AN ESTIMATE OF GREENHOUSE GAS EMISSIONS FROM COMMON KENYAN COOKSTOVES UNDER CONDITIONS OF ACTUAL USE

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ABSTRACT

We report on greenhouse gas emissions from wood and charcoal cookstoves measured during actual conditions of use in 19 randomly selected rural Kenyan households. CO, particulate matter (PM_{10}), mass of fuel, and the state of combustion were measured or recorded in real-time. Emissions of pollutants other than CO and particulates were estimated using data adapted from extant literature. We find the average daily emissions from charcoal stoves are lower than woodstoves when measured in terms of carbon released. However, when the emissions are weighted to account for global warming potential, charcoal stoves are much more polluting than wood stoves by any metric. Further, accounting for emissions from charcoal production increases the disparity between charcoal and firewood. However charcoal still carries potential health benefits at the household level because of reduced particulate emissions relative to firewood combustion. Some policy options are discussed in light of these potentially conflicting findings.

INDEX TERMS

Greenhouse gases, woodfuel, biomass combustion, emissions factors, household energy

INTRODUCTION

Between one-third and one-half of the world's population rely on solid biofuels – wood, crop residues, charcoal, and dung – for the majority of their energy needs. Solid biofuel users typically rely on "three-stone" fires and mud, clay, or metal stoves, which do not achieve complete combustion and release pollutants that are damaging to human health. The linkages between indoor air pollution from biomass fuels and human health in developing countries have been examined in a number of research projects (Bruce et al. 2000; Smith et al. 2000a; Ezzati and Kammen, 2001a, b). An additional consequence of domestic biomass combustion that may influence public health, although in a less direct way, is the emission of greenhouse gases.

Under optimal conditions, combustion of biomass results solely in the emission of water vapor and carbon dioxide (CO_2). Therefore, if biomass is harvested in a sustainable way and burned under ideal combustion conditions, it is effectively GHG neutral. However, under incomplete combustion conditions, hundreds of gaseous and aerosolized compounds are emitted from biofuels in addition to CO_2 and water (Smith, 1987; UNDP, 2000). These compounds, known collectively as products of incomplete combustion (PICs), include carbon monoxide (CO), methane (CH_4), non-methane hydrocarbons (NMHCs), particulate matter (PM) and an array of additional pollutants. CO, CH_4, and NMHCs all affect the radiative balance of the atmosphere to an equal or greater extent than an equivalent amount of CO_2

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(IPCC, 2001). If fuel is harvested sustainably, CO_2 released by combustion is removed from the atmosphere by future plant growth. However non-CO_2 GHGs are not absorbed by new biomass growth and remain in the atmosphere (Levine et al., 1995). This paper reports estimates of greenhouse gas (GHG) emissions from domestic biomass-burning cookstoves used by an agro-pastoral community in central Kenya. We measured emissions from cookstoves commonly used by the community as well as new stoves introduced to the community as part of a broader study on household energy, indoor air pollution, and health, explained in detail in prior publications (Ezzati and Kammen, 2001a,b).

The ability of a chemical compound to trap heat in the atmosphere is termed *radiative forcing*. A convenient way to compare this ability across different compounds is to define a global warming potential (GWP), which is a time-dependent ratio of the radiative forcing of the compound in question to an equivalent quantity of CO_2 (IPCC, 2001). Table 1 shows the 20-yr global warming potential (GWP) on a molar basis for the most prevalent greenhouse gases in typical biomass combustion emissions.

Table 1. 20 Year Global Warming Potentials – molar basis (from IPCC, 2001).

Compound	CO_2	CO	CH_4	NMHC	N_2O
20 Year GWP	1	2-6	22.5	12	275

METHODS

The study took place at Mpala Ranch and Research Centre, in Laikipia District, central Kenya. Firewood and charcoal are the main fuels in the study households. The houses are cylindrical with mud and dung walls and conical straw roofs. The stoves used by the households are unvented, and burn firewood or charcoal. Wood is collected by household members and consisted mostly of acacia species and is normally air-dried. Dryness was confirmed qualitatively in each measurement day. We assume the dry wood has a 20% moisture content (wet-basis) and an energy content of 16 MJ/kg. Charcoal is produced locally, also from acacia species, and has an energy content of ~29 MJ/kg (Smith et al., 2000b).

Table 2. Emissions ratios for firewood and charcoal combustion from Brocard et al. (1996).

	Firewood Combustion (%)					Charcoal (%)	
	Weighted avg[a]	Ignition	Flaming	Glowing	Smoldering	Making	Burning
CO/CO_2	7.9	26.1	5.7	15.0	21.0	24.0	15.5
CH_4/CO_2	0.38					6.8	0.25
$NMHC/CO_2$	0.57					1.3	0.06
TSP/CO_2	1.17					3.3	0.314[b]

[a] The authors calculated a weighted average for firewood by assuming 80% of the fuel is consumed in the flaming stage, 15% in the glowing stage, and 5% in the smoldering stage.

