253-256

Ezzati M, Saleh H, Kammen DM (2000) The contributions of emissions and spatial microenvironments to exposure to indoor air pollution from biomass combustion in Kenya. Environmental Health Perspectives 108: 833-839

FAO (1983) Wood fuel surveys. UN Food and Agriculture Organization

Fuglestvedt JS, Shine KP, Berntsen T, Cook J, Lee DS, Stenke A, Skeie RB, Velders GJM, Waitz IA (2010) Transport impacts on atmosphere and climate: Metrics. Atmospheric Environment 44: 4648-4677

Hansen J, Sato M, Kharecha P, Russell G, Lea DW, Siddall M (2007) Climate change and trace gases. Philosophical Transactions of The Royal Society A 365: 1925–1954

Hansen J, Sato M, Ruedy R, Lacis A, Oinas V (2000) Global warming in the twenty-first century: An alternative scenario. Proceedings of the National Academy of Sciences of the United States of America 97: 9875-9880

IPCC (1990) Climate change: The IPCC scientific assessment. Intergovernmental Panel on Climate Change, 052140360X, Cambridge; New York

Jacobson MC, Hansson HC, Noone KJ, Charlson RJ (2000) Organic atmospheric aerosols: Review and state of the science. Reviews of Geophysics 38: 267-294

Jacobson MZ (2010) Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health. J. Geophys. Res. 115: D14209

Johnson M, Edwards R, Alatorre Frenk C, Masera O (2008) In-field greenhouse gas emissions from cookstoves in rural Mexican households. Atmospheric Environment 42: 1206-1222

Johnson M, Edwards R, Berrueta V, Masera O (2009a) New Approaches to Performance Testing of Improved Cookstoves. Environmental Science & Technology 44: 368-374

Johnson M, Edwards R, Ghilardi A, Berrueta V, Gillen D, Frenk CA, Masera O (2009b) Quantification of Carbon Savings from Improved Biomass Cookstove Projects. Environmental Science & Technology 43: 2456-2462

Kasibhatla P, Arellano A, Logan JA, Palmer PI, Novelli P (2002) Top-down estimate of a large source of atmospheric carbon monoxide associated with fuel combustion in Asia. Geophysical Research Letters 29: doi:10.1029/2002GL015581

Kituyi E, Marufu L, Wandiga SO, Jumba IO, Andreae MO, Helas G (2001) Carbon monoxide and nitric oxide from biofuel fires in Kenya. Energy Conversion and Management 42: 1517-1542

Ludwig J, Marufu LT, Huber B, Andreae MO, Helas G (2003) Domestic combustion of biomass fuels in developing countries: A major source of atmospheric pollutants. Journal of Atmospheric Chemistry 44: 23-37

MacCarty N, Ogle D, Still D, Bond T, Roden C (2008) A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. Energy for Sustainable Development 12: 56-65

MacCarty N, Still D, Ogle D (2010) Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. Energy for Sustainable Development 14: 161-171

Parrotta JA (1999) Productivity, nutrient cycling, and succession in single- and mixed-species plantations of Casuarina equisetifolia, Eucalyptus robusta, and Leucaena leucocephala in Puerto Rico. Forest Ecology and Management 124: 45-77

Pennise D, Brant S, Agbeve SM, Quaye W, Mengesha F, Tadele W, Wofchuck T (2009) Indoor air quality impacts of an improved wood stove in Ghana and an ethanol stove in Ethiopia. Energy for Sustainable Development 13: 71-76

Pennise D, Charron D, Wofchuck T, Rouse J, Hunt A (2010) Evaluation of Manufactured Wood Stoves in Dadaab Refugee Camps, Kenya. United States Agency for International Development

Pennise DM, Smith KR, Kithinji JP, Rezende ME, Raad TJ, Zhang JF, Fan CW (2001) Emissions of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. Journal of Geophysical Research-Atmospheres 106: 24143-24155

Ramanathan V, Carmichael G (2008) Global and regional climate changes due to black carbon. Nature Geoscience 1: 221-227

Reddy MS, Boucher O (2007) Climate impact of black carbon emitted from energy consumption in the world's regions. Geophysical Research Letters 34: -

Rehfuess E, Mehta S, Pruss-Ustun A (2006) Assessing household solid fuel use: Multiple implications for the Millennium Development Goals. Environmental Health Perspectives 114: 373-378

Roden CA, Bond TC, Conway S, Benjamin A, Pinel O (2006) Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves. Environmental Science & Technology 40: 6750-6757

Roden CA, Bond TC, Conway S, Osorto Pinel AB, MacCarty N, Still D (2009) Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves. Atmospheric Environment 43: 1170-1181

Smith KR (1989) Dialectics of Improved Stoves. Economic and Political Weekly 24: 517-522

Smith KR, Uma R, Kishore VVN, Lata K, Joshi V, Zhang J, Rasmussen RA, Khalil MAK (2000) Greenhouse gases from small-scale combustion devices in developing countries. United States Environmental Protection Agency, EPA/600/R-00/052, Washington D.C.

