GREENHOUSE GASES FROM BIOMASS AND FOSSIL FUEL STOVES
IN DEVELOPING COUNTRIES: A MANILA PILOT STUDY

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ABSTRACT

Samples were taken of the combustion gases released by household cookstoves in Manila, Philippines. In a total of 24 samples, 14 cookstoves were tested. These were fueled by liquefied petroleum gas (LPG), kerosene (three kinds of stoves), charcoal, and wood. Ambient samples were also taken. All samples were analyzed for CO_2, CO, CH_4, N_2O, and total non-methane organic compounds (TNMOC). Results generally confirm increasing emissions for most products of incomplete combustion moving down the "energy ladder" from gaseous to liquid to processed solid to unprocessed solid fuels. Although the sample size and number of background samples were too small to give great confidence in the results, extrapolation of the emission ratios (each gas relative to CO_2) to global estimates indicates that published global inventories of several gases important in atmospheric chemistry may be somewhat too small for the fuelwood combustion category. When weighted by global warming potentials, the greenhouse impact of the emissions of non-CO_2 greenhouse gases from wood combustion may rival or exceed those from CO_2 alone. If verified, this could have substantial implications for energy and environmental policies in developing countries. These tentative findings indicate that more measurements of this type in developing countries would be justified.

1. INTRODUCTION

It is clear that the products of biomass combustion play significant roles in global atmospheric chemistry and thus in the potential for global warming from an enhanced greenhouse gas effect (Seiler and Crutzen, 1980). As shown in Table 1, for example, three recent

Table 1. Estimates of global greenhouse-gas emissions from biomass burning (Tg/y, element basis)

	Biomass	Total	% Biomass[1]	% Biomass[2]	% Biomass[3]
CO_2	3500	8700	40	25-45	
CO	350	1100	32	15-50	
CH_4	38	380	10[4]	3-10	8
N_2O[2]	0.1-0.3	12-14	--	0.8-2	0.4-2
TNMOC*	24	100	24		
CH_3Cl	0.51	2.3	22		

Source: Andreae (1991) unless noted otherwise.

*Total non-methane organic compounds (including, but not limited to, NMHC, i.e., non-methane hydrocarbons)
[1] Levine, 1990; agrees with (4).
[2] Crutzen and Andreae, 1990.
[3] IPCC, 1990
[4] Cicerone and Oremland (1988).

reviews estimate the contributions of biomass combustion to global emissions to be as high as one-half for some of the major greenhouse gases. Although uncertain (Robinson, 1989), the contribution of biomass combustion to the global carbon cycle has been estimated by Crutzen and Andreae (1990). Their categories are reorganized and expanded in Table 2, which shows four categories representing large-scale open combustion (i.e., outdoor fires associated with swidden agriculture, permanent deforestation, savannas, and crop residues).

Much crop residue, however, is also burned in small-scale closed or semi-enclosed conditions inside cooking and heating stoves (perhaps 800 million people rely on such cookfuels according to Barnard, 1985). As shown, Meyers and Leach (1989) estimate crop residues used in stoves to be approximately 350 million tonnes (see also Kohlmaier et al., 1987). In addition, most firewood in the developing world is burned in semi-enclosed conditions or made into charcoal for use in such conditions. Thus, the developing-country biomass fuel flow (crop residues, fuelwood, and wood for charcoal) represents a significant fraction of total global carbon emissions from all biomass combustion, more than one-fifth and perhaps approaching one-half (based on data in Table 2).

Table 2. Total carbon released by biomass combustion

	Tg (carbon)/year
Open burning[1]	
Swidden agriculture	500-1000
Permanent deforestation	200-700
Savanna fires	300-1600
Crop residues	150-450
Enclosed burning in developing countries[2]	
Crop residues*	350
Firewood	540
Wood for charcoal	70
Wood in developed countries[3]	80
Total biomass	2100-4700
Total fossil fuels	5700

* Includes animal dung used as fuel.

[1] Crutzen and Andreae (1990)
[2] Meyers and Leach (1989)
[3] Andreae (1991)

In recent years, the wide uncertainty about the emissions from open large-scale biomass fires has led to a substantial increase in attention given to measuring and understanding these processes (Levine, 1991). Substantially less attention, however, has been given to the latter two categories, firewood and crop residues in small-scale combustion devices (e.g., one paper, Joshi, 1991).

In both categories, the uncertainty about total emissions is partly due to uncertainty in the source terms (i.e., how much is burned each year) and partly to uncertainty in the emission factors (i.e., how much of each greenhouse gas is emitted per kilogram biomass burned). In general, emissions factor estimates are based on limited sets of published measurements made in field and laboratory situations. Most of these have been designed to duplicate the conditions of open large-scale combustion (e.g., Lobert et al., 1990). As a result, the emissions from fuelwood combustion have been rated in category D in certainty, where E is least certain (Watson et al., 1991).

This is unfortunate, for it is clear that the emission factors for biomass are quite sensitive to changes in combustion conditions (Cooper and Malek, 1982; Cofer et al., 1991;

Ward and Hardy, 1991). It should not be assumed, therefore, that the emission factors derived for open large-scale combustion can be appropriately applied to small-scale semi- or completely enclosed combustion. And yet, it seems that perhaps 90% of the firewood (FAO, 1989) and a large fraction of the combusted crop residues in the world (Table 2) are burned in such conditions in household cooking and heating stoves. Although household heating stoves are important in some developed countries, cooking and space heating in developing countries account for most small-scale wood combustion on a global basis. Globally about half the households in the world use simple biomass fuels (wood, charcoal, crop residues, animal dung) for cooking (Smith, 1987).

Thus, more extensive field measurements of greenhouse-gas emission factors for a range of fuels and combustion devices would be useful in pinning down global greenhouse-gas emissions inventories that are now known within rather wide ranges of uncertainty. In addition, they would help in the design of greenhouse-gas reduction strategies, for it is possible that changes in fuel and/or combustion conditions in these small devices may be a cost-effective way to address part of the greenhouse-gas problem on a global basis.

To some observers, it might seem more appropriate to monitor greenhouse-gas emissions from such stoves in controlled settings, as is done with other combustion devices, such as gas stoves and automobiles. Unfortunately, experience has shown that slight changes in combustion conditions can have large impacts on emission factors (Ahuja et al., 1987; Joshi et al., 1989; Joshi et al., 1991). This means that it is difficult to know how well laboratory conditions actually duplicate those in the field. In any case, a better data base of field measurements will be a necessary step in eventually designing reliable laboratory measurement protocols.

Since little is known about emission factors of small-scale combustion of other fuels in developing countries, it would be valuable to sample them as well. Kerosene and liquified petroleum gas (LPG), for example, are often the fuels that first substitute for biomass as development occurs in poor countries (Smith, 1990). Consequently, their emission levels provide reasonable interim targets for what might be achieved by a program to reduce biomass fuel use in households.

Since a large-scale sampling effort to determine greenhouse-gas emission factors in developing countries would entail significant costs with uncertain benefit, it was decided to undertake a pilot study first.

