A laboratory comparison of the global warming impact of five major types of biomass cooking stoves

Nordica MacCarty, Damon Ogle, and Dean Still
Aprovecho Research Center, 79093 Highway 99, Cottage Grove, OR, USA

Tami Bond and Christoph Roden
Department of Civil and Environmental Engineering, University of Illinois, Urbana-Champaign
Newmark Civil Engineering Laboratory, MC-250, 205 N. Mathews Ave., Urbana, IL 61801, USA

With over 2 billion of the world's population living in families using biomass to cook every day, the possibility of improved stoves helping to mitigate climate change is generating increasing attention. With their emissions of CO_2, methane, and black carbon, among other substances, is there a cleaner, practical option to provide to the families that will need to continue to use biomass for cooking? This study served to help quantify the relative emissions from five common types of biomass combustion in order to investigate if there are cleaner options. The laboratory results showed that for situations of sustainable harvesting where CO_2 emissions are considered neutral, some improved stoves with rocket-type combustion or fan assistance can reduce overall warming impact from the products of incomplete combustion (PICs) by as much as 50-95%. In non-sustainable situations where fuel and CO_2 savings are of greater importance, three types of improved combustion methods were shown to potentially reduce warming by 40-60%. Charcoal-burning may emit less CO_2 than traditional wood-burning, but the PIC emissions are significantly greater.

Key-words: improved cookstoves, global warming, carbon dioxide, methane, soot, black carbon, products of incomplete combustion, sustainable harvesting, biomass

1. Background

While much of the recent work in the cook stove community has been focused on the potential health benefits of improved stoves, data is emerging supporting possible benefits that improved cook stoves could have for the health of the climate as well. Some of the major greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), are present in the emissions from biomass cooking stoves. Particulate matter emissions from traditional biomass cooking stoves are also significant and have strong and visible effects on the climate. An August 2007 headline in the online BBC News stated "Clouds of pollution over the Indian Ocean appear to cause as much warming as greenhouse gases released by human activity" [BBC, 2007]. These clouds are composed primarily of soot, or black carbon particles. A similar article in the *Scientific American* stated "The dominant source for all this black carbon is cooking fires" [Biello, 2007]. A later article in *Nature Geoscience* [Ramanathan and Carmichael, 2008], summarized in the *New York Times* [Revkin, 2008], showed the contribution of cooking fires on the overall Asian black carbon concentrations, as shown in [Adhikary et al., 2007].

Further, studies are showing that the soot particles, which enhance the solar absorption by snow and ice, are contributing to the ice melt in the Himalayas and the retreat of Arctic sea ice [Flanner et al., 2007]. Reduction of soot emissions can show a more immediate effect on halting climate change than reducing the longer-lived emissions of CO_2 only.

Just how much gaseous pollutants and black carbon do cooking stoves emit and are there feasible biomass combustion options that can help to reduce emissions from traditional cooking methods? The emissions from five cooking stoves were measured by a team of researchers from the Aprovecho Research Center, the University of Illinois Urbana-Champaign, and at Colorado State University. The stoves were tested in an effort to examine four common methods of wood combustion: open burning, "rocket" combustion chamber-type combustion, gasification, and forced draft. The emissions from a common charcoal stove were also investigated.

1.1. Sustainable vs. non-sustainable harvesting of biomass

The manner in which fuel is harvested has a large influence on the climate change potential when cooking with biomass. If biomass is harvested sustainably, the CO_2 released in combustion is theoretically reabsorbed by the biomass growing to replace it. If biomass is not harvested sustainably, then the CO_2 released when burned is contributing to the build-up of CO_2 in the atmosphere. The products of incomplete combustion (PICs) such as carbon

monoxide, methane, and particulate matter contribute to the changing of the climate in both cases.

Kirk Smith has pointed out the importance of PICs. "Simple stoves using solid fuels do not merely convert fuel carbon into carbon dioxide (CO_2). Because of poor combustion conditions, such stoves actually divert a significant portion of the fuel carbon into products of incomplete combustion (PICs), which in general have greater impacts on climate than CO_2. Eventually most PICs are oxidized to CO_2, but in the meantime they have greater global warming potential (GWP) than CO_2. Indeed, if one is going to put carbon gases into the atmosphere, the least damaging from a global warming standpoint is CO_2; most PICs have a higher impact per carbon atom" [Smith et al., 2000].

1.2. Emissions from biomass cooking stoves

In perfect combustion, emissions from burning fuel would be only carbon dioxide and water. If biomass was completely combusted, and the fuel was harvested sustainably, cooking with biomass could be a carbon-neutral situation. Unfortunately, most biomass-burning also produces many PICs, which have greater impacts on climate than CO_2. These are discussed below.

Carbon monoxide (CO). Carbon monoxide is one of the primary products of incomplete combustion. Emissions of carbon monoxide in unimproved wood-burning stoves are frequently as much as 10-15 % of the CO_2 emissions, and this figure is even higher for charcoal. Carbon monoxide has a GWP of 1.9 times that of carbon dioxide [IPCC, 2007], and is a large contributor to the localized air pollution in urban areas.

Methane (CH_4). Methane is a relatively potent greenhouse gas. Averaged over 100 years, CH_4 has a GWP 25 times as much as the same mass of CO_2. Methane has an atmospheric lifetime of about 12 years. Methane is a part of the Kyoto Accords and is considered one of the most important greenhouse gases resulting from biomass burning [IPCC, 2007].

Non-methane hydrocarbons (NMHCs). Hydrocarbons are substances consisting primarily of hydrogen and carbon. Emissions of unburned hydrocarbons indicate incomplete combustion and the vapors can be harmful if inhaled. Overall, the 100-year GWP of the NMHCs is approximately 12 times that of CO_2, with climate-forcing occurring because of their contribution to ozone formation [Edwards and Smith, 2002].

Nitrous oxide (N_2O). A powerful greenhouse gas, nitrous oxide has an atmospheric lifetime of 120 years and a GWP of 298 over 100 years. N_2O is also a part of the primary Kyoto Accords and one of the primary gases considered in inventories of biomass-burning [IPCC, 2007].

Oxides of nitrogen (NO_x). NO_x is a broad term for the various nitrogen oxides (other than N_2O) produced during combustion when combustion temperatures reach a high enough level to burn some of the nitrogen in the air. NO_x is an ozone precursor and when dissolved in atmospheric moisture can result in acid rain. Oxides of nitrogen affect atmospheric chemistry in complex ways, including interactions with OH radicals and contributing to ozone chemistry. They are presently thought to be greenhouse-neutral overall [Bond, 2007], and as such the IPCC does not present a GWP for NO_x [IPCC, 2007].

Particulate matter (PM). PM is composed of tiny solid or liquid particles. The effects of inhaling particulate matter have been widely studied in humans and animals. They include asthma, cardiovascular disease, and premature death. By weight, particles can have an extremely strong effect on the atmosphere by absorbing and/or scattering the sun's incoming radiation. Different types of particles have varying levels of scattering vs. absorption, defined by their single scattering albedo (SSA). If the particles have low SSA, they absorb more sunlight and create more warming in the atmosphere. Generally, particles that have low SSA have a higher ratio of elemental to organic carbon in their composition. Though not a part of the Kyoto agreement, the climate-forcing effects of the particles emitted from biomass combustion are quite substantial.