[b] Brocard et al. did not report any emissions ratio for TSP from charcoal combustion, however Smith et al. (2000b) report a value of 0.314% for an insulated charcoal stove from.

Our estimates of carbon-based GHG emissions rely on a carbon-balance calculation, in which the carbon content of the fuel minus any unconsumed carbon in char and ash is assumed to equal the sum of carbon contained in the gaseous and aerosolized combustion emissions. See Smith et al. (2000b) for a complete discussion of these methods. The variables measured in the field included the mass of fuel input, the concentrations of CO and $PM_{10,}$ and a qualitative observation of the state of the fire. The latter was noted because fires were typically allowed to smolder throughout the entire day. To account for changes in emissions characteristics, the observed condition of the fire was divided into 5 categories: starting; burning; dying fire; hot coals; and dying coals. Calculating the net emissions required the emission ratios of some gases that were not measured directly. These were obtained from the work of Brocard et al.

(1996), who defined emission ratios relative to CO_2 (shown in Table 2). In this analysis these were adjusted to so that ratios could be expressed relative to CO. Emission ratios not reported by Brocard et al. (1996) (blank cells in Table 2) were estimated by assuming that each ratio can be scaled in proportion to the ratios that were reported for CO/CO_2. Then, direct analogies were drawn between Brocard et al.'s stages of combustion and those reported in this study. The results were added to the measured ratio of PM_{10} to CO for the separate phases of combustion in each day's measurements. Note that the carbon balance calculation should include TSP rather than PM_{10} to account for all of the carbon emitted by combustion. However, 90-95% of PM mass emitted by biomass combustion consists of particles $< 3\ \mu m$ in diameter (Smith, 1987). By measuring only PM_{10} we are likely accounting for more than 95% of TSP. The unaccounted for mass represents a negligible fraction of overall carbon mass. Further, we assume that TSP does not contribute to global warming commitment (GWC), so that a small error in TSP mass accounting will have no effect on our final calculations.

RESULTS

The estimated GHG emissions varied considerably across households using different stove/fuel combinations and between households using the same fuels. Considering the daily emissions of each household, the sum of non-CO_2 GHGs from charcoal-burning households ranged from 1600 to over 9600 g-C in CO_2 equivalent units (20-yr GWP). Despite a larger sample size, households burning wood in 3-stone fires showed a narrower range of emissions: between 1800 and 3900 g-C (CO_2 eq.). Households using ceramic stoves, the smallest group sampled, had the smallest range of daily emissions: between 1700 and 3000 g-C (CO_2 eq.).

Looking at the variability among households using the same stove/fuel combination, Figure 1 provides a picture of the total pollutant emissions in terms of carbon mass released (not weighted by GWP). It illustrates the variation that arose due to differing levels of fuel consumption and different patterns of fire maintenance. Such variation was evident even among the same households on different measurement days, as indicated by identical household number codes along the x-axis. Note the graph uses a logarithmic vertical scale.