2. METHODS

Using a previously prepared city-wide stratified random sample in Manila (Garcia and Manegdeg, 1991; Sathaye and Tyler, 1991), fourteen homes using six different fuel/stove combinations were chosen for taking twenty-four samples (see Table 3). Sampling involved filling an evacuated 850 cc stainless-steel canister to 2 atmospheres pressure by use of a battery-operated pump, a process taking about two minutes. Each sample was taken directly above the lit stove, at a point where the temperature of the combustion gases had cooled to about 65°C ±5°C (none of the stoves had flues or chimneys). This reduced differential condensation of hydrocarbons in the fluegas stream. The same pot was taken to each household and, with 2 liters water, placed on each stove before lighting and kept on throughout the measurement period. Because it is known that emissions from most solid fuels can vary during the burning process (Cooper and Malek, 1982), three samples were taken for each wood and charcoal session: just after lighting, after ten minutes, and at the end (i.e., at approximately thirty minutes when only char was left). These give some idea of the variation in time and can be weighted in different ways when estimating the overall average. Two outdoor samples at breathing height were also collected in the nearby residential area of Manila.

Table 3. Sampling strategy for monitoring stove emissions (Twenty-six samples total: Twenty-four emission samples and two ambient samples.

| | Wood | Charcoal | LPG | Kerosene | | | Ambient |
				Wick	Gravity	Pressure	
Sessions	3	2	2	3	2	2	2
Samples/ session	3	3	1	1	1	1	1
Total	9	6	2	3	2	2	2

The canisters were shipped back to Oregon and analyzed by techniques and methods of quality control described in Rasmussen and Khalil (1980, 1981). TNMOC was determined by the procedure established as EPA Compendium Method TO-12.[1] Laboratory blanks were retained for the canisters sent to the field. Data reported for field samples are net of the

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[1]Not reported here are results for non-methane hydrocarbons (NMHC), which are obtained by GC-FID analysis (Smith et al., 1992). TNMOC include NMHC plus others (e.g., oxygenated hydrocarbons).

concentrations found in these blanks after the field samples returned. The chromatograph were calibrated daily by the EPA TO-14 method using NIST traceable reference material.

Extensive experience on the part of one of the authors (Rasmussen) has revealed that it is not worth the cost to send out and analyze field blanks. Since the major potential contamination is outgassing from material left on the walls of the canisters, field blanks provide little information beyond what is learned from lab blanks. Furthermore, having evidence of field blank contamination during transport and handling would not help much, since there would still be need to identify just which samples were also contaminated. Conversely, even if there was no evidence of field blank contamination, there still would be such a need. To send enough field blanks to be usable on their own would be prohibitively expensive. Most important, unlike other sampling media, each canister is tested separately for leaks and contamination before being sent to the field.

One common quality assurance procedure is to take duplicate samples for comparison. For trace gas measurements in remote locations, for example, it is common to take samples in triplicate. Because of the high concentrations in this pilot study, duplicates of stove samples were not thought to be needed. Future full-scale studies might plan to take some duplicates to verify this assumption.

To guard against contamination of the canisters, there was a metal filter in line to remove aerosol from the pumping train. To prevent any possible contamination of samples from material left on the filter, one-time use of disposable filters should be used in the next study.

3. RESULTS

Table 4a lists the emitted concentrations (net of the mean Manila background levels) for the principal gases of interest here: CO, CH_4, CO_2, N_2O, and total non-methane organic compounds (TNMOC). Table 4b shows the resulting emission ratios in a dimensionless format, that is, as a molecular ratio to CO_2.[2]

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[2] Not reported here are data for three CFCs, five other halocarbons, detailed speciation for several dozen hydrocarbons, and three ambient samples taken in Bangkok, Thailand (Smith et al., 1992).

Table 4a. Net concentrations (flue gas minus ambient)

Fuel	CO_2 ppm	CO ppm	CH_4 ppm	N_2O ppb	TNMOC ug/m³
LPG	5600	12.3	- 0.3	54.5	460
	1380	31.1	0.1	14.5	3396
Kero-pres	1812	49.5	0.7	0.5	8964
	3491	20.5	- 0.3	24.5	1766
Kero-grav	331	7.3	0.2	16.5	764
	6142	139.8	4.9	47.5	26159
Kero-wick	666	8.3	0.3	17.5	18007
	4727	109.9	3.3	23.5	27581
	3647	93.3	10.4	28.5	11048
Char #1	690	90.0	7.5	13.5	1578
	9039	746.4	68.2	188.5	6683
	764	68.7	2.1	4.5	2403
Char #2	5482	720.4	63.2	49.5	19468
	4080	721.9	49.3	78.5	6808
	3912	677.1	20.7	24.5	5448
Wood #1	5164	635.9	54.3	149.5	58476
	4562	43.1	1.7	155.5	8994
	1715	285.9	75.4	22.5	44973
Wood #2	5558	191.1	8.8	316.5	19736
	786	64.8	4.6	46.5	5860
	1938	260.6	40.6	109.5	30001
Wood #3	8863	698.4	80.4	494.5	96902
	9215	727.4	199.3	174.5	75504
	3305	537.1	79.6	59.5	50053

Ambient (actual measurements)

Fuel	CO_2 ppm	CO ppm	CH_4 ppm	N_2O ppb	TNMOC ug/m³
Manila	381	1.1	3.4	315	420
	379	1.5	2.0	310	193

Note: All digits used in calculations are shown, but only one or two places of precision are justified in terms of actual uncertainty.

Table 4b. Emission ratio to CO_2

Fuel	CO	CH_4	N_2O	TNMOC
LPG	0.002	-5.4E-05	9.7E-06	1.4E-04
	0.023	7.2E-05	1.1E-05	4.1E-03
Kero-pres	0.027	3.9E-04	2.8E-07	8.3E-03
	0.006	-8.6E-05	7.0E-06	8.4E-04
Kero-grav	0.022	6.0E-04	5.0E-05	3.9E-03
	0.023	8.0E-04	7.7E-06	7.1E-03
Kero-wick	0.012	4.5E-04	2.6E-05	4.5E-02
	0.023	7.0E-04	5.0E-06	9.7E-03
	0.026	2.9E-03	7.8E-06	5.1E-03
Char #1	0.130	1.1E-02	2.0E-05	3.8E-03
	0.083	7.5E-03	2.1E-05	1.2E-03
	0.090	2.7E-03	5.9E-06	5.3E-03
Char #2	0.131	1.2E-02	9.0E-06	5.9E-03
	0.177	1.2E-02	1.9E-05	2.8E-03
	0.173	5.3E-03	6.3E-06	2.3E-03
Wood #1	0.123	1.1E-02	2.9E-05	1.9E-02
	0.009	3.7E-04	3.4E-05	3.3E-03
	0.167	4.4E-02	1.3E-05	4.4E-02
Wood #2	0.034	1.6E-03	5.7E-05	5.9E-03
	0.082	5.9E-03	5.9E-05	1.2E-02
	0.134	2.1E-02	5.7E-05	2.6E-02
Wood #3	0.079	9.1E-03	5.6E-05	1.8E-02
	0.079	2.2E-02	1.9E-05	1.4E-02
	0.163	2.4E-02	1.8E-05	2.5E-02

See note, Table 4a.

