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Implications of changes in household stoves and fuel use in China

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Abstract

In recent decades China has pursued a number of national energy policies as integral components of its 5-year development plans including the unprecedented dissemination of several generations of fuel saving stoves in the majority of its rural populations. These programs, although designed for conservation of fuel wood resources and using deceptively simple technologies, have much wider impacts on both a national and a global level through their impacts on health and emission of pollutants that have warming consequences for the atmosphere. In the current manuscript we examine these implications using emissions data collected as part of a comprehensive evaluation of 28 typical stove/fuel technologies in common use.

We illustrate that relative benefits of biomass and fossil fuels, and subsequently policies regarding promotion of different fuel types, are dependent on which products of incomplete combustion are considered. If one only considers gases included within the Kyoto protocol, the burning of renewably harvested biomass appears to have an advantage over kerosene or LPG as a large component of PIC emissions from inefficient biomass stoves are not included in the calculation. If, however, one considers a more comprehensive list of compounds that have direct or indirect effects on global warming, at best the burning of fuel wood when 100% renewably harvested has a similar GWC to these better quality fuels, and, under conditions experienced in many rural areas of the world, often considerably worse. Comprehensive evaluation would require all major radiative forcing agents to be considered, even though that presents considerable difficulties considering reported uncertainties of some global warming potentials.

The stove types in this study demonstrated a wide range of emission factors. This offers an effective mechanism for achieving short-term reduction in emissions of health damaging pollutants, and also accomplishes the longer-term goal of reducing of greenhouse gas emissions. Not all the improved stoves resulted in benefits on all levels, however, and it is possible, therefore, to implement policies with the best intentions for alleviating the burden of collecting fuel, which may actually, result in increased exposure of the population to health damaging pollutants and increased global warming contributions.

In addition, the difference between global warming commitments for renewable and non-renewable harvesting of biomass fuels was of such magnitude, especially compared to differences between stove types, that more detailed accounting of the renewable nature of the harvesting of biomass fuels is essential and has profound implications for global accounting of carbon emissions and credit through the clean development mechanism. Clearly, however, evaluation of biomass burning in residential stoves requires a more holistic, or full fuel cycle approach that considers both the production of the fuel wood, the burning of the fuel, sequestration of gases during the next growing season and the environmental degradation and shift in fuels that may occur due to mining of the resource.

Keywords: Greenhouse gases; Improved stoves; Health damaging pollutants

1. Introduction

Policies to widely promote and disseminate improved rural energy technology have been undertaken in China since the early 1980s (Lu, 1993). The most successful components of these policies are the extensive dissemination of fuel-saving improved biomass stoves, mini-hydropower plants, and biogas digesters. China's dissemination of improved biomass stoves (mainly designed for wood or crop residues) remains the most successful such program worldwide with estimates of over 99 million installed between 1983–1988 (Lu, 1993),

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some 130 million by 1991 (Smith et al., 1993) and 185 million by the end of 1998 (CERS and CAREI, 2000; Goldemberg et al., 2000). The scale of this program qualifies it as perhaps the most extensive household-level rural development program in history. Implementation of these stoves was designed to improve fuel efficiency so that fewer household resources were spent gathering or purchasing fuel and more biomass would become available for other purposes, such as soil conditioner and forest growth. The dissemination of fuel-saving improved stoves has been reported to be the most cost-effective measure in rural energy conservation undertaken in China (Lu, 1993). Such cost analysis, however, is only a partial picture. It is important that new technologies or policies favoring changes in rural energy use patterns be fully evaluated with respect to all major impacts of their use, positive or negative, at the outset. In addition, not only should improved technologies be evaluated with respect to traditional practices, but also with respect to other major options for residential energy, including fuel switching. Improved biomass stoves are intermediate steps along the "energy ladder" toward eventual provision of clean liquid and gaseous fuels and expanded use of electricity for all households. Although widespread adoption of clean fuels is likely to be decades in the future, given the large variety of economic and agro-climatic conditions in China, there are undoubtedly many communities where policies to promote movement to cleaner fuels are more cost-effective today than improved biomass stoves. Promotion of biomass stoves in such areas, therefore, may well be sub-optimal or even counterproductive.