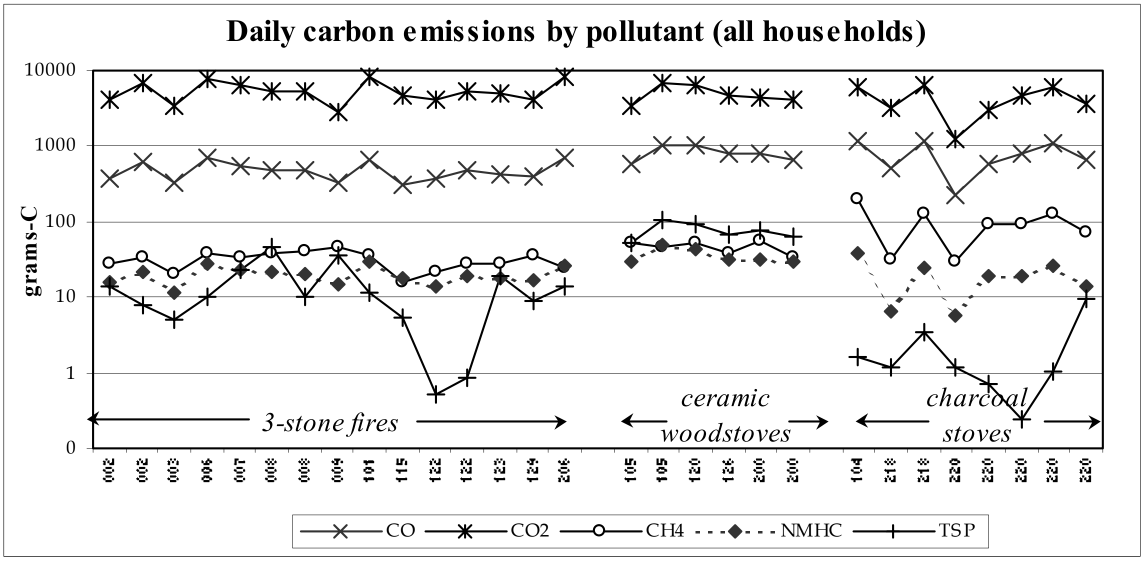

Figure 1

The daily emissions of each pollutant averaged by stove type are shown in Table 3. The table presents emissions in terms of carbon released (not weighted by GWP) and in terms of carbon in CO_2 equivalent units (weighted by 20-yr GWP) in the left and right-hand sides respectively. Because of charcoal's higher energy content, charcoal-using households tend to consume less fuel by mass and emit fewer pollutants when they are measured by mass of carbon released. However, because charcoal emits more PICs per unit mass of fuel than firewood, and those PICs have large GWPs, charcoal-use has a substantially higher daily GWC than wood burned openly or in ceramic stoves. This disparity between wood and charcoal is enhanced when fuels are used sustainably and CO_2 is omitted from the calculation.

Table 3. Estimated daily emissions in g-C (left) and GWC weighted by 20-yr GWP (right).

	Avg daily emissions (g-C)						Avg daily GWC (g-C as CO_2 in 20-yr GWP)					
	3-stone fire		Ceramic woodstoves		Charcoal stoves		3-stone fire		Ceramic woodstoves		Charcoal stoves	
	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.	mean	s.d.
Non-CO_2 GHGs							2860	680	2410	540	5550	2700
Total GHGs	5980	1900	6270	1400	5200	2000	8310	2400	8200	1800	9850	4600

Due to the assumptions in the estimations, emissions factors varied little for each phase of combustion within households using the same type of stove and fuel. Averaging over the course of the day by weighting these emission factors according to the fraction of time the fire was observed in each phase of combustion introduced variations across households using the same stove/fuel combinations because of different fire maintenance practices.

Taking CO as an example, it is estimated that in the starting phase of combustion, a three-stone wood fire emits about 188g CO per kg-fuel. Additional estimates in other phases of combustion are 52g CO per kg-fuel in the burning phase, 91g in the dying fire phase, 126g in the hot coal phase and 156g in the dying coal phase with little variation across households. Averaging over each measurement-day introduces variation for reasons discussed above, so that the CO emissions factor for each household using the 3-stone fire, averaged over the course of the measurement day, ranges from about 61g to 95g CO per kg-fuel (79 ± 7 g-CO per kg-fuel: mean ± s.d.). Emissions factors for each GHG, averaged over each stove/fuel grouping, are given in Table 4, including comparisons to findings from other studies.

Considering the uncertainties inherent in the estimations from this study, many of the results shown in Table 4 are in reasonable agreement with the results of measurements of actual stoves in use (as in Brocard et al. 1996 and Smith et al. 2000b) as well as the default factors used by the IPCC to estimate emission baselines. There are, however, some disparities. Notable among these are CH_4 and TSP for charcoal stoves. In addition, there is a lack of agreement in emission factors of NMHCs among the other studies, with the results of this study falling toward the lower end of the range. The most troubling disparity is the emissions factor for CH_4 from charcoal. Because of its large GWP, the net GWC is quite sensitive to CH_4 emissions, which may be the result of an overestimate of the GWC from charcoal stoves in this study. We discuss the sensitivity of our results to initial assumptions below.

The energy density of charcoal is roughly double that of wood so that energy-based emission factors reduce the emissions from charcoal stoves by about half relative to woodstove emission factors. Despite the favorable decrease that this calculation grants to charcoal stoves relative to woodstoves, charcoal stoves still have higher GHG emissions than woodstoves. The results of Smith et al. (2000c) show a similar outcome.

Table 4. Average emission factors per unit mass of fuel consumed for each stove/fuel grouping. All factors are reported in g-pollutant per kg-fuel except where otherwise stated.

	Estimations from this study (mean ± s.d.)			Findings from other studies						
				Brocard et al. (1996)		Smith et al. (2000b)			IPCC default factors[b]	
	3-stone fire	Ceramic wood	Charcoal	3stone fire	Char-coal	3stone fire	Ceramic wood	Char-coal	Wood	Char-coal
CO_2	1390 ± 19	1400 ± 10	2280 ± 34	1470	2260	1370	1350	2410	1370	2400
CO	79 ± 7	74 ± 6	260 ± 10	70	211	64.7	79.0	275	80	200
CH_4	3.2 ± 1.5	2.5 ± 0.9	18 ± 6	2.0	2.4	9.40	3.42	7.91	5	6
NMHC	1.6 ± 0.2	1.6 ± 0.1	3.2 ± 0.9	2.9	0.42	9.65	12.6	10.5	9	3
TSP[a]	1.1 ± 1.2	5.9 ± 0.4	0.4 ± 0.5	5	--	2.05	3.32	2.38	2.1	2.4

[a] TSP is reported in g-Carbon only. This study reports PM_{10} rather than TSP, as described above.
[b] From the Intergovernmental Panel on Climate Change (IPCC, 1997).