Note that the high variability seen in Table 4a is expected, because of variations in the geometry and other uncontrolled conditions of sampling, such as room temperature. Assuming that the fire is the major source of the net measured combustion-related gases, the differences among the ratios to CO_2 in Table 4b, should mainly reflect differences in actual stove emissions.

Table 5 and Figure 1 show the same data aggregated into the overall mean, coefficient of variation (CV), and median for each fuel and pollutant (the high CVs for LPG reflect the small sample size (2). Shown also for the solid fuels are the means and Cvs of those samples taken at each of the three times during the burn (start, ten minutes, end). For the solid fuels, weighted means are created by multiplying the means of samples taken at the beginning and end of the burn by 0.25 each and the mean of the middle sample by 0.5 and then summing (see Dasch, 1982, for a discussion of changes in emissions during wood burning).

Table 5. Emission ratio to CO_2: Summary statistics

Fuel (n)	CO	CV	CH_4	CV	N_2O	CV	TNMOC	CV	Statistic
LPG (2)	0.012	1.2	3.6E-05	1.4	1.0E-05	0.05	2.1E-03	1.3	mean
Kero (7)	0.020	0.39	8.3E-04	1.1	1.5E-05	1.2	8.8E-03	0.96	overall mean
	0.023		7.0E-04		7.8E-06		7.1E-03		overall median
Char (6)	0.13	0.30	0.0083	0.45	1.3E-05	0.53	3.6E-03	0.51	overall mean
	0.13	0.01	0.011	0.04	1.4E-05	0.52	4.9E-03	0.31	start
	0.13	0.51	0.0098	0.33	2.0E-05	0.06	2.0E-03	0.57	≈ 10 min
	0.13	0.45	0.0040	0.45	6.1E-06	0.04	3.8E-03	0.56	end
	0.13		0.011		1.9E-05		3.8E-03		overall median
	0.13		0.0087		1.5E-05		3.2E-03		weighted mean
	1.00		1.04		1.12		0.89		weighted/overall
Wood (9)	0.10	0.56	0.015	0.90	3.8E-05	0.51	0.019	0.66	overall mean
	0.08	0.56	0.0071	0.68	4.7E-05	0.34	0.014	0.51	start
	0.06	0.72	0.0093	1.19	3.7E-05	0.54	0.010	0.58	≈ 10 min
	0.15	0.11	0.030	0.42	2.9E-05	0.81	0.032	0.34	end
	0.08		0.011		3.4E-05		0.018		overall median
	0.09		0.014		3.8E-05		0.016		weighted mean
	0.90		0.90		1.00		0.88		weighted/overall

CV = Coefficient of variation = (sample standard deviation)/mean
The two negative values in Table 4b have been treated as zeros.
The median value is that one that has an equal number of values below and above it. If there is an even number of total values, the median is chosen to be halfway between the two middle values.
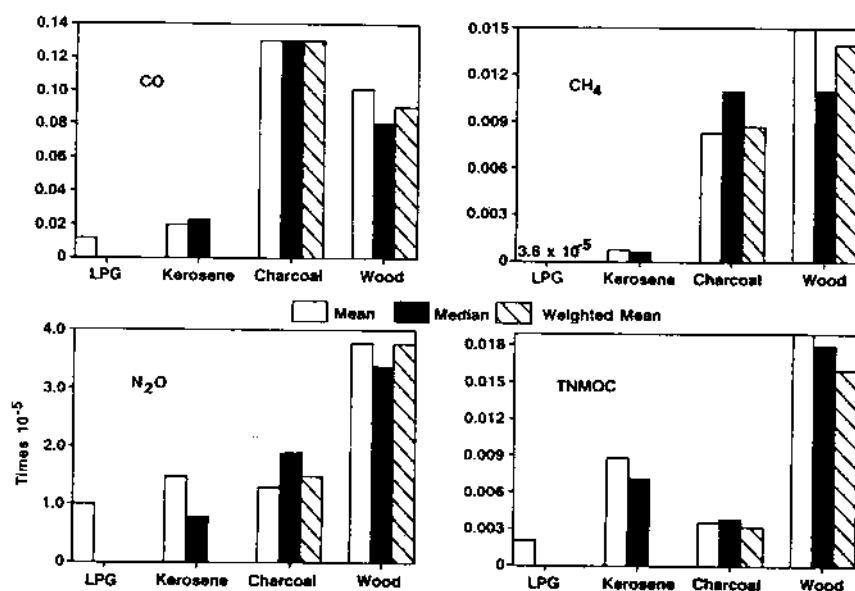
Figure 1. Emission ratios for each fuel and pollutant (carbon in pollutant divided by carbon in carbon dioxide). Shown are the mean and median values for all fuels except LPG, which consists of only two data points. Also shown are the weighted means for wood and charcoal, in which the middle-burn data are given twice the weight of the measurements taken at the start and end phases of the burn. See Table 5.

Although the calculations below use overall means, Figure 1 shows that substitution by medians or weighted means would not change the results significantly. As expected for this pilot study, the small sample sizes and large Cvs limit the degree of statistical inference that can be drawn.

3.1. Discussion

In determining the net concentrations and emissions ratios in Tables 4a and b, it was necessary to subtract the ambient values, of which there were only two in Manila. As shown in the table, there is not much difference between them for the combustion-related gases and thus it seems reasonable to use the mean of the two for netting out the emission values for the different fuel/stove combinations. To be more confident, however, it would be better to

take ambient samples at the approximate place and time of the stove sampling. There would seem to be two potential sources of error: (1) dilution of the sample by room air that might have built up significant concentrations of the gases toward the end of the burn cycle (2) modified by potential combustion of these gases should they pass through the combustion zone, a sort of inadvertent secondary combustion. These would tend to act in opposite directions on the final result. The overall bias is reduced because emissions ratios rather than absolute emissions are being determined. Nevertheless, future studies should include at least one ambient sample per location, perhaps both at the beginning and end of emission samples taken over long periods and conduct the sampling in relatively uncontaminated conditions, i.e., with good ventilation.

In general, there is a tendency for the ratios representing different points during each woodstove session to increase with time, with the third being the highest for each pollutant (Table 4b). This probably indicates that a significant amount of volatiles was still remaining in the wood even at the time of the third sample. There does not seem to be any simple pattern for the charcoal ratios.

The Indian standard for domestic LPG stoves specifies 0.02 as the limit allowed for the CO/CO_2 emission ratio (ISI, 1984). Although the means for both the Philippine LPG and kerosene stoves would meet this standard, about half of the stoves of each type had higher values. None of the charcoal and wood stoves came close to meeting this standard.

