II. CONCLUSIONS AND RECOMMENDATIONS

This database contains a systematic set of measurements of the CO_2, CO, CH_4, TNMOC, N_2O, SO_2, NO_2, and TSP emissions from the most common combustion devices in the world, household stoves in developing countries. A number of different stoves using 8 biomass fuels, kerosene, LPG, and biogas were examined – a total of 28 fuel/stove combinations. Since fuel and stove parameters were monitored as well, the database also allows examination of the trade-offs of emissions per unit fuel mass, fuel energy, and delivered energy as well as construction of complete carbon and mass balances.

Confirming the preliminary results in the Manila pilot study (Smith *et al.*, 1992, 1993), the database shows that solid biomass fuels are typically burned with substantial production of PIC (products of incomplete combustion). Some fuel/stove combinations diverted more than 20% of the fuel carbon into PIC. No biomass stove produced less than 5%. In addition, as has often been shown in the past, biomass stoves usually have substantially lower thermal efficiencies than those using liquid and gaseous fuel. As a result, the total CO_2 and PIC emissions per unit delivered energy are substantially greater in the biomass stoves. In general, the ranking follows what has been called the "energy ladder" from lower to higher quality fuels, i.e., emissions decrease and efficiencies increase in the following order: dung-crop residues-wood-kerosene-gas. There are important variations, however, depending on the specific stove designs.

The global warming commitment (GWC) of the fuel/stove combinations depends on which PIC gases are included in the calculations and whether the biomass fuels are considered to be renewably harvested. (Crop residues, dung, and biogas - which is made from dung - are assumed always to be renewable; LPG and kerosene are always non-renewable.) In the non-renewable case, because of their low efficiencies and high PIC emissions, all biomass stoves produce substantially more total GWC per unit delivered energy than the kerosene and LPG stoves, of which LPG is best. If GWC from only CO_2 , CH_4, and N_2O are considered (Basic GHG Set), a few of the crop residue and dung stoves are comparable to kerosene. In the renewable basic set, about half the biomass fuel/stove combinations produce less GWC than kerosene. If the GWP of all PIC are included (Full = Basic set plus CO and TNMOC)[1], a few wood and rootfuel stoves are comparable to kerosene, but no others. Interestingly, however, biogas is by far the best of all, with only some 10% of LPG GWC and more than a factor of 100 less than the most GWC-intensive solid biomass fuel/stove combinations.

For a complete analysis, the GWC of the rest of the fuel cycles should be included as well. The fossil fuels, for example, will have GHG releases at the oil well, refinery, and transport stages of the fuel cycle (Schlamadinger, *et al.* 1997). Biogas will lose some of its apparent lead because of CH_4 leaks from the digester and pipelines, although preliminary measurements indicate that these are relatively small (Khalil *et al.*, 1990). Charcoal's GWC will rise dramatically because of the inefficient operation of most charcoal kilns (Smith *et al.*, 1999). Nevertheless, it is clear that the database confirms some of the preliminary counter-intuitive conclusions of the Manila pilot

[1] There is disagreement, however, about the appropriate mean GWP values of CO and hydrocarbons to use for such calculations because of geographic and seasonal variations (IPCC, 1995). Here we apply those published in IPCC (1990).

study, i.e., that in some circumstances a switch from solid biomass fuels, even if renewably harvested, to kerosene or LPG can be recommended for the purpose of reducing GHG emissions. One surprising result, however, is that LPG is only marginally superior to kerosene. The remarkable performance of biogas is because it is the only fuel tested here that is favored with both the high thermal and combustion efficiency of gaseous fuel along with the advantages of renewability. As such, it foreshadows the large potential for liquid and gaseous fuels made from biomass to substantially reduce the GWC and health-damaging emissions from household use of unprocessed biomass.