Increased fuel efficiency, the original motivation for the Chinese improved-stove program, remains an important criterion today. In addition, however, two other issues related to fuel/stove performance have also come into prominence over the last decade: emissions of health-damaging pollutants and greenhouse-related pollutants. Thus, all of the following should be considered in evaluation of residential energy provision and new fuel/stove technologies:

(1) *Energy efficiency*. Chinese economic development is integrally linked to its energy supply. "Continued strong emphasis must be placed on energy efficiency improvements in all sectors, especially at the point of end-use. This will reduce costs for energy services and help meet other sustainable development objectives" (WGEST, 2001). Thus, policies for adequate and sustainable energy provision based on scientific evaluation of resources, capacity, and distribution combined with realistic measures for significant energy conservation are essential to achieve economic goals.

(2) *Human exposures to health-damaging pollutant (HDP) emissions*. Residential solid-fuel use has traditionally been associated with combustion devices that produce substantial health-damaging pollution (Sinton et al., 1996), and thus contribute significantly to the global burden of disease (Smith, 1993). Health damaging pollutants emitted from cook stoves include small particles (RSP, PM_{10}, $PM_{2.5}$), carbon monoxide (CO), nitrogen oxides and numerous volatile organic compounds that have a variety of health effects depending on concentrations to which individuals are exposed. In addition to indoor contamination, household fuels contribute to neighborhood (Smith et al., 1994), urban (World Bank, 2001), regional (Streets and Waldhoff, 2000), and global (Lelieveld et al., 2000) health-damaging pollution. It has been estimated that 200,000 (World Bank, 1997) to a million (Florig, 1997) premature deaths occur annually from exposures to household fuel smoke in China (coal and biomass). Other health endpoints may also result in reduced mobility and productivity, in addition to increased demand on health services. Household energy policies need to reflect the potential for large human and economic damage when fuel/stove conditions lead to such exposures.

(3) *Greenhouse pollutant (GHP) emissions*.[1] Global climate change as a result of greenhouse emissions has become a focus not only for the scientific community but also for responsible governments all over the world (IPCC, 2001). With over one fifth of the world's people, economic growth rates substantially greater than the world average, and heavy reliance on coal, China's share of global GHP emissions will increase, therefore, in spite of improvements in energy efficiency, as demonstrated with an increase share of global emissions from 10% to 12% in the 1990s (World Bank, 2001). Burning of biomass in household stoves accounts for a significant fraction of total primary energy consumption in China (12.7% for the year 2000 reported by Jingjing et al., 2001), due to the wide distribution of these individually quite small devices in rural communities. In addition, due to poor total energy efficiencies, emissions per unit of delivered household energy are high and cost-effectiveness of control may be greater than in other sectors, especially if one considers costs associated with emissions of HDP. There are strong arguments, therefore, for adjusting the priority among GHP control measures to reflect the benefits of the accompanying HDP reductions (Wang and Smith, 1999).

(4) *Environmental impact*. Household energy use is also linked to other forms of environmental impact and play roles in regional pollution leading to acid precipitation (World Bank, 2001) and other ecological impacts including disruption of the global nitrogen cycle with effects on ozone and air pollution. Depending on

[1] Here we use GHP, rather than the more commonly used "greenhouse gases (GHG)" to include the potential importance of black carbon, a particulate pollution now thought to play a significant role in human-generated global warming. (Jacobson, 2001).

local conditions, the choice to burn biomass may involve trade-offs with deforestation leading to land degradation and biodiversity loss, diversion of agricultural residues otherwise used for organic fertilizer and soil conditioner leading to soil degradation, and reduction of residues for fodder leading to decreased animal husbandry. In some areas, there are social implications of impact on time budgets of family members assigned to gather biomass fuels.

Although there has been considerable focus in the international community on the development of an emissions trading framework, whereby foreign investment in programs to reduce GHG emissions can result in sharing of the emissions–reduction credits, there are considerable difficulties in the inclusion of household stoves in the clean development mechanism (CDM) or similar mechanisms. Excluding rural household energy use in international agreements, however, means that about one-quarter of Chinese primary energy consumption (for the year 2000 reported by Jingjing et al., 2001) would not be available for emission-reduction credit. This is a matter of some concern considering the substantial co-benefit potentially achievable. Inclusion of this sector would require that we both improve our understanding of emissions from the wide variety of household stove designs scattered over large areas under typical conditions, and also devise mechanisms to calculate the carbon reductions from application of technological improvements or fuel switching in individual communities and regions. Further, improvement in estimates of non-commercial fuel consumption and our limited estimates of the renewable nature of harvesting of the fuel under the wide variety of agro-climatic conditions in China would be essential for estimation of biomass contributions.