Black, elemental carbon (EC). Elemental or black carbon particles are carbon particles that will not volatilize at a temperature of ~600º C (in an inert environment). EC is produced in flaming fires and is also called soot. Soot is most commonly emitted from the burning of biomass, coal, and diesel fuel. It is one of the most important absorbing aerosol species in the atmosphere. Elemental carbon from combustion has a GWP 680 times that of CO_2 [Roden and Bond, 2006; Bond and Sun, 2005].

Organic carbon (OC) and organic matter (OM). OC and OM are generally produced in smoldering fires. Organic carbon primarily consists of scattering particles/aerosols that can be white to clear to brown. OC contributes to global cooling because it is composed of aerosol particles that reflect sunlight back into space. The pollutants can also become nuclei for cloud droplets, which reflect even more sunlight back into space, but those clouds also trap heat radiated from the earth, so the effects of clouds are complex. In aerosols, organic carbon does not exist in isolation; it is bonded to oxygen and hydrogen. Together, the organic compounds are called *organic matter (OM).* The typical OM to OC ratio is 1.5 to 2.1, but can vary widely. The GWP of OM was recently estimated as -75 times that of CO_2 (i.e., a cooling 75 times that of CO_2) [Bond et al., 2004]. Since the time of that estimate, organic carbon from biofuel combustion has been shown to be slightly absorbing, and therefore has a lower (negative) GWP. According to the leading author of the previous work, a likely estimate is now -50. Research is under way to verify that value [Bond, 2007].

Official IPCC estimates of the GWP of major direct greenhouse gases and recent estimates for other pollutants are presented in Table 1.

2. Methodology

Five stoves were tested in an effort to examine five common methods of wood combustion: open burning, "rocket"-type combustion, gasification, forced draft, and charcoal-burning. The "rocket" stove, gasifier, and forced-draft fan stove are considered "improved" stoves. The three-stone fire is a traditional cooking technology. These

Table 1. Global warming potential as 100-year CO_2 equivalent

Emission	Global warming potential, 100-year CO_2 equivalent	Source
CO_2	1	IPCC, 2007
CO	1.9	IPCC, 2007
CH_4	25	IPCC, 2007
NMHC	12	Edwards and Smith, 2002
N_2O	298	IPCC, 2007
PM - EC	680	Roden and Bond, 2006; Bond and Sun, 2005
PM - OM	-50	Estimate – Bond, 2007

Notes

1. PM = particulate matter; EC = elemental carbon; OM = organic matter.
2. GWP of EC and OM are still uncertain. Research is ongoing to determine the effects of these particles on the basis of their behavior in the atmosphere. Better estimates will likely result from this research [Bond, 2007].

stoves are all essentially combustion chambers that can be used in many models and sizes of cooking stove. Photographs of all the stoves tested are shown in Figure 1.

- Three-stone fire. Sticks of wood were burned directly under the pot which was held 22 cm above the testing surface by three bricks. It is estimated that 2.5 billion people worldwide live in households that use a three-stone fire or similar traditional method for cooking.
- Household rocket stove. A well-insulated rocket stove prototype with a 10 cm diameter and 30 cm tall combustion chamber. The stove was developed by Larry Winiarski and Aprovecho Research Center, USA. The "rocket stove" technology has been available for 25 years [Bryden et al., 2005]. It is estimated that at least half a million rocket stoves may be in use worldwide.
- Household Karve gasifier stove. In this gasifier stove, 5 cm long pieces of wood fill a cylindrical combustion chamber. The batch of wood is top-lit. Secondary air passes over the top of the combustion chamber. This