Figures 1 and 2 summarize the results aggregated by fuel and divided according to type of analysis (renewable/nonrenewable; Basic/Full GHG). Note the strong performance of kerosene and LPG when the full set of GHG is used and that even in the renewable case wood has only a relatively modest advantage over fossil fuels using the basic GHG set. The strikingly superior performance of biogas is seen in all cases. All these results, of course, represent the means for the particular mix of stoves tested for each fuel in this study, which does not necessarily represent the mix in the country as a whole.

Three main conclusions can be drawn:

--Even if renewably harvested, biomass fuel cycles are not GHG neutral because of their substantial production of PIC.
--To be nearly GHG neutral, not only must biomass fuel cycles be based on renewable harvesting, they must have close to 100% combustion efficiency, which most do not in their current configurations in India.
--In the processed form of biogas, however, biomass seems to offer the opportunity of providing a renewable source of household energy with extremely low GWC because of its double blessing of being gaseous when burned and renewable when harvested.

Compared to the default emission factor values recommended by the IPCC (1997) for residential "oil" and natural gas, our results for kerosene and LPG are substantially higher for CO, TNMOC, and N_2O, but similar for CH_4. The IPCC values for biomass fuels are generally within the range we found for the different biomass-stove combinations.

From these measurements it seems that CH_4 emissions from biomass combustion in India may be about 1.9 Tg (million ton). It is thought that Indian biomass stoves represent about 27% of the global total (UNDP, 1997). Thus, if the distribution of stove types globally is similar to India's, it could be expected that biomass stoves produce globally about 7.1 Tg of CH_4 annually. This is approximately 7% of total methane emissions from all global activities related to fossil fuel harvesting and use (Houghton *et al.*, 1996).

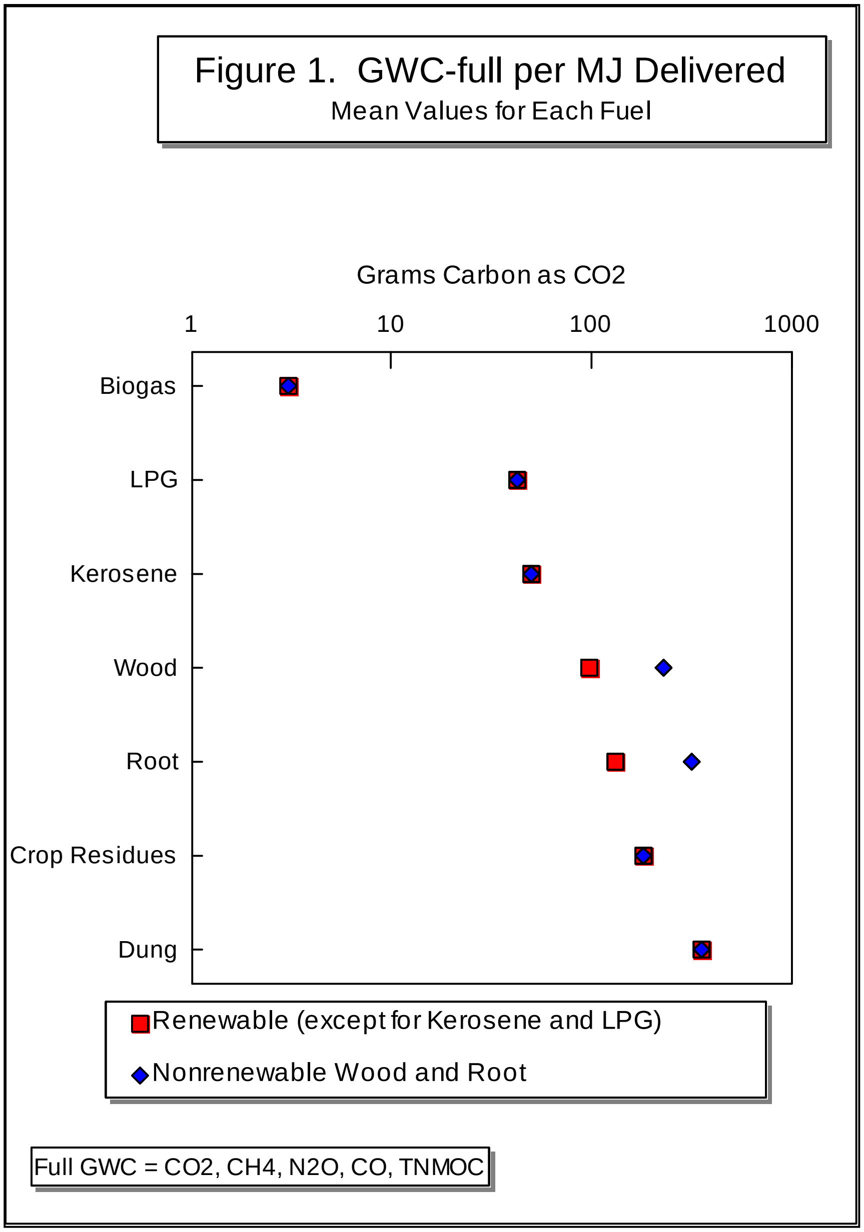
Figure 1. GWC-full per MJ Delivered
Mean Values for Each Fuel
Grams Carbon as CO2
1
10
100
1000
Biogas
LPG
Kerosene
Wood
Root
Crop Residues
Dung
Renewable (except for Kerosene and LPG)
Nonrenewable Wood and Root
Full GWC = CO2, CH4, N2O, CO, TNMOC