The current analysis focuses on energy efficiency, human exposures to HDP emissions and GHP emissions within a common framework, called the "triple carbon balance" approach (Smith, 1994b). This framework involves carefully measuring the fate of fuel carbon in different fuel/stoves so that their implications for energy, health, and global warming can be evaluated. Used here are emissions data collected as part of a comprehensive evaluation of 28 stove/fuel technologies in use in China (Zhang et al., 2000)[2], to examine public policies to change household fuel and/or stove patterns in China. Sets of important HDP and GHP from a range of fuels was examined, including several types of biomass, coal, and gas, along with efficiencies and other characteristics of several types of stoves in common use.

[2] A similar set of measurements was undertaken in India for which separate policy evaluations are being conducted (Smith et al., 2000).

2. The database

The current data set has been created from measurements done over three standard burn cycles each for 28 fuel/stove combinations, totaling 102 samples including duplicate measurements made for each fuel type. The methods used and the resulting emission factors for these fuel/stove combinations have been described in Zhang et al. (2000), including full description of quality control procedures and composition of the original fuels. Briefly, the fuel types represented those commonly used in urban (gaseous fuels, coal, LPG and kerosene) and rural households (crop residues, wood, coal, LPG and kerosene) in China. All solid fuels were procured in one lot, sun-dried and stored in a large storage room prior to tests. Although washed unprocessed coal powder produced the highest coal emissions in the current study, a simple household level washing process with water was used. The application of these results is limited to this household level washing process, therefore, and should not be used to draw any conclusions about industrial washing processes and emissions. Although this washing process reduced the sulfur content of the coal from 0.85% S to 0.35% S (Zhang et al., 2000), emissions data per 1 MJ delivered energy, indicate that levels of TSP, CH_4 and possibly CO appear to be higher for washed versus unwashed coal powder due to increased water content of the coal.

The stove types were those most typical for burning each type of fuel and were the most popular models found in the market or rural households. Fuel/stove combinations using piped gas fuels were measured using one burner of standard multiple burner gas ranges in actual homes, with and without an infrared head. The infrared head on gas burners converts a portion of the heat released into the surrounding air into infrared radiation, which irradiates the pot bottom. All other fuel/stove combinations were tested in a simulated village house at a rural research station of Tsinghua University (Beijing, China). Fuel stove combinations and fuel composition are shown in Table 1. Brick and improved stoves were built on the floor with flues attached to a sidewall of the simulated kitchen as typically found in rural situations. All other stoves were locally purchased. Improved stoves were similar to traditional stoves in shape and structure but were better designed to improve thermal efficiencies (Smith et al., 1993a). Flues were present on brick stoves for coal and biomass, improved biomass stoves, and metal coal stoves. Metal coal stoves were also available without flue.

The "water-boiling test" (VITA, 1985), developed as a standard international method to compare stove efficiencies, was used with slight modification to define a burn cycle that was reasonably close to common cooking practice in residences. Burn cycles were from

Table 1
Fuel/stove combinations

Fuel	Agricultural residue		Wood brush	Fuel	Unprocessed coal		Processed briquettes		Kerosene	LPG	Coal gas	Natural gas
	Maize	Wheat			Washed	Unwashed	Honeycomb	coal				
Stoves	Brick improved	Brick improved	Brick improved India	Brick improved India	Metal	Metal brick	Metal improved	Metal	Wick press	Traditional IR	Traditional	Traditional IR
Fuel[a]	Yes	Yes	Yes	Yes	Yes	Yes/no	Yes/no	Yes/no	No	No	No	No
	Yes	Yes	Yes	Yes		Yes	No					
			No	No								
% carbon	35	40	44	46	77	74	64	49				
%sulfur	0	0	0	0	0.35	0.852	0.166	0.257				
% water	9.09	7.26	7.65	7.98	4.73	2.08	3.94	3.48				

[a] Yes/No refers to each of the stove types in the rows above.