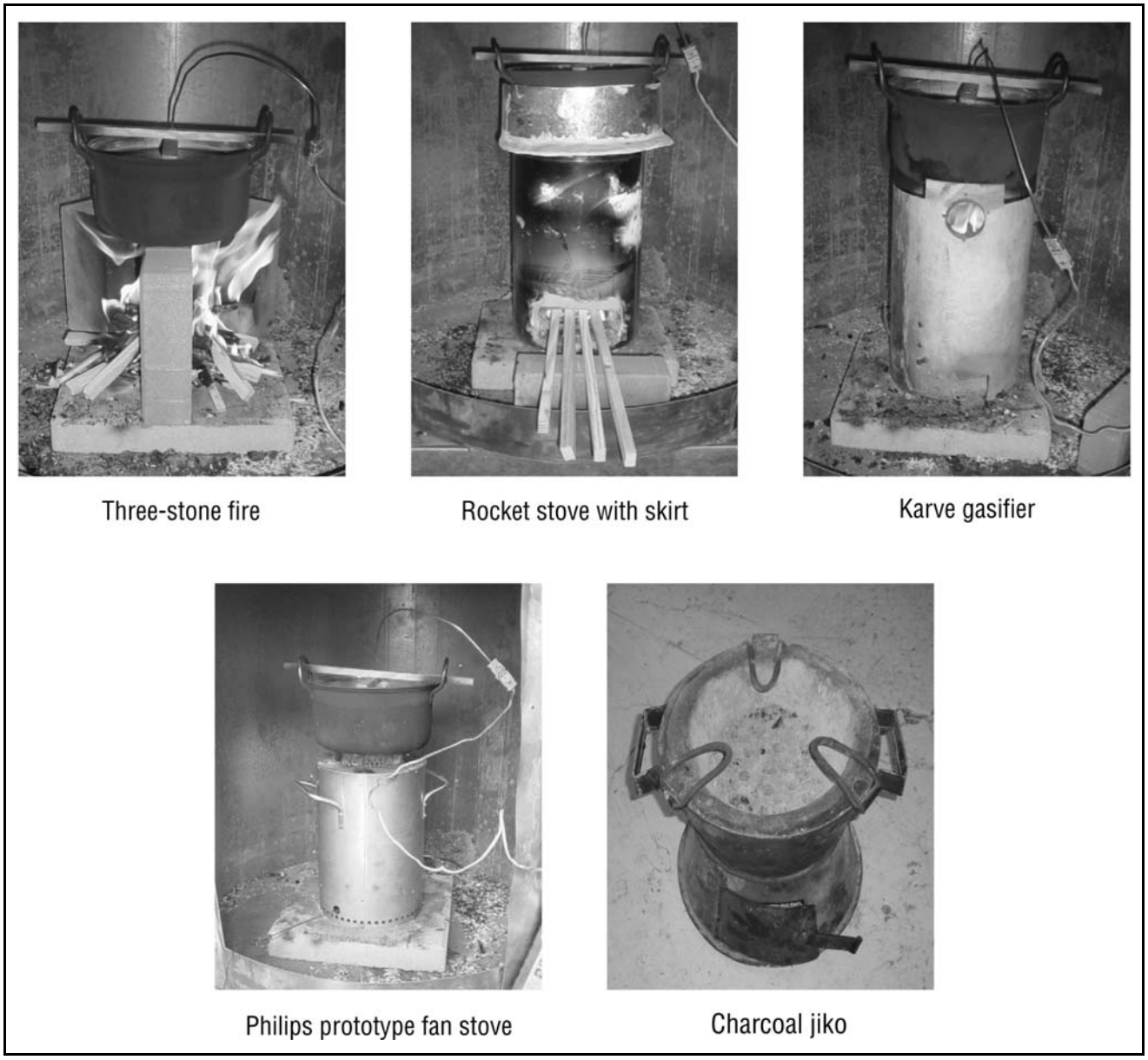

Figure 1. The five stove models investigated

stove was recently developed by A.D. Karve, Appropriate Rural Technology Institute, India [Raj, 2007].
- Philips prototype fan stove. Forced-air jets provide better mixing of the flame, gases, and air. 5 cm long pieces of wood are fed into the combustion chamber in a space between the top of the stove and the pot. The fan was run at full speed for both high power (bringing water to boil) and low power (simmering). The stove is being developed and manufactured by the Philips company in the Netherlands [Philips, 2006].
- Charcoal Jiko. Pieces of charcoal are combusted in a bowl-shaped combustion chamber. Holes allow air to enter the combustion zone from underneath the charcoal. The charcoal Jiko has been disseminated in many African countries. Note that the data presented in this report does not count the energy lost or emissions produced when wood is made into charcoal.

A modified University of California at Berkeley (UCB) 2003 water boiling test (WBT) was used to test each stove three times [Bailis et al., 2007a]. There were 2.5 liters (l) of water used in a standard 3 l pot. Due to time constraints, the hot-start phase of the test was omitted. Also, the water was simmered for 30 rather than 45 minutes.

The open fire and rocket stoves were started with a small amount (10-15 g) of newspaper. The fan and gasifier stoves were started with wood kindling soaked in charcoal lighter fluid. The charcoal stove was started with lighter fluid. The emissions from these starting aids were estimated to be negligible. Between the high- and low-power phases, the fuel was removed from the three-stone, rocket, and fan stoves for weighing, sometimes leading to a brief emission spike that was removed from the calculations.

The fuel used for the wood stoves was 1 cm x 2 cm sticks of kiln-dried Douglas fir. The sticks were cut into approximately 5 cm lengths for the fan and gasifier stoves. Moisture content was determined by the oven drying method to be an average of 3.4 % on a wet basis [Bailis et al., 2007b]. Natural mesquite charcoal in roughly 5-10 cm diameter pieces was used in the Jiko stove.

The UCB WBT was used in order to combine the stove emission measurements with quantifications of the heat transfer efficiency for each stove. It should be noted that the results are from carefully-tended fires in the laboratory with dry fuel. Field results will vary considerably due to operation by cooks, the use of different fuels, pots, fuel moisture content, cooking practices, and quantities of food cooked. The WBT minimizes these variables in an attempt to determine the difference between the heat transfer and potential combustion efficiencies of the stoves when operated in a controlled fashion.

2.1. Gas analysis

In July 2006, Aprovecho mechanical engineers Nordica MacCarty and Damon Ogle traveled to Colorado State University's Engines and Energy Conversion Laboratory in Fort Collins, Colorado. Under the guidance of Bryan Willson and the Aprovecho team, an emission collection hood was created by students to allow for gas measurements from cooking stoves, using a Fourier-transform infrared (FTIR) system for measurement of 23 different species. The hood design was based on the work of Grant Ballard-Tremeer [Ballard-Tremeer, 1997].

In FTIR, IR radiation is passed through a sample of gas. Some of this light is transmitted through the sample while the rest is absorbed, producing a spectrum. Because different gases have a unique combination of atoms, each produces a unique infrared spectrum, or "molecular fingerprint". Through analysis of this spectrum and the corresponding intensity, the make-up and concentrations of a sample gas are determined.

Emissions were collected under a typical emission collection hood in which a constant volume pump draws the flow into an exhaust collection system. A sample of the exhaust was brought into the FTIR. Unfortunately, there was a technical problem with the measurement of flow through the system. Thus, only ratios of gas concentrations were available for analysis.

2.2. Particle analysis

Particles were collected at the Aprovecho Research Center using the laboratory emission collection hood. The measurement of particulate matter can be extensive, including mass calculations, composition, sizing distribution, and measurement of SSA. The equipment used in these tests included a nephelometer to measure particle scattering, a particle soot absorption photometer (PSAP) to measure particle absorption in real time, and also a pump-and-filter system to collect and later analyze mass and elemental carbon/organic carbon ratios using a Sunset Laboratories carbon analyzer. This portable equipment is part of the UIUC ARACHNE system, detailed in Figure 2. Further details about this collection system are available in [Roden and Bond, 2006].

The particles collected on filters during the tests were analyzed for composition by the Bond research group at the University of Illinois laboratory. Organic and elemental carbon composition was measured by a Sunset Laboratories carbon analyzer. Organic matter was estimated by multiplying the organic carbon by 1.9 as recommended by Roden [2006]. He states, "The total mass associated with carbonaceous aerosols, defined as organic matter plus EC, is estimated from the EC and OC measurements. Organic matter (OM), or organic carbon plus associated elements, is usually estimated from OC measurements. Typical OM/OC ratios vary between 1.2 and 3.1 depending on the source and age of the aerosol. We use a value of 1.9 suggested for fireplace combustion of pine or oak. The estimated OM + EC emission factor usually agrees well with the PM emission factor" [Roden and Bond, 2006; Turpin and Lim, 2001; Smith et al., 1993].

3. Results

3.1. Specific fuel consumption

Investigation of specific fuel (or energy) consumption is the first step in quantifying the difference between cooking stoves, since the amount of fuel burned is directly related to the amount of climate- and health-harming emissions produced. Figure 3 shows the time to boil and