At 0.1 in Table 5, the CO emission ratio for woodstoves is higher than the 0.06 reported by Hao et al. (1990), for open combustion of a range of biomass types. The mean ratio for CH_4, 0.015, is at the high end of the range (0.01 +/- 0.006) for all biomass in Crutzen and Andreae (1990), but well above the range (0.001-0.0025) reported by Delmas et al. (1991) for savanna burning, and by Hao et al. (1990) for a range of biomass types, 0.004. Hao et al. (1991) find the emission ratio for TNMOC to be 0.011, reasonably close to the value found here, 0.015. The value for N_2O, at 3.8 E-5, is substantially lower than quoted by Crutzen and Andreae, 0.007, but similar to that of Hao et al. (1991).[3]

There are clearly a number of uncertainties remaining in these data and consequent limitations to the inferences that can be drawn. To explore the potential utility of these kinds of data and thus the possible value of continuing such measurements, however, we continue by using these pilot data in a series of illustrative analyses.

3.2. Carbon Balances and Absolute Emission Factors

With these emission ratio measurements, it is possible to construct rough carbon balances and emission factors (grams pollutant per kilogram fuel) for the different fuel/stove combinations. The necessary assumptions are:

--These two-minute grab samples are representative of the emission ratios throughout the burn.

--The fuel is the only source of the net carbon measured in the grab samples.

--The carbon-containing gaseous species other than those measured contain a negligible fraction of the carbon, <1%.

--The carbon contents of the fuels are close to those reported in the literature, that is, 50% for wood, 85% for charcoal, 85% for kerosene, 86% for LPG (Smith, 1987; Culp, 1979).

--The carbon contained in unmeasured flows, that is, ash (including remaining char) and aerosol, is relatively small. This is supported by evidence that aerosol (total suspended particulates) emission factors for wood-burning cookstoves are generally less than 5 g/kg (Smith, 1987). Even if the aerosol was 100% carbon, which it is not, this would amount to only 1% of the fuel carbon. At more typical aerosol carbon contents (60%) and emission factors (2g/kg), the contribution is smaller still (0.24%). Aerosol emissions from the other fuels are even less. Ash from the solid fuels are possible sources of error, although experience has shown that the char left after a cooking cycle that, as in Manila, incorporates a low power phase (i.e., char burning) contains less than 2% of the fuel carbon (Baldwin, 1987). Ash from kerosene or LPG is negligible.

Here, we calculate the wood emission factors under two assumptions for the ash and aerosol carbon to CO_2 carbon ratio (AAC): zero and 0.05. These bracket the probable actual values. As will be shown, this uncertainty is not a serious source of error for the purposes of the rough calculations in this pilot study. Future studies, however, should measure carbon contents of fuel, ash, and aerosol, if possible.

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[3] Recent data show that N_2O can be generated inside canisters between sampling and analysis, particularly in the presence of SO_2 and water vapor (Hao et al., 1991). Our N_2O values are low and the SO_2 levels probably small for wood and charcoal, but we cannot rule out enhancement in this fashion.

With these assumptions, on a carbon-balance basis (Ward et al., 1979):

$$CO + CH_4 + TNMOC + CO_2 + AAC = FC \qquad (1)$$

where FC is fuel carbon. Thus,

$$1 = FC/CO_2 - (CO+CH_4+TNMOC+AAC)/CO_2, \text{ or } 1 = FC/CO_2 - K \qquad (2)$$

Since the last term (K) is known, the absolute CO_2 emission factor can be calculated:

$$CO_2 = FC/(1+K) \qquad (3)$$

To illustrate, for wood, which is 50% carbon, Table 6 shows K = 0.13 (with AAC = 0):

$$CO_2 = 500/1.13 = 440 \text{ g carbon/kg fuel}, \qquad (4)$$

or 1620 g CO_2/kg fuel.

The emission factors for the other pollutants can now be calculated easily. For example, Table 5 shows the CO from wood has an emission ratio of 0.10,

$$CO/440 = 0.10; CO = 44 \text{ g C as CO/kg fuel; or } 103 \text{ g CO/kg fuel.} \qquad (5)$$

Table 6: Emission factors, grams per kilogram dry fuel (K = sum of emission ratios, see Table 5)

	K	Carbon Content	CO_2	CO	CH_4	N_2O	TNMOC[1]
LPG	0.015	0.86	3110	24	0.04	0.03	3
Kerosene	0.03	0.85	3030	38	1	0.05	11
Charcoal	0.14	0.85	2740	230	8	0.04	4
Wood-1[2]	0.13	0.5	1620	100	9	0.06	13
Wood-2[3]	0.18	0.5	1560	99	8	0.06	12

[1]TNMOC: Per carbon molecular weight taken as 18.
[2]Wood-1: No carbon in ash or aerosol.
[3]Wood-2: Ash and aerosol emission ratio = 0.05 (carbon basis). Assuming that ash and aerosol have an average carbon content of 0.67, the resulting ash and aerosol emission factor is 32 g/kg of dry wood.
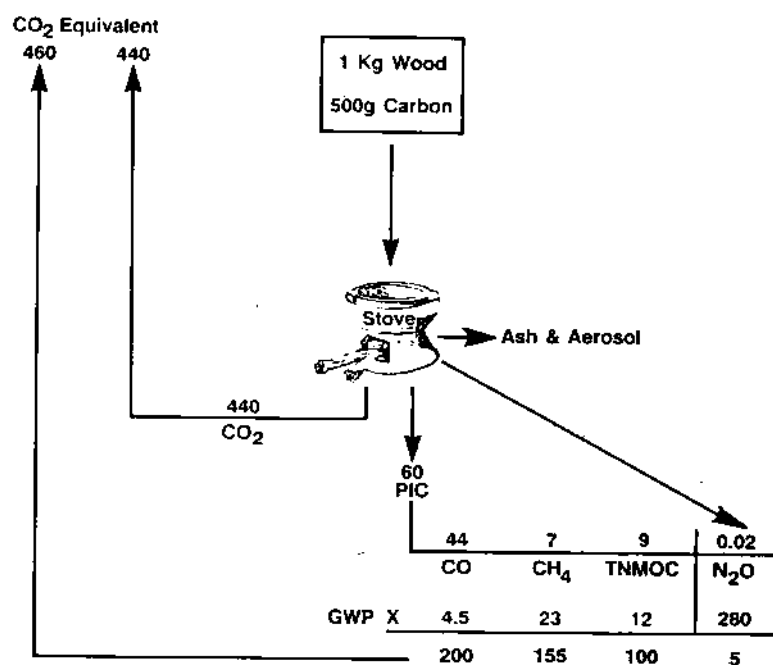
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Figure 2. The carbon cycle derived for the mean woodstove in Table 6. Shown is the fate of one kilogram of wood (500 g carbon). Approximately 11% of the carbon (60 g) is diverted into PIC (products of incomplete combustion) by the stove and distributed among CO, CH_4, and TNMOC as shown. Although not part of the carbon balance, the emissions of N_2O are also shown. Based on these data, the stove achieves about 89% combustion efficiency. Shown also are the 20-year GWPs (global warming potentials--see Figure 3), which are multiplied by the PIC and N_2O emissions to determine the non-CO_2 contribution to total global warming. The result, 460 g CO_2-equivalent, slightly exceeds that of the CO_2 itself (440 g). Nearly all of the PIC, of course, eventually changes to carbon dioxide in the atmosphere. Ash and aerosol were not measured, but, as shown in Table 6, are not likely to contain enough carbon to significantly affect this balance.