35–60 min for all fuels except coal burning, which needs a longer cycle especially during the initial phases. Preliminary experiments were performed to standardize the burn cycle and minimize operator variability until method precision roughly $<20\%$RSD for major parameters was achieved. Combustion products were collected using a stainless steel sampling probe attached to a filter holder, a pump and then a clean gas-collection bag. For stoves with flues the sampling probe was inserted into the flue for measurement. Stoves with no flues were measured underneath a hood built for test purposes, and the sampling probe was inserted into an exhaust vent for the hood. The flow rate of the sampling pump was adjusted to fill one or two bags throughout a whole burn cycle. For each fuel type a parallel sampling of flue gas was conducted. Filters used to collect total suspended particles (TSP) were quartz fiber filters and the mass of collected particles was determined gravimetrically using standard laboratory methods. One TSP filter for each fuel/stove combination was analyzed for carbon content using a thermal optical carbon analysis. SO_2 and NO_x were analyzed by standard methods for ambient measurements. CO, CH_4 and CO_2 were separated using a column packed with carbon spheres and analyzed by gas chromatograph. TNMHC was measured by subtracting CH_4 from the total hydrocarbon.

3. The triple-carbon-balance method

Before discussing the results and their policy implications, it is necessary to explain several aspects of the triple-carbon-balance (TCB) approach:

3.1. Stove efficiencies

Overall stove efficiency (OE), which relates directly to fuel use, is a combination of two internal efficiencies, which to a large extent can be influenced separately by stove design:

$$OE = NCE \times HTE. \quad (1)$$

Combustion efficiency indicates how much of the energy in the fuel is converted to heat. Used in the TCB approach is the closely related term, nominal combustion efficiency (NCE), which indicates the percentage of the fuel carbon converted to carbon dioxide. The remaining carbon is released as products of incomplete combustion (PIC), which, if they had been burned, would have released additional heat in converting completely to carbon dioxide. Thus, 1-NCE indicates the fraction of fuel carbon diverted into PIC. Included in the PIC are nearly all the HDP and GHG of interest.

Heat transfer efficiency (HTE) refers to the percentage of heat released by combustion that makes its way into the cooking vessel. In the TCB approach, it is calculated by dividing the measured OE by the calculated NCE:

$$HTE = OE/NCE. \quad (2)$$

A stove's fuel efficiency can be improved, therefore, by actions taken to improve either NCE or HTE. Unfortunately, as seen below, a common method is to make changes that increase HTE at the expense of NCE, in other words to increase the fraction of heat going into the pot but in the process increase PIC releases per unit fuel. In some cases a counter-intuitive result is achieved, where fuel use per meal declines, but PIC per meal increases. Thus, to determine the overall impact of a stove, all three efficiencies need to be examined.

3.2. Emission factors

Emission factors can be reported in different ways. Here, depending on the policy question being considered, we report emissions per kilogram of fuel, per unit energy content (MJ) of the fuel, or per unit energy (MJ) delivered to the pot. The third of these includes correction for the stove efficiency and is most closely related to the emission factor most relevant for many policy questions, i.e., emissions per meal. Since emissions were measured on the basis of average energy delivered over the standard cooking cycle, however, it is not a precise measure of energy per actual meal in the field, which can only be determined in real household settings. Another source of uncertainty and reason to do more tests in field setting is that wood fuels seem to have higher emission rates of products of incomplete combustion during the smouldering phase of combustion (Brocard et al., 1996). Since smouldering can continue in the field between cooking sessions, these emissions are difficult to measure in simulated settings. This is only a serious issue with wood fuels, however, as our Chinese tests did include smouldering phase for coal, and crop residues do not smoulder significantly after fueling stops. Gases and liquids, of course, have no such smouldering phases.

3.3. Instant versus ultimate emissions

When burning solid fuels, such as wood, part of the fuel carbon is often left at the end of the cooking period as charcoal. In this case, the emissions are calculated in two fractions. The first, called "instant emissions," addresses the emissions during a particular test. The rate of these emissions is appropriate for estimating indoor or local pollutant concentrations. The second, called "ultimate emissions," is an estimate of the ultimate emissions in typical household conditions in China from a unit of fuel and are most appropriate for determining greenhouse-gas inventories or other large-scale impacts from fuel demand, such as acid precipitation. The two types of emissions differ only for the solid fuels that produce a significant amount of char at the end of a burn cycle, such as wood.