Sensitivity Analysis

The emission ratios adopted from the work of Brocard et al. are the foundation of the carbon balance calculations. In order to test the sensitivity of GHG emissions to the emission ratios that were assumed in the calculations, the entire analysis was repeated with the emission ratios changed from 0.10 to 2.0 times their original (baseline) values. Changing the emission ratio for each gas individually showed that the emissions of woodstoves are most sensitive to changes in CO emission ratios, while emissions of charcoal stoves are slightly more sensitive to changes in CH_4 than to changes in CO. For example, a 25% increase in CO emissions relative to CO_2 results in a net increase of the non-CO_2 GWC of 15% for both types of woodstoves and 6% for charcoal stoves. Alternatively, a 25% increase in CH_4 relative to CO_2 results in a 6% increase in non-CO_2 GWC for 3-stone fires, 4% increase for ceramic woodstoves, and 9% increase for charcoal stoves. Results for each stove-fuel category, weighted by 20-yr GWP, are shown in Figure 2. In each graph, the lines represent the percent change in net GWC, including CO_2, occurring when the emission ratio of each GHG is varied.

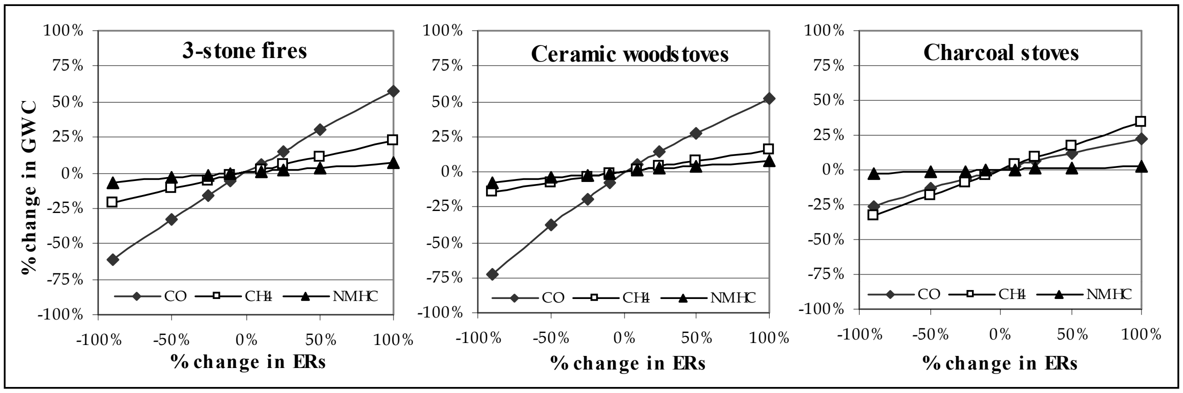

Figure 2. Sensitivity of estimated GWCs to changes in emission ratios with respect to CO_2.

CONCLUSIONS AND IMPLICATIONS

Our findings show that charcoal stoves have higher GHG emissions when the radiative forcing of the gases is included in the calculation. The GHG picture becomes still bleaker for charcoal when one considers the entire life cycle of the fuel. Unlike woodfuel, which involves few, if any, GHG emissions prior to its final combustion, charcoal combustion only represents a fraction of the net GHG emissions from the charcoal life cycle. Based on data reported in Pennise et al. (2001), charcoal production and use emits over 2600 g-C per kg (CO_2 equivalent units and 20 yr-GWP), even when stocks of biomass are not depleted. In comparison, emissions of non-CO_2 GHGs from firewood are in the range of 200-400 g-C (CO_2 equivalent units and 20 yr-GWP) per kg fuel consumed. However, when making policy decisions, the additional GHG burden associated with charcoal production and use should be considered together with several other factors including health impacts and consumer preference for, and availability of, alternative fuels. In addition, charcoal production in sub-Saharan Africa is a highly polluting process (Pennise, et. al, 2001). There are numerous technical interventions that would result in lower emissions, but the semi-illicit nature of the charcoal industry in the region makes this difficult in practice.

Assessing GHG emissions from biofuels draws attention to an aspect of domestic biofuel use that has been overshadowed by more immediate health concerns relating to emissions and exposure to health damaging pollutants (HDPs). As discussed above, biofuel-based HDPs and GHGs result from identical processes. Expanding the study of indoor air in developing countries to include emissions of GHGs would have the co-benefit of directing more attention and financial resources to mitigating one of the world's leading risk factors of morbidity and mortality.

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