The mean emission factors for all fuels and pollutants are shown in Table 6. Wood-1 assumes that ash and aerosol contain no carbon, while Wood-2 assumes that they together amount to 5% of CO_2 carbon. Note that the change has little effect on the greenhouse-gas emission factors. Figure 2 illustrates the resulting total carbon balance for the mean wood cookstove of Tables 5 and 6 (Wood-1).

The CO emission factor for wood cookstoves (~100 g/kg) is well within the range reported for CO emissions measured by other means, e.g. 17-130 g/kg in a broad range of wood-fired cookstove measurements summarized by Smith (1987) and for biomass combustion in Crutzen and Andreae (1990) and Ward and Hardy (1991). The kerosene CO emission factor of 38 g/kg is near the 41-67 measured by TERI for wick stoves (1987) and much above levels typically found for kerosene radiant heating stoves, that is, 2.8 g/kg in Apte and Traynor (1986).

3.3. Global Inventories

Twenty-six samples cannot represent the world's huge variety of small-scale combustion devices using these fuels for different kinds of cooking in different seasons. Nevertheless, to give an indication of whether these kinds of measurements should be continued, it is useful to extrapolate these emission ratios to global emissions. These then can be compared to previous estimates, as shown, for example, in Table 1.

As shown in Table 7, these indicate that combustion of firewood (including that made into charcoal) is responsible for 10-45% of the 38 Tg/y CH_4 released from all biomass combustion (Table 1). This is higher than would be expected by the ratio of firewood to total biomass, which is 10-15%. Table 6 indicates that wood stoves could release 10-25% of the 350 Tg/y CO accounted to biomass. The 40-95 Tg/y is slightly higher than the 10-65 Tg/y previously estimated for fuelwood by Khalil and Rasmussen (1990).

Table 7. Global emissions extrapolated from emission ratios determined in this study (In Tg/y, element basis)

	CO	CH$_4$	N$_2$O	TNMOC
LPG	1.0	3.0 E-3	8.2 E-4	0.18
Kerosene	0.6-0.8 (0.2-1)	0.005-0.05 (0-0.1)	1.3-10 E-4 (1-170 E-5)	0.16-0.49 (0.03-0.95)
Charcoal*	9.2 (6-12)	0.3-0.8 (0.2-0.8)	0.001	0.14-0.34 (0.09-0.42)
Wood	31-84 (5-90)	4-16 (0.2-24)	0.016-0.026 (0.007-0.03)	5.3-17 (1.8-24)

*Assumes that emission ratios for charcoal making are the same as those for charcoal combustion. They are probably much greater, however, especially for hydro-carbons (Foley, 1986).

Shown are the ranges among the means for the three different kerosene stoves and, for wood, the ranges of the means of the grouped early, middle, and late burn measurements. The ranges of values from all the measurements are in parentheses.

Fuel consumption data for calculations of annual global greenhouse gas emissions:

LPG: 1.5 E+8 tons x 0.98 (fraction oxidized) x 0.87 (fraction carbon) x 0.66 (estimated fraction used in small stoves) = 83 Tg carbon. Illustrative calculation of global CO emissions: 83 Tg x 0.012 (from Table 5) = 1.0 Tg C as CO (UN, 1990; IEA, 1990).

Kerosene: 4.1 E+7 tons x 0.99 (fraction oxidized) x 0.86 (tons C per ton kero) = 35 Tg C (UN, 1990; IEA, 1990)

Charcoal: Meyers and Leach (1989) estimate that 140 E+6 tons fuelwood (or 70 E+6 tons carbon) are made into charcoal in developing countries.

Fuelwood: 1.7 E+9 m^3 (FAO, 1989) x 0.9 (fraction oxidized) x (0.7 Tg dry matter/1.0 E+ 6 m^3) x 0.5 (fraction C in dry matter) = 540 Tg C (comparable to the range in Table 2). This is close to the total for developing-country fuelwood use of 1080 E+6 tons (50% carbon) estimated by Meyers and Leach (1989).

The TNMOC emissions in Table 6 (5.4-17 Tg) would confirm fuelwood and charcoal as a significant proportion of the estimated total of 100 Tg from all human activities (IPCC, 1990). Other estimates, for example, show about 17 Tg (on a carbon basis) for all volatile organic compounds from global fuelwood use (Watson et al., 1991).

The N$_2$O emissions seem quite small compared to the available estimates. Little is known about the global inventory of sources (Lyon et al., 1989; Hao et al., 1991) and further work could provide valuable additional information (IPCC, 1990).[4]

Ahuja (1990) has estimated the contribution of biomass combustion in small stoves to total anthropogenic greenhouse-gas radiative forcing/warming as about 2.0%, using a thousand year time horizon (Lashof and Ahuja, 1990). About half (1.1%) is due to CO_2, a calculation based on the author's estimate that about one-eighth of the observed deforestation in the world is due to fuel demand, the rest being caused by logging, road building, and land clearance. The other half of the stoves' contribution is due to the trace gases, CO = 0.6%; CH_4 = 0.2%; and N_2O = 0.2%. Using the same assumptions, the Manila measurements reported here imply similar values for wood alone, that is, CO = 0.4-0.6%; CH_4 = 0.1-0.5%.

Crop residues and other lower quality biomass fuels such as shrubs and grass are significant contributors as well, both because of their widespread use (60% of wood on a carbon basis in Table 2) and their non-CO_2 emission factors, which can be expected to be higher than those for wood in small-scale combustion because of their increased surface-to-volume ratios (Smith, 1987). Because of their origin, however, they produce little net CO_2. Considering also that the Manila data imply that wood stoves are also responsible for 5-17% of total human global emissions of TNMOC, it would be consistent to say that the non-CO_2 gases in biomass stove emissions might be responsible for 1-2% percent of total greenhouse impacts, with the CO_2 accounting for a similar amount, depending on the degree to which the fuel is harvested on a sustainable basis. Such statements, of course, implicitly include a number of assumptions, such as the time horizon chosen (see following).

Clearly, more data are needed on emission factors and quantities burned before more detailed estimates can be relied upon.

3.4. Global Warming Potential of Combustion Gas Mixtures

Another way of looking at this issue is to examine the relative greenhouse-gas impact of the different gases in the emissions. To do this, it is necessary have some indexing method to compare fairly the different gases, which have different radiative properties and different lifetimes (Smith and Ahuja, 1990). Table 8 uses Global Warming Potentials

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[4]Care would have to be taken, however, that N_2O is not created inside the canisters during storage (Hao et al., 1991).

(GWPs) proposed by IPCC (1990) and derived from the radiative forcings, chemical interactions, and lifetimes to weight the direct and indirect impacts of the gases relative to CO_2. To handle the different patterns of warming over time, it is necessary to choose a time horizon up to which effects will be counted. The table compares the four time horizons used by IPCC (0 [i.e., instantaneous forcing]; 20; 100; and 500 years), but other choices could be made (Smith et al., 1991).