The instant emissions measured in a single experiment are specific to the conditions of the tests, but need modification to reflect actual field conditions when a significant amount of fuel carbon is diverted into production of low-quality charcoal in wood stoves. In households, of course, this charcoal is subsequently burned along with fresh fuel at the next meal or extracted and stored for later use in the home for cooking or, in many parts of China, for use in small braziers for warmth in the winter. In some places, this residual charcoal will be sold to local blacksmiths. The instant emissions, therefore, do not account for the subsequent use of this charcoal. Ultimate emissions incorporate this use and all the major pollutants increase by roughly the same amount as the fraction of charcoal carbon compared to the fuel carbon, i.e., 20–30%, except for CO, which nearly doubles. The larger increase for CO in ultimate emissions reflects the dominance of char burning compared to flaming combustion because of charcoal's low volatile content compared to wood. In reporting emissions per unit delivered energy, we take the energy efficiency measured in the primary stove (the one using the original solid fuel).

3.4. Global Warming Commitment

The Global Warming Commitment is defined as the total atmospheric warming committed by an activity, such as burning of a kilogram of fuel or adding a MJ of energy to the cooking vessel. It is the sum of the global warming potentials (GWP) associated with each GHP:

$$GWC_j = \Sigma_j \, GHP_j^{*} GWP_j, \quad (3)$$

where j refers to the set of GHPs. In this study, we focus only on greenhouse gases (GHG), although there is evidence that cook stove emissions of black carbon (the major non-gas component of GHP) may also be significant (Jacobson, 2001).

Although many gases resulting from combustion have direct global warming effects or have an indirect global warming effect through the action of hydroxy-radicals on the concentration of other GHG in the atmosphere, only CO_2 and CH_4 are included in international negotiations surrounding the Kyoto protocol (along with others that are not significant pollutants from residential cook stoves). To illustrate the implications of which gases are included in definitions of GWC for household stoves we use three groups of gases to calculate GWC as follows: (a) GHGs specified within the Kyoto protocol CO_2, CH_4—hence forward referred to as GWC^{CO_2,CH_4}, (b) A slightly expanded set to include CO_2, CH_4, CO—referred to as $GWC^{CO_2,CH_4,CO}$, and (c) and extended set, GWC of CO_2, CO, CH_4, TNMHC (total non-methane hydrocarbon as g carbon) representing a more comprehensive list. Henceforward referred to as $GWC^{CO_2,CO,CH_4,TNMHC}$. It should be noted that we apply a GWP of 12 (per carbon atom compared to CO_2) to TNMHC as opposed to attempting to sum all the individual GWPs for each non-methane volatile organic compound thought to influence the tropospheric ozone and hydroxyl radical distribution. More detailed discussion of these effects may be found in Collins et al. (1997).

3.5. Renewable and non-renewable global warming potentials

With renewable harvesting of biomass, CO_2 emissions are completely recycled and thus there is no net increase in GWC from CO_2. If burning of this renewably harvested biomass were completely efficient there would be no net increase in GWC as emissions would be all CO_2. If combustion is inefficient, however, as is the case in most household stoves, some fuel carbon is diverted into PIC. Before eventual conversion to CO_2 in the atmosphere, PIC generally have a greater impact on climate than CO_2 per carbon atom. As renewable harvesting only affects GWC by eliminating the warming attributed to the final CO_2 in the atmosphere, emission of PIC results in a net increase in GWC even if the fuel is renewably harvested. In non-renewable harvesting all the carbon in biomass is a net addition to the atmosphere, as for fossil fuels (Smith et al., 2000).

Here we assume that crop residues and biogas always derive from renewable harvesting and that LPG, coal gas, coal, and kerosene are always non-renewable. Thus, only the GHG from wood and brushwood have different GWPs according to how they are harvested. For these wood fuels, therefore, there is a difference between GWC (renewable) and GWC (non-renewable) (Fig. 1).

4. Results and discussion

4.1. Global warming contributions

Fig. 2 shows relative global warming contributions (GWC) of each stove/fuel combination, based on a 20-year time horizon for global warming potentials (IPCC, 1990), for groups of greenhouse gas compounds. Global warming contributions have been calculated per MJ delivered energy (Smith et al., 2000) and fuels have been arranged from poor quality fuels to cleaner fuels that burn at higher efficiency. N_2O emissions data were not available for China, but contributed only an average of 1% of the renewable GWC for fuel wood combustion per MJ delivered energy in similar emission tests of fuel stove combinations in India (Smith et al., 2000).