Solomon S (2007) Climate change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate. Cambridge University Press, Cambridge ; New York

Streets DG, Bond TC, Carmichael GR, Fernandes SD, Fu Q, He D, Klimont Z, Nelson SM, Tsai NY, Wang MQ, Woo JH, Yarber KF (2003) An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. Journal of Geophysical Research-Atmospheres 108: doi:10.1029/2002JD003093

Tan Q, Chameides WL, Streets D, Wang T, Xu J, Bergin M, Woo J (2004) An evaluation of TRACE-P emission inventories from China using a regional model and chemical measurements. Journal of Geophysical Research-Atmospheres 109: doi:10.1029/2004JD005071

Turpin BJ, Lim HJ (2001) Species contributions to PM2.5 mass concentrations: Revisiting common assumptions for estimating organic mass. Aerosol Science and Technology 35: 602-610

Venkataraman C, Rao GUM (2001) Emission factors of carbon monoxide and size-resolved aerosols from biofuel combustion. Environmental Science & Technology 35: 2100-2107

WHO (2002) The World Health Report: Reducing Risks, Promoting Healthy Life. Bulletin of the World Health Organization

Zhang J, Smith KR, Ma Y, Ye S, Jiang F, Qi W, Liu P, Khalil MAK, Rasmussen RA, Thorneloe SA (2000) Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors. Atmospheric Environment 34: 4537-4549