Table 8 shows the relative GWP for CO, CH_4, N_2O, and TNMOC compared to CO_2 for each fuel. Note that the 20-year time frame gives most relative importance to these gases, mainly because of the fairly short-lived indirect chemical impact of CH_4 and TNMOC. (The IPCC (1990) has specified a GWP for non-methane hydrocarbons (NMHC), rather than for all TNMOC. In this study, the difference is only about 7%.)

For LPG, the non-CO_2 greenhouse-gas addition to CO_2 is minimal, a few percent at most (1.7-8.5%, in Table 8). It is higher for kerosene but, except for the 20-year values, still modest, albeit perhaps twice that of LPG. As one would expect from semi-enclosed small-scale combustion of solid high-volatile fuels, wood gives a substantially higher range: 13-180% across the four time horizons in Table 8. In other words, the GWP of these four greenhouse gases together may rival or even exceed the impact of the CO_2 released during wood burning. Figure 3 shows the relative contribution of each greenhouse gas to woodstove GWP according to time horizon. Note the importance of CH_4 and TNMOC under short time horizons.

Figure 2 shows how GWPs can be incorporated into the carbon balance of the mean woodstove in Tables 5 and 6 (Wood-1). Note that the total GWP of this average woodstove (900) is more than twice that of the CO_2 alone (440). Although these estimates are only based on a few measurements, as demonstrated previously they are consistent with many other similar measurements of biomass combustion. It thus seems safe to say that, under some circumstances and assumptions, the global warming implication of the non-CO_2 gases from wood-fired cookstoves (mainly the PIC - products of incomplete combustion) can rival or exceed that of the CO_2 alone.
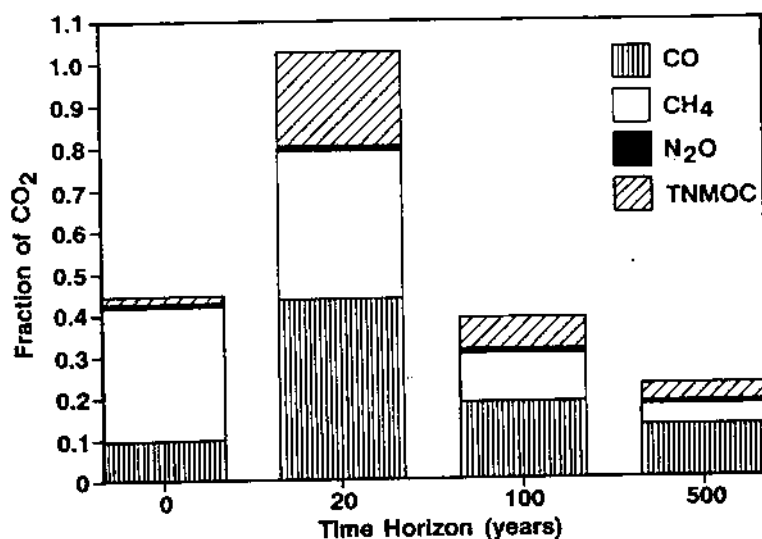
Figure 3. Greenhouse contributions (global warming potentials) at four time horizons from the non-CO_2 gases of the mean woodstove in Table 5. The vertical axis is marked in fractions of the CO_2 released by the same stove at the same time. Note that at a 20-year time horizon, the total contribution of the four non-CO_2 gases is about equal to that of the CO_2 alone, that is, the total contribution is double that of CO_2. Strictly speaking, it is the subset, non-methane hydrocarbons (NMHC), rather than TNMOC that has been assigned a global warming potential (IPCC, 1990). The difference for these woodstoves, however, is only about 7%.

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Table 8. Increase in global warming potential from non-CO_2 emissions released from cookstoves. These are based on the additional greenhouse impact above that from the CO_2 alone. Percentage increase for various time horizons of warming based on emission ratios in Table 5 and the Global Warming Potentials listed below, which are from IPCC (1990); see also Smith et al., 1992.

Fuel	Instantaneous	20 years	100 years	500 years
LPG	1.7%	8.4%	3.5%	2.3%
Kerosene 3 types	2.5-6.5 (0.6-9.2)	13-29 (3.7-40)	5.2-11 (1.6-15)	3.3-6.6 (1.1-8.5)
Charcoal*	22-37 (15-44)	73-91 (53-110)	30-36 (22-45)	19-22 (14-28)
Wood	25-82 (2.8-110)	60-180 (10-230)	23-66 (4.5-83)	13-37 (2.8-46)

*There are additional greenhouse-gas contributions from fuel-cycle facilities, which may be particularly large at charcoal kilns.

Shown are the ranges among the means for the three different kerosene stoves and, for the solid fuels, the ranges of the means for the data grouped by time of measurement during the burn. The ranges for all individual measurements for the fuel in question are in parentheses.

Global Warming Potentials (ratio to CO_2) at four time horizons:

Instantaneous: $CO = 1$; $CH_4 = 21$; $N_2O = 210$; TNMOC (NMHC) = 1
20-year: 4.5, 23, 280, 12.
100-year: 1.9, 7.6, 300, 4.1.
500-year: 1.3, 3.2, 200, 2.3.

For illustration: multiply the 20-year values by the mean emission ratios for LPG in Table 5 and sum, that is, (0.012x4.5) + (0.000036x23) + (0.00001x280) + (0.0021x12) = 0.0848 (8.5%).

For charcoal, however, not only is the non-CO_2 impact significant (up to 91%), there can be expected to be substantial additional contributions of all four greenhouse gases during the charcoal manufacturing process. Charcoal, therefore, is probably substantially worse than wood on an overall GWP basis. Systematic measurements at charcoal kilns in developing countries are needed to determine emission ratios more accurately.

Table 9 shows how this information might be used in designing an international greenhouse-gas control program. If wood is harvested on a completely non-renewable basis,

Table 9. Global Warming Potential (GWP) benefits from fuel switching in cookstoves depending on time horizon. This includes the relative production of CO_2 as well as the non-CO_2 greenhouse gases: CO, CH_4, N_2O, and TNMOC and is dependent on relative stove efficiencies (see below). GWPs taken from Table 8.

Case A: Where wood is harvested on a completely nonrenewable basis (i.e., woodstove and charcoal CO_2 emissions, as well as those from fossil fuels, are included as net atmospheric additions).

Relative GWP in going from Wood to	Instantaneous	20 yr	100 yr	500 yr
Charcoal*	0.74	0.77	0.77	0.77
Kerosene	0.22	0.19	0.23	0.25
LPG	0.14	0.12	0.16	0.17

Case B: Where wood is harvested on a completely renewable basis (i.e., CO_2 emissions are not included for wood stoves because the CO_2 is completely recycled, but is included for the fossil fuels).