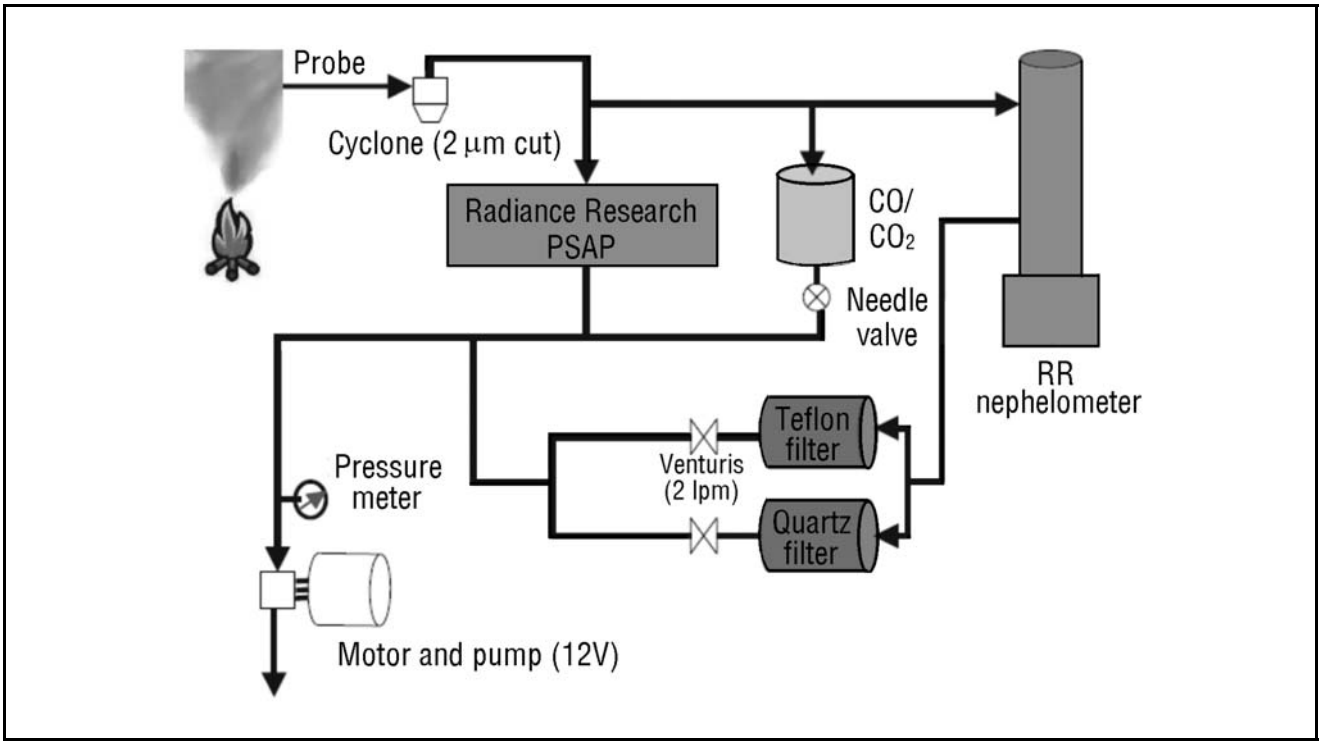

Figure 2. University of Illinois Urbana Champaign ARACHNE system. The portable system serves to sample the stove exhaust from within the emissions plume and then analyze it using both real-time and particle collection instruments. This results in data for CO, CO_2, and PM_4 in terms of total carbon, black carbon, and organic matter. [Roden and Bond, 2006].

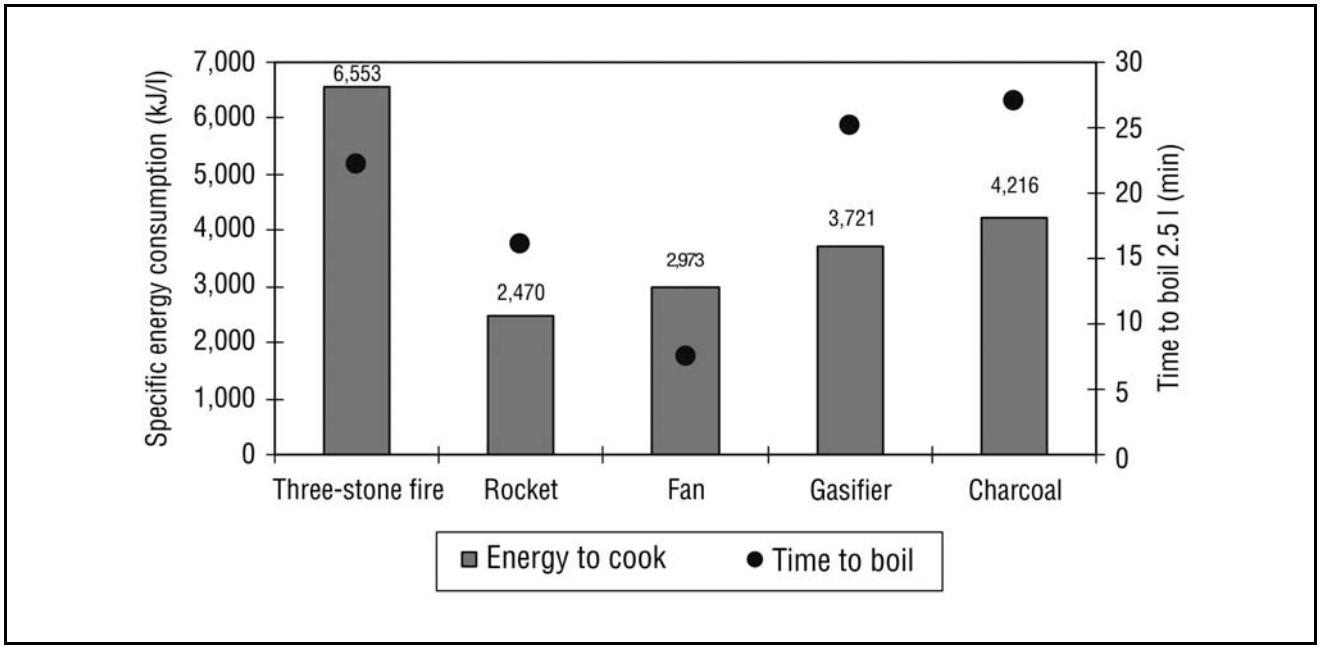

Figure 3. Specific energy consumption (energy consumed to bring to boil 1 l water and then simmer for 30 minutes) and time to boil 2.5 l for the various stoves. Average of three tests. This chart does not include the energy to power the fan, running at 1 W for 37 minutes, or 2.25 kJ of additional energy input. Similarly, the charcoal energy consumption does not consider the energy lost while making the charcoal fuel.

amount of fuel required to complete the WBT cooking task: to bring 2.5 l of water to boil and then simmer the remaining water for 30 minutes. This data was taken during the collection of gases at the Colorado State University (CSU) laboratory. For comparison on the same scale, mass of each fuel used (wood or charcoal) is converted to energy consumption based on the calorific value for the fuel.

As expected, the three-stone fire used the most energy to boil and simmer the water when compared to the three other wood-burning stoves. The rocket stove with a skirt used the least amount of energy to complete the task. Time to boil was lowest in the fan stove, followed by the rocket stove. Time to boil was similar for the three-stone fire, the gasifier, and charcoal stoves.

