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 CO2, 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 CO2 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 CO2 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 CO2 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 (CO2), methane (CH4), and nitrous oxide (N2O), 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 CO2 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 CO2 released in combustion is theoretically reabsorbed by the biomass growing to replace it. If biomass is not harvested sustainably, then the CO2 released when burned is contributing to the build-up of CO2 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 (CO2). 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 CO2. Eventually most PICs are oxidized to CO2, but in the meantime they have greater global warming potential (GWP) than CO2. Indeed, if one is going to put carbon gases into the atmosphere, the least damaging from a global warming standpoint is CO2; 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 CO2. 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 CO2 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 (CH4). Methane is a relatively potent greenhouse gas. Averaged over 100 years, CH4 has a GWP 25 times as much as the same mass of CO2. 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 CO2, with climate-forcing occurring because of their contribution to ozone formation [Edwards and Smith, 2002].

Nitrous oxide (N2O). A powerful greenhouse gas, nitrous oxide has an atmospheric lifetime of 120 years and a GWP of 298 over 100 years. N2O is also a part of the Kyoto Accords and one of the primary gases considered in inventories of biomass-burning [IPCC, 2007].

Oxides of nitrogen (NOx). NOx is a broad term for the various nitrogen oxides (other than N2O) produced during combustion when combustion temperatures reach a high enough level to burn some of the nitrogen in the air. NOx 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 NOx [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 firing flames 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 CO2 [Rodan 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 CO2 (i.e., a cooling 75 times that of CO2) [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

<table>
<thead>
<tr>
<th>Emission</th>
<th>Global warming potential, 100-year CO$_2$ equivalent</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>1</td>
<td>IPCC, 2007</td>
</tr>
<tr>
<td>CO</td>
<td>1.9</td>
<td>IPCC, 2007</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>25</td>
<td>IPCC, 2007</td>
</tr>
<tr>
<td>NMHC</td>
<td>12</td>
<td>Edwards and Smith, 2002</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>298</td>
<td>IPCC, 2007</td>
</tr>
<tr>
<td>PM - EC</td>
<td>680</td>
<td>Roden and Bond, 2006; Bond and Sun, 2005</td>
</tr>
<tr>
<td>PM - OM</td>
<td>-50</td>
<td>Estimate – Bond, 2007</td>
</tr>
</tbody>
</table>

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].

Three-stone fire

Rocket stove with skirt

Karve gasifier

Philips prototype fan stove

Charcoal jiko

Figure 1. The five stove models investigated

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
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 fuel 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-Tremere [Ballard-Tremere, 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...
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.
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/CO₂ 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 CO₂ produced, using a carbon balance:

\[
\frac{\text{mass CO}_2}{\text{mass fuel}} = \left(\frac{\text{g carbon}}{\text{g fuel}}\right) \times \% \text{ carbon converted to CO}_2
\]

For example, in the first row, the figures would be obtained as (grams of CO/28) × 100/(grams of CO₂/44), the molecular weights of CO and CO₂ being 28 and 44 respectively.

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

<table>
<thead>
<tr>
<th>Fuel</th>
<th>g carbon/g fuel</th>
<th>% carbon to CO₂</th>
<th>Mass CO₂/mass fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas fir</td>
<td>0.5 [FAO, 1997]</td>
<td>90</td>
<td>1.7</td>
</tr>
<tr>
<td>Charcoal</td>
<td>0.82 [Ferreira, 2006]</td>
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Table 3. Gaseous emissions in percentage relative to CO₂ on a molar basis, average of three tests

<table>
<thead>
<tr>
<th></th>
<th>Three-stone fire</th>
<th>Rocket Philips fan</th>
<th>Gasifier</th>
<th>Charcoal</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>3.75</td>
<td>1.74</td>
<td>0.36</td>
<td>2.95</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.13</td>
<td>0.11</td>
<td>0.02</td>
<td>0.27</td>
</tr>
<tr>
<td>NMHC</td>
<td>0.24</td>
<td>0.22</td>
<td>0.37</td>
<td>0.67</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.05</td>
<td>0.07</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>0.04</td>
<td>0.03</td>
<td>0.01</td>
<td>0.05</td>
</tr>
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</tr>
</tbody>
</table>

Note 1. Ratios are taken for number of moles of the pollutant emitted and number of moles of CO₂ 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 CO₂/44), the molecular weights of CO and CO₂ being 28 and 44 respectively.

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

<table>
<thead>
<tr>
<th></th>
<th>Cooling particles from smoldering fire</th>
<th>Warming particles from flaming fire</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EF OM (g/kg)</td>
<td>% OM</td>
</tr>
<tr>
<td>Three-stone fire</td>
<td>1.45</td>
<td>62</td>
</tr>
<tr>
<td>Rocket</td>
<td>0.55</td>
<td>32</td>
</tr>
<tr>
<td>Karve</td>
<td>0.82</td>
<td>74</td>
</tr>
<tr>
<td>Fan</td>
<td>0.14</td>
<td>71</td>
</tr>
<tr>
<td>Charcoal</td>
<td>1.54</td>
<td>88</td>
</tr>
</tbody>
</table>

3.2. Emissions from incomplete combustion

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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 CO₂ equivalent.

Figure 5 presents the overall global warming impact, or radiative forcing, including CO₂ 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 CO₂ 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 CO₂ 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
The average American emits about 20 tonnes (t) of CO\textsubscript{2} overall per year [UCS, 2006], while driving an average gasoline vehicle emits about 5 t of CO\textsubscript{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

![Graph showing total global warming impact of different stoves](image)

**Figure 5.** Total global warming impact, grams CO\textsubscript{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\textsubscript{2} and all PICs.

<table>
<thead>
<tr>
<th>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\textsubscript{2} equivalent on a 100-year time frame, per liter of water, and percentages.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO\textsubscript{2} (g/l)</td>
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<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>536</td>
</tr>
<tr>
<td>Non-CO\textsubscript{2} gases (g CO\textsubscript{2}e/l)</td>
</tr>
<tr>
<td>Particles</td>
</tr>
<tr>
<td>Impact of PICs (g CO\textsubscript{2}e/l)</td>
</tr>
<tr>
<td>Relative to three-stone fire, PIC only (%)</td>
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<tr>
<td>Total impact (gCO\textsubscript{2}e/l)</td>
</tr>
<tr>
<td>Relative to three-stone fire, PIC + CO\textsubscript{2} (%)</td>
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<tr>
<td>PIC/total impact (%)</td>
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</table>
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

<table>
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<th>Table 7. Potential annual savings (tCO₂e) per stove based on 10 l cooked per day</th>
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<tr>
<td>Three-stone fire</td>
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<tr>
<td>PICs emitted per year[1]</td>
</tr>
<tr>
<td>PICs + CO₂ emitted per year[1]</td>
</tr>
<tr>
<td>Savings over three-stone fire</td>
</tr>
<tr>
<td>Non-sustainable biomass harvesting</td>
</tr>
</tbody>
</table>

Note 1. Estimate based on laboratory study. Specific field data are necessary for estimating real-world emission reductions through improved stoves.
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 N₂O 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 CO₂ 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.

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References