APPENDIX A: EMISSION SAMPLING METHODS

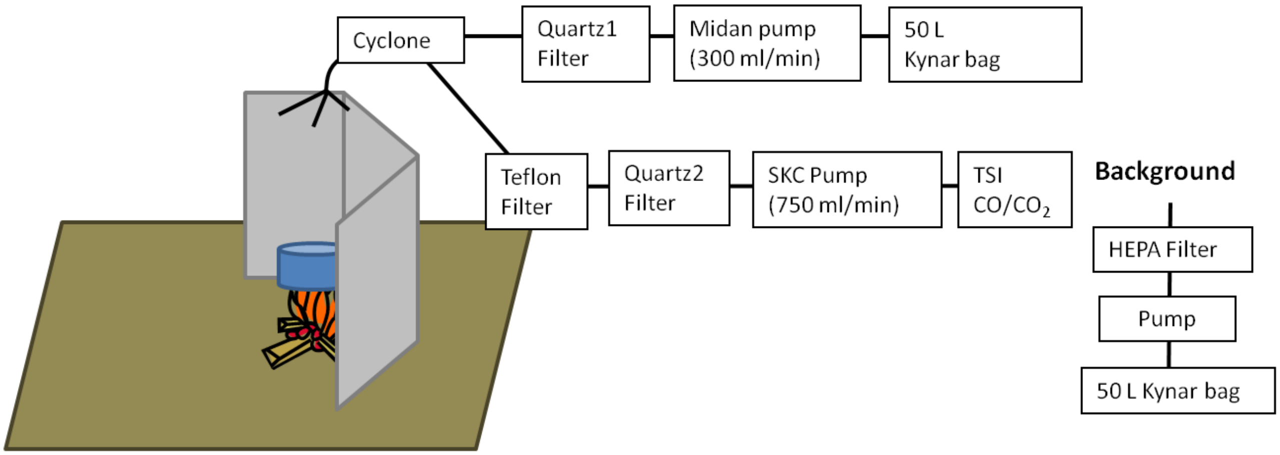
6.1 EMISSIONS SAMPLING

Emissions were collected directly above the stove using a three-pronged aluminum sampling probe. The probe is designed to collect emissions throughout the plume, with inlets at the end of each prong and 10 cm from the manifold. Use of this sampling probe in place of emission hoods has been validated during previous studies in Mexico (Johnson et al. 2009a; Johnson et al. 2009b), and similar approaches have been used in Honduras (Roden et al. 2006; Roden et al. 2009). A three-sided aluminum curtain was placed around the stove to minimize impacts on the plume from air currents. After passing through a cyclone to select for $PM_{4.0}$ (particulate matter less than 4 microns in diameter), the sample was split into two lines as shown in Figure 3. One line leading to a Teflon filter for quantification of $PM_{4.0}$[20] and a secondary quartz filter[21] followed by a TSI IAQ-Calc monitor (TSI, USA) for real-time measurements of CO_2 and CO. The other line led to a 47mm quartz filter for analysis of elemental to organic carbon ratios in the particulate matter and then to a 50L Kynar bag for analysis of CO_2, CO, CH_4, and total non-methane hydrocarbons (TNMHC). A small aliquot of the gas sample was transferred to a metalized bag for sample stability and transport. A simultaneously collected sample away from the emissions plume but at stove height in the kitchen was taken over the course of the cooking event and used to correct emissions for background concentrations of CO_2 and CO. All flow rates were measured before and after sampling by a calibrated rotameter. A schematic and photograph of the emissions sampling installation are shown in Figure A1. Filters were immediately placed in a cooler following sampling and stored in a freezer until analysis was conducted. The filters were also stored in a cooler during transit back to the United States.

[20] Emissions of particulate matter are often collected as total-suspended particulate matter (TSP) or $PM_{4.0}$. $PM_{4.0}$ was monitored here to remove dust particles, which are generally larger than 4.0 microns in diameter, while capturing emissions particles, which are generally smaller than 4.0 microns.

[21] The secondary quartz filter is used to account for gaseous organic carbon, which should not be included in the particulate organic carbon.

Figure A1. Schematic of emissions sampling train and photo of a typical installation.



6.2 ANALYSIS

Gas samples were analyzed for CO_2, CO, CH_4, and TNMHC using a Perkin Elmer 8500 gas chromatograph (Perkin Elmer, USA) with dual flame ionization detectors and equipped with a nickel catalyst methanizer (SRI Instruments, USA). CO_2, CO, and CH_4 were separated using a 6ft x 1/8" column packed with 80/100 mesh Carbosphere (Grace Davidson, USA), and samples for total hydrocarbon analysis were run through a 2ft x 1/8" glass bead packed column (Grace Davidson, USA). CH_4 was subtracted from total hydrocarbons to determine TNMHC. All gases were quantified using 5-point calibration curves (all r^2>0.995) made from NIST traceable calibration gas.

$PM_{4.0}$ was determined gravimetrically with the Teflon filters, which were weighed before and after sampling on a microbalance in a temperature and humidity controlled room. PM samples collected on quartz filters were analyzed by the Bond Research Group at the University of Illinois, Champaign-Urbana, for elemental carbon and organic carbon composition using the thermal-optical technique (Birch and Cary 1996). Elemental carbon was assumed to be the same as black carbon, the light-absorbing component of the PM emissions, which is a common assumption for source characterization studies (Bond et al. 2004)[22]. The ratio of organic matter to organic carbon was assumed to be 1.9, as was found for aerosols emitted from wood-burning fireplaces (Turpin and Lim 2001).

[22] We refer readers to section 1.3 "Classifying Carbonaceous Aerosols" in Bond et al. 2004 (A technology-based global inventory of black and organic carbon emissions from combustion) for a detailed discussion on the definitions of black carbon, elemental carbon, organic carbon, and organic matter.

APPENDIX B: CALCULATION OF EMISSION FACTORS

The carbon balance was developed by Crutzen et al. (1979) for determination of large scale biomass fire emissions and has been commonly employed in stove emissions studies (Crutzen et al. 1979; Brocard et al. 1996; Smith et al. 2000; Zhang et al. 2000; Kituyi et al. 2001; Bhattacharya et al. 2002; Ludwig et al. 2003; Roden et al. 2006). The carbon balance requires only a representative emission sample and determination of the total emitted carbon. Total emitted carbon was determined as follows:

$$C_T = C_F - C_A$$

where C_T is the total emitted carbon, C_F is the carbon in the fuel before the test, and C_A is the remaining ash and char carbon after the test is completed. Fuel carbon was derived by weighing the fuel before and after the sampling period, subtracting moisture content, and assuming a carbon content of 46% for eucalyptus wood (Parrotta 1999), which was the dominant local fuelwood species. Carbon content for the remaining ash and char was assumed to be 21% as reported by Smith et al. (2000).