Relative GWP in going from Wood to	Instantaneous	20 yr	100 yr	500 yr
Kerosene	0.69	0.44	0.96	1.5
LPG	0.46	0.27	0.63	1.0

In either case:

Relative GWP in going from Kerosene to	Instantaneous	20 yr	100 yr	500 yr
LPG	0.67	0.61	0.66	0.67

*This does not take into account greenhouse gases emitted during the other parts of these fuel cycles (e.g., at oil refineries). In particular, the inclusion of emissions from charcoal kilns might greatly shift the results.

These calculations depend on (1) the available combustion energy per carbon atom being about the same for LPG and kerosene and approximately two-thirds as much for charcoal and wood (Culp, 1979); and (2) cookstove efficiencies of 20%, 30%, 50%, and 70%, respectively, for wood, charcoal, kerosene, and LPG stoves (Smith, 1987; World Bank, 1985).

all of the CO_2 from woodburning results in a net atmospheric increase, and there are significant advantages in going from wood to kerosene or LPG (Table 9A). The size of the benefit ranges from 74-80% reductions for kerosene or 83-88% reductions by going to LPG (the range depending on the time horizon chosen).

Surprisingly, even in the opposite situation (Table 9 Case B), where none of the CO_2 from wood stays in the atmosphere (i.e., no net deforestation), there are still apparent advantages in moving from wood to kerosene or LPG at the shorter time horizons preferred by many analysts. The advantages are smaller, however, (possible reductions of 4-56% for kerosene, 37-63% for LPG). The reason is that wood produces a tremendous amount of non-CO_2 greenhouse gases, overwhelming the fossil carbon CO_2 emissions of the fossil fuels. Only under the longest time horizon shown (500 years) is wood better than kerosene.

Any actual situation, of course, is likely to fall between complete deforestation (no recycling of carbon) and no deforestation (complete recycling of carbon).

One implication of these results is that fuel substitution or increases in the combustion efficiency of small biomass-fired stoves through improved biomass stove programs (Caceres et al., 1989; ESMAP, 1991) may have substantially more benefit than the already considerable benefits of bringing the CO_2 cycle closer to balance and enhancing local environments by reducing pressure on biomass resources.

4. CONCLUSIONS OF PILOT STUDY

Based on these evaluations, there seem to be good arguments for embarking on a more detailed study of these small-scale combustion devices in developing countries. The reasoning is as follows:

1. Based on previous work, emissions from biomass combustion play large, but still uncertain, roles in global atmospheric chemistry.

2. A significant fraction of all biomass combustion occurs in enclosed or semi-enclosed small-scale devices (Table 2).

3. There is evidence that such devices have somewhat different emission factors compared to open large-scale combustion, such as forest and savannah burning.

4. Preliminary evidence from this Manila study shows that emission factors of wood combustion in small devices seem to be high for CH_4, CO, and TNMOC, important greenhouse-related gases.

5. For illustrative purposes, extrapolations of these factors to global emissions indicate that presently estimated global inventories of these gases from biomass burning may be somewhat low.

6. Analysis also reveals that, from wood combustion, the global warming potential of the four non-CO_2 gases, CO, CH_4, N_2O, and TNMOC, may rival or exceed that from CO_2 itself.

Point 5 suggests taking more measurements so that knowledge of global inventories can be improved. Point 6 argues for more monitoring so that measures to reduce greenhouse-gas and other emissions in developing countries can be designed more effectively (e.g., so that policy measures do not just reduce CO_2 in one place while the non-CO_2 gases are increased even more in another).

Based on experience, there are several additional factors that might be considered when designing the next study:

A. Since a large proportion of crop residues in developing countries are also burned in such stoves, their emission factors can be expected to be higher than previously indicated by open field burning. The next study should include sampling of crop-residue burning stoves. This will likely change the emissions inventory for this source.

B. Since a growing amount of coal is being used in small-scale combustion in many developing countries (e.g., China, India, Botswana, Haiti), it would be appropriate to include it in the next study. This is unlikely to change the global inventories for all coal combustion but might make large local differences (e.g., in China).

C. A greater proportion of ambient samples should be taken next time and emission samples should be taken in conditions verified to be well-ventilated. It might also be possible to use background concentrations of inert gases such as F-11, to derive more accurate emission factors can be determined for the gases at lower concentrations in the combustion-gas streams.

D. A protocol is needed for monitoring combustion of solid fuels because the emission rates vary so much at different times during the burn cycle. One approach would be to use low-flow pumps that slowly fill the canisters during the entire burn.

E. To eliminate the potential variation in emissions because of different geometrical arrangements of fuel, stove, and measurement probe, some means of mixing flue gases from unflued devices might be employed.

F. To complete the carbon balance, future studies should consider monitoring the carbon in aerosol emissions and in the ash and char left after combustion. This will also allow health impacts, which depend heavily on aerosol emissions, to be estimated.

G. Since the emissions during charcoal making can be expected to have high emission ratios, future studies might include monitoring of charcoal kilns, although this may prove difficult because of the long processing period.

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REFERENCES

Ahuja, D.R. (1990), Research needs for improving biofuel burning cookstove technologies, *Natural Resources Forum* 12(2):25-134.

Ahuja, D.R., et al. (1987), Thermal performance and emission characteristics of unvented, metal, biomass-burning cookstoves: A proposed standard method for evaluation, *Biomass* 12:247-270.

Andreae, M.O. (1991), Biomass burning: Its history, use, and distribution and its impact on environmental quality and global climate, *Proceedings of the 1990 Chapman Conference on Global Biomass Burning*, J.S. Levine, Editor (MIT Press, Cambridge) 3-21.

Apte, M.G., and G. W. Traynor (1986), Comparison of pollutant emissions from unvented kerosene and gas space heaters, *Proceedings, '86 Managing Indoor Air for Health and Energy Conservation* (ASHRAE, Atlanta, Georgia).

Baldwin, S. (1987), *Biomass Stove Technologies: Engineering Design, Development, and Dissemination* (Princeton University, NJ and Volunteers in Technical Assistance [VITA], Arlington, Virginia).

Barnard, G.W. (1985), The use of agricultural residues as fuel, *Ambio* 14:259-266.

Caceres, R., J. Ramakrishna, and K.R. Smith (editors) (1989), *Stoves for People* (Intermediate Technology Publications, London).

Cicerone, R.J., and R.S. Oremland (1988), Biogeochemical aspects of atmospheric methane, *Global Biogeochemical Cycles* 2:299-327.

Cofer, W.R., J.S. Levine, and E.L. Winstead (1991), Trace gas and particulate emissions from biomass burning in temperate ecosystems, *Proceedings of the 1990 Chapman Conference on Global Biomass Burning*, J.S. Levine, Editor (MIT Press, Cambridge) 203-208.

Cooper, J.A., and D. Malek, editors (1982), *Residential Solid Fuels: Environmental Impacts and Solutions* (Oregon Graduate Center, Beaverton, Oregon).

Crutzen, P.J., and M.O. Andreae (1990), Biomass burning in the tropics: Impact on atmospheric chemistry and biochemical cycles, *Science* 250:1169-1678.