Immediately apparent is the difference between biomass fuels and fossil fuels. Contributions of CO and NO_x were much greater for biomass fuels compared to fossil fuels, which results in considerable range of global warming contributions computed using GWC^{CO_2,CH_4}, $GWC^{CO_2,CH_4,CO}$ and $GWC^{CO_2,CH_4,CO,NO_x,TNMHC}$, compared to those computed for fossil fuels. Clearly evaluations of relative benefits of biomass and fossil fuels, and subsequently policies regarding promotion of different fuel types, are dependent on which products of incomplete combustion are considered. If one only considers GWC^{CO_2,CH_4}, which are the gases emitted from residential fuel combustion included within the Kyoto protocol, the burning of renewably harvested biomass appears to have an advantage over kerosene, LPG, and similar if not better than other fossil gaseous fuels (coal gas and natural gas). GWC^{CO_2,CH_4} for renewably harvested biomass computes the global warming contribution solely based on the contribution of CH_4, as CO_2 is not included due to the renewable nature of the harvesting (equivalent mass of CO_2 will be removed from the atmosphere in subsequent growing seasons). The other products of incomplete combustion that are emitted from inefficient biomass stoves are not included in the calculation and therefore do not contribute to the calculated global warming contribution. As a large component of emissions from kerosene, LPG and gaseous fuels are CO_2, compared to PIC, global warming contributions appear greater than those of biomass.

If, however, one considers a more comprehensive list of compounds that have direct or indirect effects on global warming a different picture emerges. The $GWC^{CO_2,CH_4,CO}$ and $GWC^{CO_2,CH_4,CO,NO_x,TNMHC}$ of better quality fuels that are more fully mixed with oxygen during the combustion process, and result in less products of incomplete combustion, have a lower global warming contribution than wheat, maize and brushwood fuels, even when renewably harvested. At best the burning of fuel wood when 100% renewably harvested has a similar GWC to these better quality fuels. While the assumption of renewable harvesting may be reasonable for maize and wheat crop residues, it is more questionable for fuel wood and brushwood when harvested and from areas where there are not programs to replant felled trees or areas that are not managed woodlots. Fig. 2 shows both the GWC of fuel wood and brushwood assuming renewable and not renewable harvesting. The degree of renewable and nonrenewable harvesting will determine the actual GWC between these two extremes.

The issue is further complicated when evaluating which stove type has lower emissions, and therefore which stove type should be promoted for marketing/dissemination in rural communities. As illustrated in

Fig. 1. Chinese Stoves (a) brick stoves, traditional (with the fire) and improved, both with a flue. Both types of stove can burn wood, crop residues, and unprocessed coal, (b) metal stove with flue (burning wood), (c) traditional metal coal stove without flue, beside the stove are honeycomb coal briquettes. (This type of stove can also burn coal briquettes.), (d) metal coal stoves with flue (both honeycomb coal and coal briquettes can be burnt in these stoves.), (e) Kerosene wick stove with sampling set-up, (f) improved metal coal stove without flue (designed for honeycomb coal briquettes), and (g) traditional gas stove.

Fig. 2, if one assumes renewable harvesting of fuel wood then clearly a brick stove would be recommended, as a large proportion of the emissions are CO_2. If, however, one assumes non-renewable harvesting the opposite would be the case and an improved stove would be recommended. The same issue does not apply when brushwood is used, as brick stoves consistently had lower GWC than improved stoves. An even more complex scenario arises when a combination of both fuel and brushwood are used, as would be expected in most rural communities.