Table 2. Gaseous emissions in percentage relative to CO_2 on a molar basis[1], average of three tests

	Three-stone fire	Rocket	Philips fan	Gasifier	Charcoal
High power					
CO	3.75	1.74	0.36	2.95	35.46
CH_4	0.13	0.11	0.02	0.27	3.91
NMHC	0.24	0.22	0.37	0.67	1.29
N_2O	0.00	0.00	0.00	0.00	0.00
NO_x	0.05	0.07	0.06	0.06	0.07
Formaldehyde	0.04	0.03	0.01	0.05	0.04
Low power					
CO	12.12	3.24	0.36	4.98	20.60
CH_4	0.29	0.17	0.07	0.48	0.29
NMHC	0.17	0.08	0.05	0.57	0.00
N_2O	0.00	0.00	0.00	0.00	0.00
NO_x	0.06	0.08	0.06	0.04	0.05
Formaldehyde	0.08	0.04	0.02	0.06	0.03

Note

1. Ratios are taken for number of moles of the pollutant emitted and number of moles of CO_2 emitted, and converted to percentage by multiplying by 100. For example, in the first row, the figures would be obtained as (grams of CO/28)×100/(grams of CO_2/44), the molecular weights of CO and CO_2 being 28 and 44 respectively.

Table 3. Particle emission factors (g/kg) and ratios relative to total emissions, one test only

	Cooling particles from smoldering fire		Warming particles from flaming fire	
	EF OM (g/kg)	% OM	EF EC (g/kg)	% EC
Three-stone	1.45	62	0.88	38
Rocket	0.55	32	1.16	68
Karve	0.82	74	0.28	26
Fan	0.14	71	0.06	29
Charcoal	1.54	88	0.20	12

Table 4. Fuel carbon ratios, estimate for both high and low power

Fuel	g carbon/g fuel	% carbon to CO_2	Mass CO_2/mass fuel
Douglas fir	0.5 [FAO, 1997]	90	1.7
Charcoal	0.82 [Ferreira, 2006]	65	2.0

3.2. Emissions from incomplete combustion

It seems that when combustion is cleaner, i.e., emissions of gaseous pollutants are lower, the effect is seen in all gases about equally. Emissions in terms of pollutant/CO_2 ratios are shown in Table 2. The fan stove showed extremely low emissions of all gases, followed by the rocket and the gasifier stoves. Charcoal-burning produced extremely high emissions of carbon monoxide, as well as methane and other unburned hydrocarbons. Emissions of nitrous oxide were negligible in these wood- and charcoal-burning stoves, though it can be present in other forms of biomass combustion.

Particulate matter emissions must be broken down into the type of particles for global warming analysis. Elemental carbon (EC), or black particles, comprising soot generated in flaming fires, is strongly warming in the atmosphere. Organic carbon (OC) and organic matter (OM), or white particles produced in smoldering fires, have a cooling effect on the atmosphere. Since the manner in which the fire is tended (whether smoldering or flaming) can have a significant effect on the type of particles produced, user tendencies should be considered. Local practice, as well as wood species and moisture content, are also important variables. However, the type of stove also seems to play a substantial role.

Table 3 shows the breakdown of particle types emitted from each stove. The three-stone fire typically consists of a larger bed of charcoal under the flaming fuel, resulting in both black and white particles. The rocket stove has a stronger draft and higher combustion temperatures, resulting in less charcoal and higher flame and thus a higher fraction of warming particles. On the other hand, the smoldering gasifier stove created little flame, but more charcoal, which produced more cooling than warming particles. Finally, charcoal-burning produced almost all white particles, which is typical of a smoldering fire.

3.3. Emissions per task completed

When the rate of exhaust flow through the emission hood is not known, the mass of fuel burned can be used to estimate the actual mass of CO_2 produced, using a carbon balance:

mass CO_2/mass fuel = (g carbon/g fuel) × % carbon converted to CO2 × (44 g CO_2/12 g carbon)

[Roden and Bond, 2006; Zhang et al., 2000; Smith et al., 1993]

The fraction of carbon going to CO_2 shown in Table 4 is estimated on the basis of the emission levels of the products of incomplete combustion, such as carbon monoxide and particles.

For every g of wood fuel, approximately 1.7 g of CO_2 are produced as emissions. The number of grams of CO_2 is then multiplied by the pollutant/CO_2 ratio to determine the mass of each pollutant produced. Finally, these masses are normalized on the basis of the starting temperature of the water and divided by the amount of water remaining at the end of each test phase which results in a measure of emissions per task (1 l of water boiled and simmered 30 minutes) completed.

Before factoring by GWPs, the equivalent mass of the gaseous emissions per task completed are shown in Table 5.

In a similar fashion, the ratios of warming and cooling particles can be applied to the total particles, showing the total mass of each particle type emitted, as

Table 5. Specific emissions, or mass of emissions produced to boil 1 l and then simmer for 30 minutes

Specific emissions (g/l)	Three-stone fire	Rocket	Fan	Gasifier	Charcoal
CO_2	536	206	277	356	300
Methane	0.6	0.1	0.0	0.4	3.0
N_2O	0.00	0.00	0.00	0.00	0.00
NMHC	1.4	0.3	0.4	1.5	2.5
CO	37	4	1	7	72