Culp, A.W. (1979), *Principles of Energy Conversion* (Mc-Graw Hill, N.Y.)

Dasch, J.M. (1982), Particulate and gaseous emissions from wood-burning fireplaces, *Environ. Sci. and Technol.* 16:635-645.

Delmas, R.A., A. Marenco, J.P. Tathy, et al. (1991), Sources and Sinks of methane in the African savanna. CH_4 emissions from biomass burning, *Journal of Geophysical Research*, 96(D4):7287-7299.

ESMAP (1991), *An Evaluation of Improved Cookstove Programs: Prospects for Success or Failure* (World Bank, Washington, D.C.)

FAO (1989), *Yearbook of Forest Products, 1987* (Food and Agriculture Organization, Rome).

Garcia, R. and F. Manegdeg (1991), *Indoor Air Pollution Survey* (Energy and Environmental Engineering Systems and Policy Analysis Research Group, College of Engineering, University of the Philippines, Manila).

Foley, G. (1986), *Charcoal Making in Developing Countries* (Earthscan, London).

Hao, W.M., D. Scharffe, J.M. Lobert, and P.J. Crutzen (1990), Biomass burning: An important source of atmospheric CO, CO_2, and hydrocarbons, presented at the Chapman Conference of the American Geophysical Union, Williamsburg, Virginia, 19-23 March.

Hao, W.M., D. Scharffe, J.M. Lobert, and P.J. Crutzen (1991), Emissions of N_2O from the burning of biomass in an experimental system, *Geophy. Res. Lett.* 18(6):999-1002.

IEA (1990), *World Energy Statistics* (International Energy Agency, OECD, Paris).

IPCC (1990), *Climate Change: The IPCC Scientific Assessment* (Intergovernmental Panel on Climate Change, Cambridge Univ. Press, UK).

ISI (1984), Specification for domestic gas stoves for use with liquefied petroleum gases (Indian Standards Institution: 4246, New Delhi).

Joshi, V. (1991), Biomass burning in India, *Proceedings of the 1990 Chapman Conference on Global Biomass Burning*, J.S. Levine, Editor (MIT Press, Cambridge) 185-195.

Joshi, V., C. Venkataraman, and D.R. Ahuja (1989), Emissions from burning biofuels in metal cookstoves, *Environmental Management* 13(6):763-772.

Joshi, V., C. Venkataraman, and D.R. Ahuja (1991), Thermal performance and emission characteristics of biomass-burning heavy stoves with flues, *Pacific and Asian Journal of Energy* 1(new):1-19.

Khalil, M.A.K., and R.A. Rasmussen (1990), The global cycle of carbon monoxide: Trends and mass balance, *Chemosphere* 20(1-2):227-242.

Kohlmaier, G.H., H. Brohl, and R. Fricke (1987), The biogenic fuels: Fuelwood, charcoal, crop residues, and animal dung as net sources of atmospheric CO_2, *SCOPE/UNEP Sonderband* Heft 64:29-43.

Lashof, Daniel A. and Dilip R. Ahuja (1990), Relative contributions of greenhouse gas emissions to global warming, *Nature* 344:529-531 (5 April).

Levine, J.S. (1990), Global biomass burning: Atmospheric, climatic, and biospheric implications, *EOS* 71(37):1075-1077.

Levine, J.S., editor (1991), Global biomass burning: Atmospheric, climatic and biospheric implications, *Proceedings of the 1990 Chapman Conference on Global Biomass Burning* (MIT Press, Cambridge, Massachusetts).

Lobert, J.M., D. Scharffe, W.M. Hao, and P. Crutzen (1990), Importance of biomass burning in the atmospheric budgets of nitrogen-containing gases, *Nature*, 346:552-554.

Lyon, R.K., J.C. Kramlich, and J.A. Cole (1989), Nitrous oxide: Sources, sampling, and science policy, *Environ. Sci. and Technol.* 23:392-393.

Meyers, S., and G. Leach (1989), *Biomass Fuels in the Developing Countries: An Overview*, LBL-27222 (Lawrence Berkeley Laboratory, Berkeley, California).

Rasmussen, R.A., and M.A.K. Khalil (1980), Atmospheric halocarbons: Measurements and analyses of selected trace gases, *Proceedings of the NATO Advanced Study Institute on Atmospheric Ozone; Its Variation and Human Influences*, A.C. Aiken, Editor (U.S. Dept. of Transportation, Washington, D.C.) 209-231.

Rasmussen, R.A., and M.A.K. Khalil (1981), Atmospheric methane: Trends and seasonal cycles, *J. Geophysical Res.* 86:5172-5178.

Robinson, J.M. (1989), On uncertainty in the computation of global emissions from biomass burning, *Climatic Change* 14:243-262.

Sathaye, J. and S. Tyler (1991), Transitions in household energy use in urban China, India, the Philippines, Thailand, and Hong Kong, *Annual Review of Energy and Environment* 16:295-335.

Seiler, W., and P.J. Crutzen (1980), Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning, *Climatic Change* 2:207-247.

Smith, K.R. (1987), *Biofuels, Air Pollution, and Health* (Plenum, N.Y.)

Smith, K.R. (1990), Indoor air quality and the pollution transition, *Indoor Air Quality,* H. Kasuga, Springer-Verlag, Berlin, 448-456.

Smith, K.R., and D.R. Ahuja (1990), Toward a greenhouse equivalence index: The total exposure analogy, *Climatic Change* 17:1-7.

Smith, K.R., J. Swisher, R. Kanter, and D.R. Ahuja (1991), *Indices for a Greenhouse Control Regime That Incorporates Both Efficiency and Equity Goals,* Working Paper 1991-22, Policy and Research Division, Environment Department (World Bank, Washington, D.C.)

Smith, K.R., R.A. Rasmussen, F. Manegdeg, and M. Apte (1992), *Greenhouse Gases from Small-Scale Combustion in Developing Countries: A Pilot Study in Manila,* EPA-600-R-92-005, (Office of R&D, USEPA, Washington, D.C.)

TERI (1987), *Evaluation of Performance of Cookstoves with Regard to Thermal Efficiency and Emissions from Combustion* (Tata Energy Research Institute, New Delhi).

UN (1990), *1988 Energy Statistics Yearbook,* Dept. of International Economic and Social Affairs (United Nations, N.Y.)

Ward, D.E., R.M. Nelson, and D.F. Adams (1979), Forest fire smoke plume documentation, *Proceedings of the 72nd Annual Meeting, Air Pollution Control Association,* No. 79-6.3, 24-29 June; Cincinnati, Ohio.

Ward, D.E. and C.C. Hardy (1991), Smoke emissions from wildland fires, *Environ. Internl.* 17:117-134.

Watson, J.J., J.A. Probert, and S.D. Piccot (1991), *Global Inventory of Volatile Organic Compound Emissions from Anthropogenic Sources,* EPA-600/8-91-002 (NTIS PB91-161687) (Research Triangle Park, N.C.)

World Bank (1985), *Test Results on Kerosene and Other Stoves for Developing Countries,* Energy Department Paper No. 27 (Washington, D.C.)