Although historically in China, rural energy shortages have led to deforestation (and vice versa) resulting in excessive collection of other plant materials, afforestation programs have been present in China since 1980 as increasing the firewood supply was considered a strategic necessity in rural development. Beginning with the sixth 5-year plan (1981–1985) the state officially listed development of fuel wood forests into the national reforestation program and rural energy development. At the end of 1998 over 5.3 million hectares of fuel wood forests had been developed with an average annual

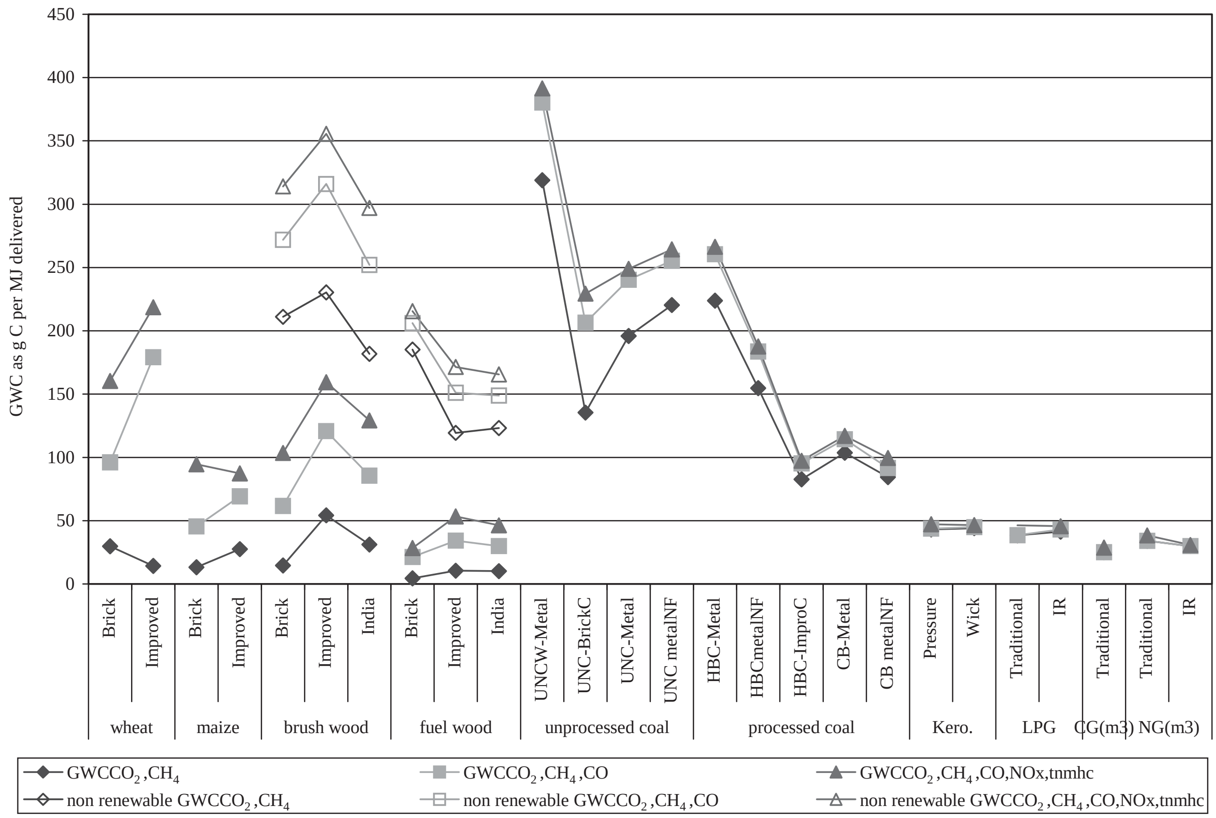

Fig. 2. Global warming contributions of different stove/fuel combinations per MJ delivered.

increase of 25 million tons of fuel wood (CERS and CAREI, 2000). These remarkable achievements in fuel wood production were reported to supply 14.7% of rural energy consumption in 1998 (CERS and CAREI, 2000). Although a rationale could be presented for selecting stoves assuming renewable harvesting, given the aforementioned efforts for increasing the fuel wood supply, the calculation of national GWC estimates for this sector of fuel use presents considerable difficulties. The difference between global warming commitments for renewable and non-renewable harvesting is large, especially compared to differences between improved and brick stoves. It is likely, therefore, that even if one were able to obtain reliable estimates of stove types used in different rural households, this information would not improve national estimates of emissions without more detailed accounting of what fraction of the wood is being harvested renewably.

This issue has profound implications for global accounting of carbon emissions and credit through the clean development mechanism (CDM). For illustration, promotion of improved brick stoves assuming non-renewable harvesting of fuel wood would result in a GWC reduction of 66 g carbon as CO_2 per MJ delivered for gases included in Kyoto negotiations. Promotion of the same stove assuming renewable harvesting would result in an increase in GWC of 6 g carbon as CO_2 per MJ delivered.