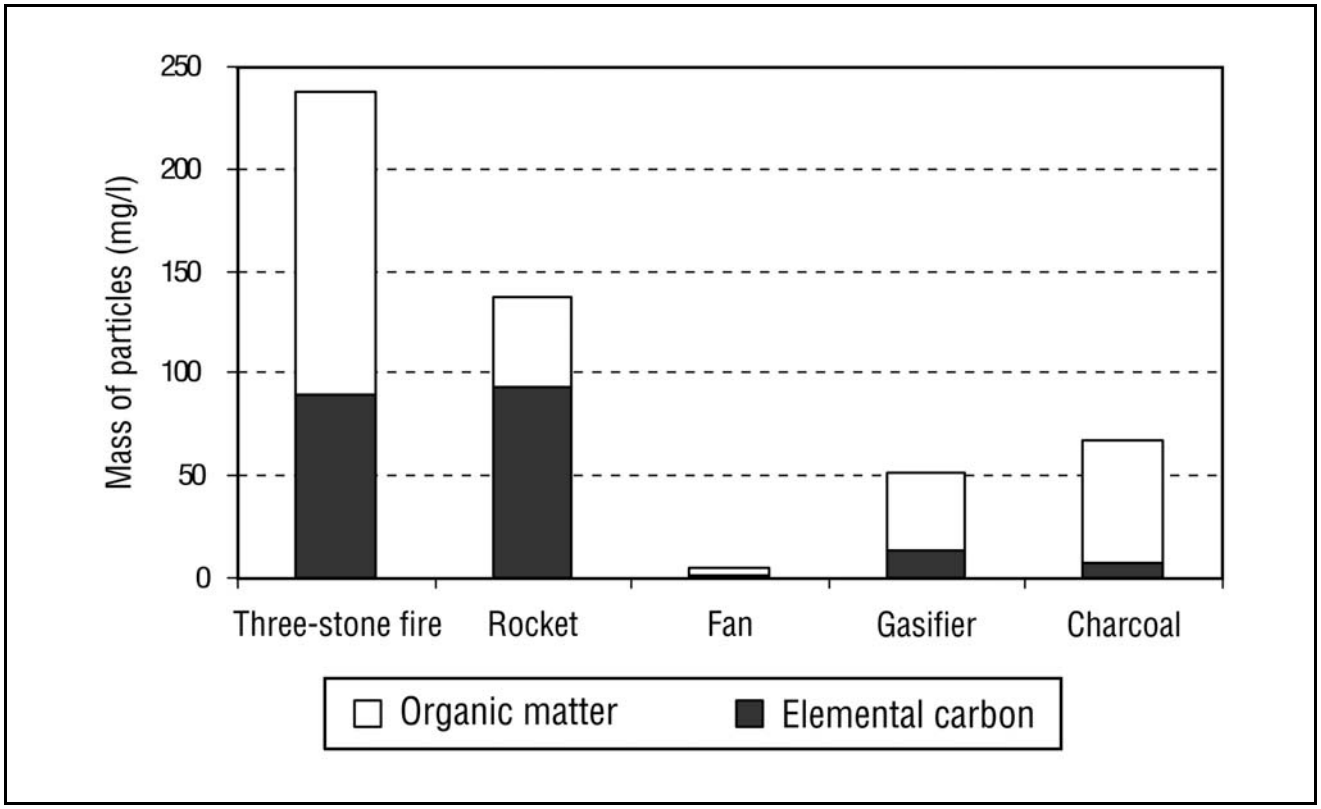

Figure 4. Speciated particle mass emissions, per liter of water boiled and simmered 30 minutes. Unweighted for global warming potential. One test only.

shown in Figure 4.

The fan stove was amazingly clean and emitted very low levels of both types of particulate matter compared to the other stoves. The gasifier and charcoal stoves made about 1/3 of the PM per liter of water compared to the three-stone fire. The hot flames produced in the vertical combustion chamber of the rocket stove created the same amount of black carbon as the open fire but significantly less organic matter, and therefore lower total particulate emission.

3.4. Total global warming impact

When the GWP for each pollutant is applied to all the emissions, including particulate matter, all emissions are combined onto the same scale as grams of CO_2 equivalent.

Figure 5 presents the overall global warming impact, or radiative forcing, including CO_2 as if the biomass was not harvested sustainably:

Notice that the warming black carbon particles have a significantly stronger (680/50 = 14 times stronger) effect than the organic carbon (cooling) particles. Due to the large difference, it is nearly impossible for the cooling particles to overpower the warming ones, even in purely smoldering fires. *It should also be noted that the emission from burning charcoal presented here does not include the significant emissions released when the charcoal is made from wood.*

Alternatively, when biomass is harvested sustainably, the CO_2 emissions from biomass-burning are considered to be greenhouse-neutral. Figure 6 shows the global warming impact of the PICs only:

Table 6 shows the global warming impact of carbon dioxide as well as products of incomplete combustion for all stoves tested.

Although this laboratory study should not be used to specifically predict real-world performance, it is interesting to project the potential savings in tonnes of CO_2 equivalent per stove per year, as shown in Table 7. The data do tend to be in line with estimates used by some carbon-offset companies, as well as data from an Aprovecho Research Center field study in India which

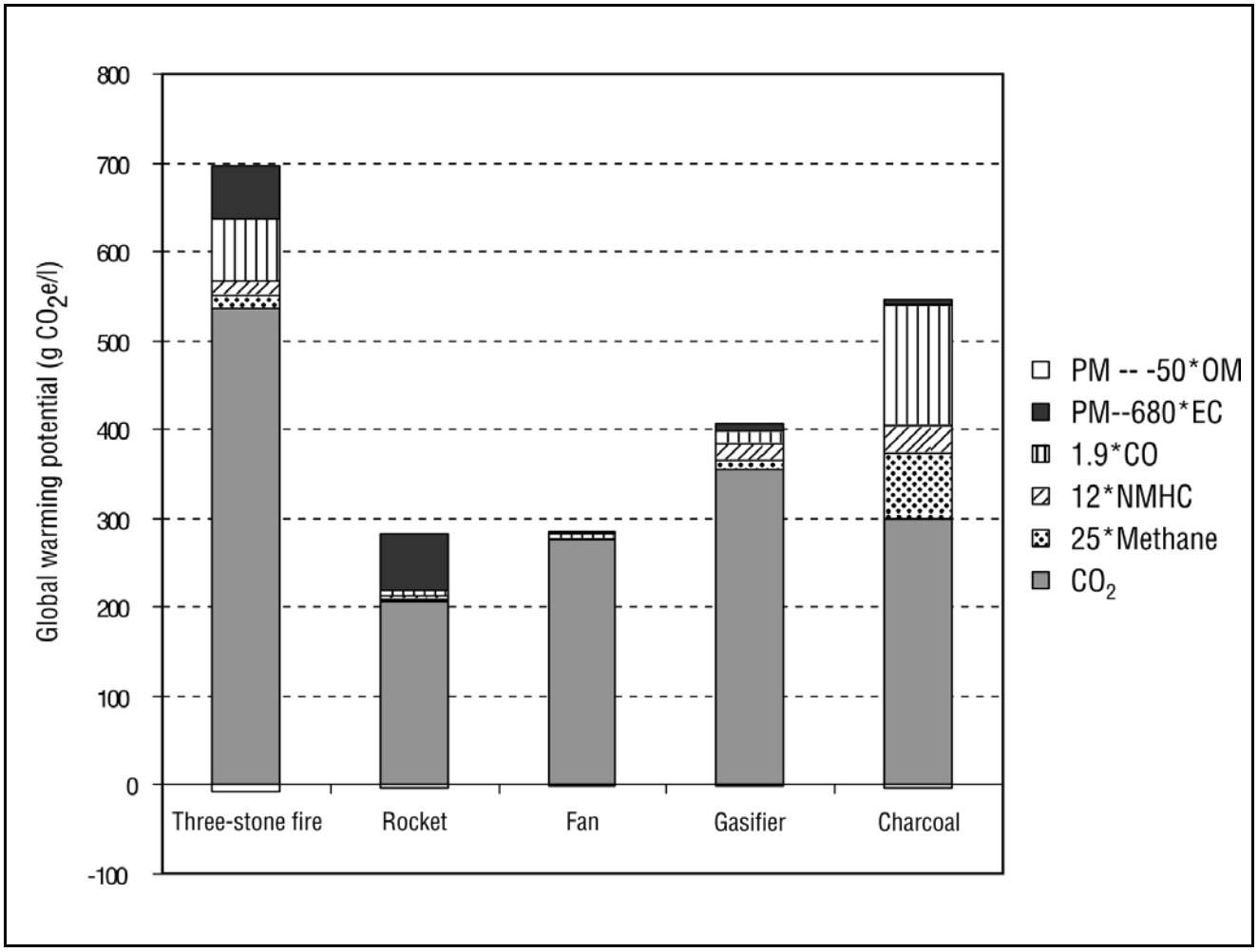

Figure 5. Total global warming impact, grams CO_2 equivalent on a 100-year time-frame, per liter of water boiled and simmered for 30 minutes, normalized for starting temperature and fuel moisture content. Inclusive of CO_2 and all PICs.