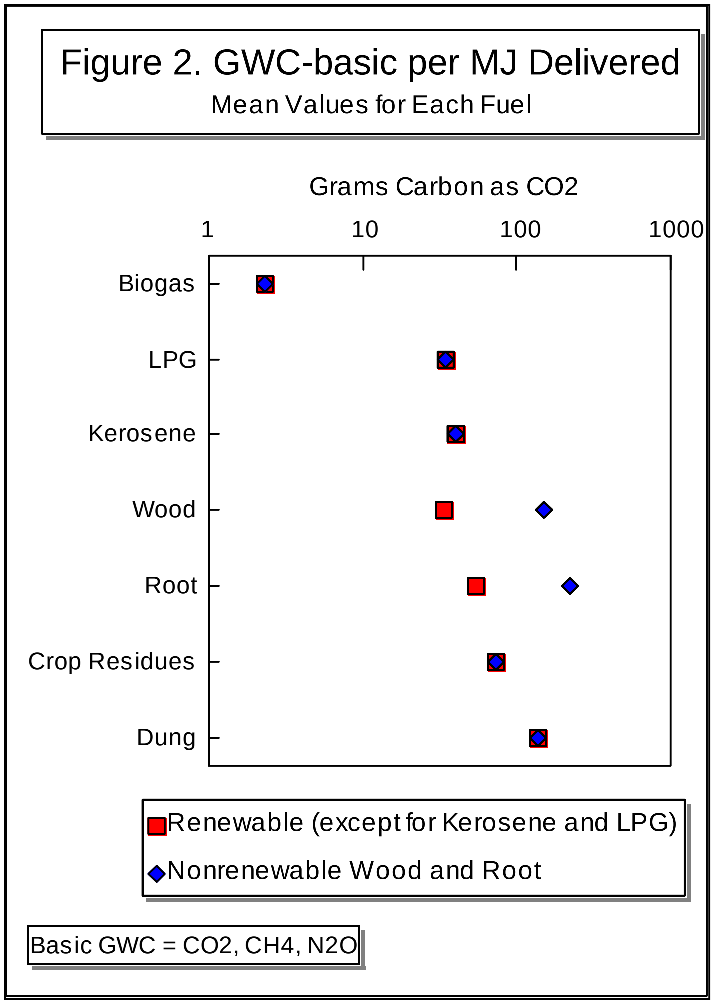
Figure 2. GWC-basic per MJ Delivered
Mean Values for Each Fuel
Grams Carbon as CO2
1
10
100
1000
Biogas
LPG
Kerosene
Wood
Root
Crop Residues
Dung
Renewable (except for Kerosene and LPG)
Nonrenewable Wood and Root
Basic GWC = CO2, CH4, N2O