To derive emission ratios, first the total carbon in the emission sample is determined as

$$C_S = C_{CO_2} + C_{CO} + C_{CH_4} + C_{TNMHC} + C_{PM}$$

where C_S is the total carbon in the emissions sample and C_{CO_2}, C_{CO}…C_{PM} are the carbon masses from each emission species in the sample. The ratio of the carbon in an emission species (C_{X_i}) to the total carbon in the sample (C_s) was then applied to the total emitted carbon (C_T) to determine the total amount of each species

$$C_T\left(\frac{C_{X_i}}{C_S}\right) = C_{X_T}$$

where C_{X_T} is the emitted carbon for a respective emission species. The total carbon emission as each species was then divided by the total fuel consumption to determine each respective emission factor.

APPENDIX C: SAMPLE DATA

Table C1: Combustion efficiency, emission factors, and fuelwood consumption for each sampled cooking event. Emission factors on a per person-meal basis can be calculated by multiplying the fuel based emission factor by the fuelwood consumption per person-meal.

Sample	NCE	CO_2	CO	CH_4	TNHMC	$PM_{4.0}$	BC	OM	fuelwood consumption
	%	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	kg per person-meal (dry basis)
Traditional Stove									
HH01	91.3%	1536	64	8.6	1.8	7.5	0.6	7.9	0.710
HH01	91.3%	1535	82	2.0	0.7	6.2	0.2	5.3	0.784
HH02	88.9%	1496	74	8.1	9.7	11.0	0.5	11.1	0.286
HH04	88.8%	1494	69	10.7	4.9	16.9	1.0	18.3	0.117
HH04	90.7%	1525	78	3.8	1.6	6.8	0.7	8.9	0.381
HH05	94.4%	1587	45	0.7	0.1	8.0	0.8	9.9	0.210
HH05	94.0%	1581	45	4.2	3.1	5.1	0.3	4.7	0.282
HH07	91.3%	1535	63	4.4	3.5	11.5	0.6	12.8	0.146
HH07	90.9%	1529	84	1.3	1.6	6.8	0.6	5.7	0.329
HH08	94.9%	1596	51	2.0	0.5	-	-	-	0.117
HH08	91.3%	1535	65	4.1	1.4	11.3	0.3	14.7	0.250
HH10	91.2%	1534	74	2.7	1.1	11.7	0.3	10.8	0.449
HH11	92.9%	1563	62	0.7	0.5	6.0	0.6	8.2	0.648
HH12	87.8%	1477	96	4.2	2.9	12.5	1.6	15.5	0.974
HH12	87.2%	1466	90	12.0	2.5	12.6	0.5	17.1	0.551
HH13	91.9%	1545	62	2.3	2.3	8.5	1.6	10.8	0.292
HH13	91.0%	1531	69	4.2	2.3	9.0	0.6	11.5	0.229
StoveTec									
HH01	93.1%	1566	41	0.2	0.0	27.7	2.0	22.8	0.150
HH01	89.5%	1506	73	10.2	7.7	7.2	0.9	5.6	0.255
HH02	90.7%	1525	90	0.4	0.1	8.7	1.7	3.4	0.240
HH02	92.1%	1549	60	5.9	2.8	6.4	1.9	4.8	0.092
HH04	92.1%	1548	78	0.4	0.3	4.1	0.5	3.2	0.112
HH04	95.3%	1602	35	2.1	1.3	8.8	0.9	6.5	0.129
HH05	88.6%	1491	79	11.2	3.8	12.9	0.9	12.4	0.253
HH05	91.4%	1537	65	1.6	1.0	15.3	2.3	14.5	0.183
HH07	88.6%	1491	91	2.3	2.7	15.4	2.8	12.6	0.155
HH07	87.2%	1467	90	13.6	14.8	-	-	-	0.138
HH08	93.2%	1567	45	6.8	4.1	7.9	0.6	6.5	0.129
HH10	86.6%	1456	99	4.5	4.6	17.2	1.8	20.7	0.266
HH11	91.0%	1530	63	2.8	1.4	12.7	3.0	15.8	0.100
HH11	92.7%	1559	39	3.2	0.6	9.8	3.7	19.2	0.204
HH12	90.2%	1516	69	6.4	7.3	14.0	0.3	10.4	0.465
HH12	85.8%	1443	96	10.9	13.2	13.3	0.6	11.7	0.469
HH13	89.2%	1499	68	3.2	3.4	-	4.9	20.5	0.549
HH13	88.6%	1489	76	5.6	0.9	16.8	3.8	21.4	0.263