Table 6. Global warming impact for the traditional and improved stoves. Each stove is also analyzed relative to the traditional three-stone fire. Data are shown in grams CO_2 equivalent on a 100-year time frame, per liter of water, and percentages.

	Three-stone fire	Rocket	Fan	Gasifier	Charcoal
CO_2 (g/l)	536	206	277	356	300
Non-CO_2 gases (g CO_2e/l)	100	14	6	42	240
Particles	54	61	1	7	2
Impact of PICs (g CO_2e/l)	154	75	7	49	243
Relative to three-stone fire, PIC only (%)	100	49	5	32	157
Total impact (gCO_2e/l)	690	281	284	405	543
Relative to three-stone fire, PIC + CO_2 (%)	100	41	41	59	79
PIC/total impact (%)	22	27	3	12	45

will be published soon.

The average American emits about 20 tonnes (t) of CO_2 overall per year [UCS, 2006], while driving an average gasoline vehicle emits about 5 t of CO_2 alone [EPA, 2005]. Considering these high developed-world emissions, a potential saving of 1.5 t per year from a simple stove can be substantial.

4. Discussion

Improved wood-burning cookstoves can significantly decrease the global warming impact of a cooking task. In these laboratory tests, several improved biomass stoves (the rocket stove, fan stove, and gasifier stove) displayed substantially reduced GWPs compared to the three-stone fire. When fuel is harvested sustainably, the fan stove

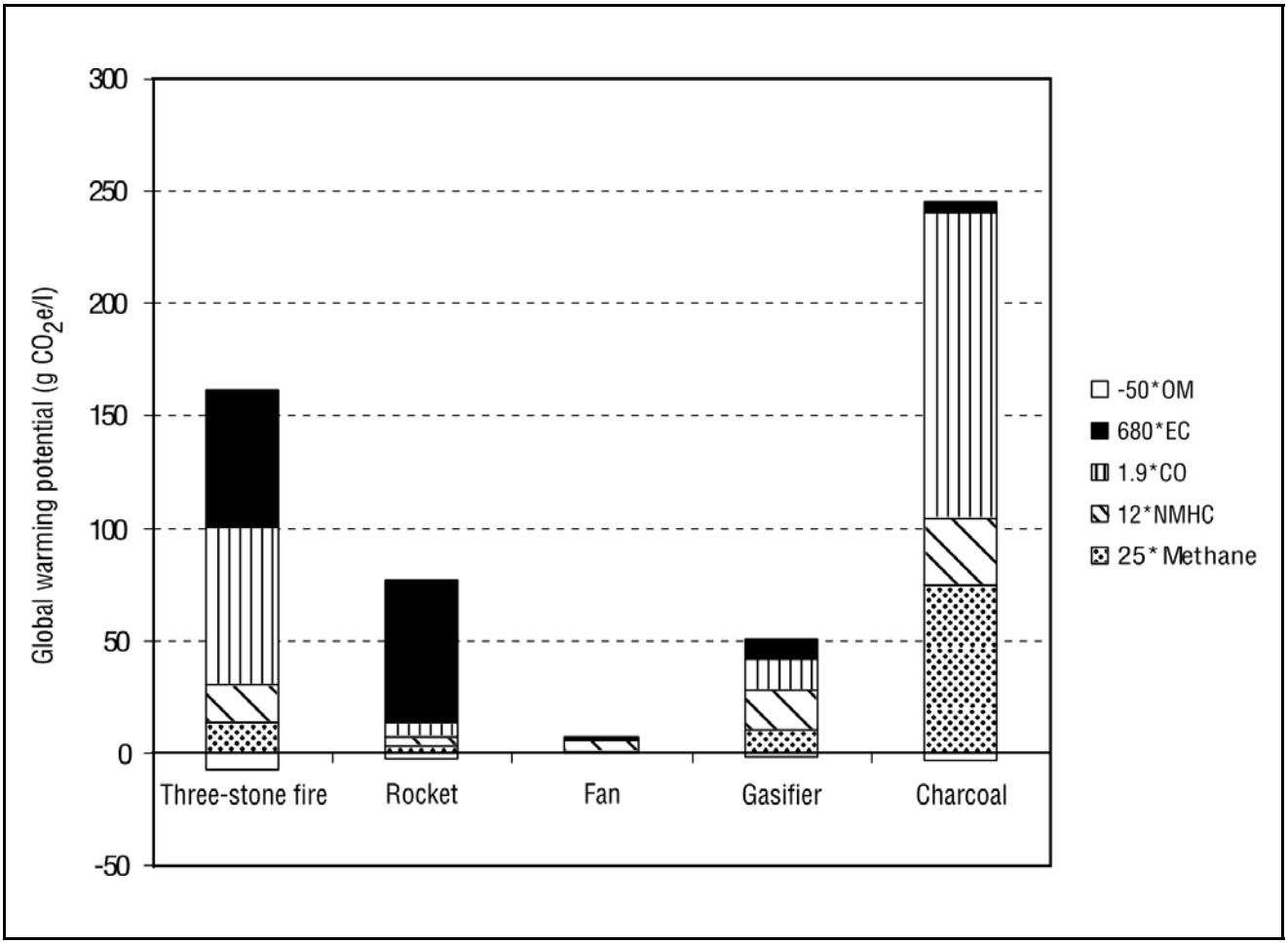

Figure 6. Global warming impact of only the products of incomplete combustion, grams CO_2 equivalent on a 100-year time-frame, per liter of water boiled and simmered for 30 minutes, normalized for starting temperature and fuel moisture content.

Table 7. Potential annual savings (tCO_2e) per stove based on 10 l cooked per day

	Three-stone fire	Rocket	Fan	Gasifier	Charcoal
PICs emitted per year[1]	0.6	0.3	0.0	0.2	0.9
PICs + CO_2 emitted per year[1]	2.5	1.0	1.0	1.5	2.0
Savings over three-stone fire					
Sustainable biomass harvesting		0.3	0.5	0.4	-0.3
Non-sustainable biomass harvesting		1.5	1.5	1.0	0.5

Note

1. Estimate based on laboratory study. Specific field data are necessary for estimating real-world emission reductions through improved stoves.

(which produced much less particulate matter) far outperformed the rocket and gasifier stoves. If wood is not harvested sustainably the fan stove and rocket stove have approximately equal effects due to the lower fuel use in the skirted rocket stove.

The products of incomplete combustion (PICs) contribute 22 % to the overall global warming impact of the open fire, 27 % to the rocket stove, and 45 % to the charcoal stove. This suggests that estimates of carbon reductions based on fuel use alone would not be accurate.

Further field studies will be necessary to quantify the carbon savings from the use of specific stoves. Laboratory data can identify which stove types look promising. However, follow-up studies in the field need to be conducted to quantify the levels of emissions found in the real world. A key intention of this study was to investigate how global warming studies can best be done in the field.

Recommendations for future field studies include the following.

- For EC/OC particle analysis, real-time measurements with a PSAP do not seem to be necessary. An inexpensive filter system can suffice, reducing the cost and

technical know-how required to conduct measurements. Subsequent filter analysis at a high-tech laboratory should be reliable.

- Similarly, real-time measurements of the gaseous emissions may not be necessary. A simple Tedlar (polyvinyl fluoride material with low vapor permeability) bag collection system could be preferable in the field, with bag samples sent to a laboratory for analysis.
- Although N_2O is a strong climate-forcing constituent, emissions from the wood- and charcoal-burning stoves were very low, contributing less than 1 % to the overall warming potentials. Since measurement of this gas is the most difficult, it may not be necessary to include it in field evaluations.
- The emission collection hood system was effective for measuring emissions. When a portable emission hood, now available from Aprovecho Research Center, is fitted with a filter and bag sampling system, reliable field data can be generated for a low cost and with minimal "expert" involvement.
- It is hoped that once a significant number of field studies have been completed, an expected relationship may be established between methane and NMHC against CO_2 for differing combustion types and fuels. If this is the case, field measurements may be further simplified.

Both burning wood and charcoal and using various combustion methods have been found to create different patterns of emissions. The data presented suggests that there are stoves that can be designed to (1) reduce the fuel used to cook, (2) reduce health-damaging emissions and (3) address climate change. The considerable difference in climate-changing emissions from the stoves in this study should be noted. Large-scale use of cleaner burning stoves might well reduce global warming effects. ■

Acknowledgements

Many thanks to the University of Illinois – Urbana/Champaign, Colorado State University, and the participants at the Aprovecho Research Center's Summer Stoves Camp 2006. Special thanks to Caroline Okwiri and the Shell Foundation for providing funding for this study.

References

Adhikary, B., Carmichael, G., Tang, Y., Leung, L.-Y.R., Qian, Y., Schauer, J.J., Stone, E.A., Ramanathan, V., and Ramana, M.V.., 2007. "Characterization of the seasonal cycle of south Asian aerosols: a regional-scale modeling analysis", *J. Geophys. Res.,* 112, doi:10.1029/2006JD008143.

Bailis, R., Berrueta, V., Chengappa, C., Dutta, K., Edwards, R., Masera, O., Still, D., and Smith, K.R., 2007a. "Performance testing for monitoring improved biomass stove interventions: experiences of the Household Energy and Health Project", *Energy for Sustainable Development,* Volume XI, No. 2, June.

Bailis, R., Ogle, D., MacCarty, N., and Still, D., 2007b. *The Water Boiling Test (WBT),* Household Energy and Health Programme, Shell Foundation, 2003, revised 2007.

Ballard-Tremeer, G., 1997. *Emissions of Rural Wood-Burning Cooking Devices,* Ph.D. thesis, Faculty of Engineering, University of the Witwatersrand, Johannesburg.

BBC News (BBC), 2007. "Asia's brown clouds 'warm planet'", August 1.

Biello, D., 2007. "Brown haze from cooking fires cooking earth, too", *Scientific American,* August 1.

Bond, T.C., and Sun, H., 2005. "Can reducing black carbon emissions counteract global Warming?", *Environmental Science and Technology,* Volume 39, Issue 16, pp. 5921-5926.

Bond, T., Venkataraman, C., and Masera, O., 2004. "Global atmospheric impacts of residential fuels", *Energy for Sustainable Development*, Volume VIII, No. 3, September, pp. 20-32.

Bond, T.C., 2007. Private communication, April 19.

Bryden, M., Still, D., Scott, P., Hoffa, G., Ogle, D., Bailis, R., and Goyer, K., 2005. *Design Principles for Wood Burning Cook Stoves,* Aprovecho Research Center/Shell Foundation/Partnership for Clean Indoor Air, USEPA EPA-402-K-05_004.

Edwards, R.D., and Smith, K.R., *Carbon Balances, Global Warming Commitments, and Health Implications of Avoidable Emissions from Residential Energy Use in China: Evidence from an Emissions Database",*
http://www.giss.nasa.gov/meetings/pollution2002/d3_edwards.html, 8 April.

EPA (US Environmental Protection Agency), 2005. Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel, EPA420-F-05-001. February.

FAO (Food and Agriculture Organization of the United Nations), 1997. *Energy and Environment Basics,* Regional Wood Energy Development Programme in Asia, Food and Agriculture Organization of the United Nations, Report GCP/RAS/154/NET, compiled in collaboration with the Technology and Development Group, University of Twente, Netherlands, Bangkok, July, http://www.rwedp.org/acrobat/rm29.pdf.

Ferreira, O.C., 2006. "Carbon content in biomass fuel", *Economy and Energy*, August-September, http://ecen.com/eee57/eee57e/carbon_content_in_biomass_fuel.htm.

Flanner, M.G., Zender, C.S., Randerson, J.T., and Rasch, P.J., 2007. "Present-day forcing and response from black carbon in snow", *J. Geophys. Res.* 112, doi:10.1029/2006JD008003.

IPCC (Intergovernmental Panel on Climate Change), 2007. "Changes in atmospheric constituents and in radiative forcing", in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* (Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L., (eds.)), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, Chapter 2 ("Changes in atmospheric constituents and in radiative forcing"), Table 2.14.

Philips, 2006. "Philips develops a woodstove that saves lives and preserves energy resources", Philips Research press release, February 2,
http://www.research.philips.com/newscenter/archive/2006/060227-woodstove.html.

Raj, N.G., 2007 "Seeking to make fire without smoke", *The Hindu,* Chennai, India, June 28.

Ramanathan, V., and Carmichael, G., 2008. "Global and regional climate changes due to black carbon", *Nature Geoscience,* Vol. 1, April, www.nature.com/naturegeoscience.

Revkin, A.C., 2008. "Soot in the greenhouse, and kitchen", *New York Times,* March 26.

Roden, C.A., and Bond, T.C., 2006. "Emission factors and real-time optical properties of particles emitted from traditional wood burning cookstoves", *Environmental Science and Technology,* Volume 40, Issue 21, pp. 6750-6757.

Samson, R., 2007. "Greenhouse gas emissions", presented at the Partnership for Clean Indoor Air Conference in Bangalore, India, March 10-13.

Smith, K.R., Uma, R., Kishore, V.V.N., Zhang, J., Joshi, V., and Khalil, M.A.K., 2000. "Greenhouse implications of household stoves: an analysis for India", *Annual Review of Energy and Environment,* vol. 25, pp. 741–63.

Turpin, B.J. and Lim, H.-J., "Species contributions to PM2.5 mass concentrations: revisiting common assumptions for estimating organic mass", *Aerosol Science and Technology,* 2001, *35,* pp. 602-610.

UCS (Union of Concerned Scientists), 2006. *What's Your Carbon Footprint?,*
http://www.ucsusa.org/publications/greentips/whats-your-carb.html, February.

Zhang, J., Smith, K.R., Ma, Y., Ye, S., Jiang, F., Qi, W., Liu, P., Khalil, M.A.K., Rasmussen, R.A., and Thorneloe, S.A., 2000. "Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors", *Atmos. Environ.,* 34, pp. 4537-4549.