In addition, if one considers only CO_2 and CH_4, burning wheat residues in a brick stove appears to have higher GWC than if burned in an improved stove. If one considers the more comprehensive list of gases the opposite is the case and a brick stove is considerably better than an improved stove for wheat residues. Comprehensive evaluation would require all major radiative forcing agents to be considered, even though that presents difficulties considering reported uncertainties of some global warming potentials (IPCC, 1995). Although not a component of the current database of emissions measurements, this would include black carbon (BC), incorporating fate of BC downwind of the source, and in the plumes transported large distances around the globe in order to relate point emissions to warming implications. Henceforward discussion of GWC refers to $GWC^{CO_2,CH_4,CO,NO_x,TNMHC}$.

The GWCs of unprocessed coal emissions are higher than those of fuel wood. GWCs of honeycomb coal are of similar magnitude, and coal briquette slightly lower magnitude than fuel wood assuming non-renewable harvesting and both are considerably above that of renewably harvested fuel wood. In contrast, GWCs of unprocessed coal are lower than non-renewably harvested brushwood, and processed coal GWC are similar to renewably harvested brushwood. Although development of increased renewable firewood supplies, therefore, would benefit in greenhouse gas reduction, due to the large number of households in rural China and limitations in firewood production, increased use of coal in rural areas is unavoidable without continued development of alternative energy sources. Increased use of coal in rural areas would result in an overall increase in rural global warming contributions.

Dramatic reductions in GWC are seen with the progression from unprocessed coal to processed coal. Such reductions, however, would still result in global warming contributions that are elevated relative to a change to other fuels. An additional reduction in emissions of approximately 50% can be achieved through change in fuel type to LPG, natural gas, coal gas, or kerosene. Thus, regulations passed in 1988 by Beijing municipal government to implement the 1987 air pollution prevention act requiring the conversion of urban residential fuel from coal to LPG and natural gas (UNEP/WHO, 1992), would result in considerable reduction of greenhouse gases in addition to the desired reduction of sulfur emissions in the urban area.

There are technologies that may potentially achieve even lower emissions, such as gasified biomass or liquid derived from gasified biomass due to combination of high combustion efficiency for gaseous fuels and renewable harvesting. Although biogas was not measured in the Chinese emissions database, similar emissions data for biogas stoves in India reported by Smith et al. (2000) indicates considerable further reduction in global warming contributions can be made.[3] Interestingly, a potential further reduction can be made using an infrared head, a circular device around the burner under the pot designed to convert a portion of the heat released into the surrounding air into infrared radiation, which irradiates the pot (Zhang et al., 2000). Evaluation of different options for residential energy provision should consider the full range of available technologies.

4.2. Health damaging pollutants

In the current manuscript relative emission factors of health-damaging pollutants from fuel and stove combinations are assessed, but it should be remembered that the relationships of emissions to personal exposures and health effects are less clear, especially when cooking activities, stove construction, and household ventilation vary. In addition some stoves vent inside the home whilst others use flues, which vent the majority of pollutants outside the home and there are differences in community household density. As flues and chimneys are not much above the height of the houses, these emissions result in elevated neighborhood and regional pollution, which penetrates back into the indoor environment. In isolated rural households the air quality improvement in the vicinity of the stove may vastly outweigh relatively small increases in background concentrations due to large dilution, but in densely populated village and slum environments, the increase in background may pose significant health problems and deterioration in air quality. Thus, although extremely high levels in the vicinity of the stove and peak personal exposure concentrations have been reduced, background levels and personal exposure concentrations of such populations may have been increased.

Fig. 3 shows emissions of health damaging pollutants per MJ delivered for different fuel/stove combinations. In combustion devices with low flue-gas velocities, both CO and particulate (measured as total suspended particulates–TSP)[4] emissions are mainly products of incomplete combustion and are related to nominal combustion efficiency, which indicates the percentage of the fuel carbon converted to carbon dioxide (the remaining carbon is released as PIC). As many of the GHG are also PIC, most changes in stove type within a fuel category that result in reduction in GWC also result in reduction in HDP. Occasional exceptions may arise if significant differences in NO_x emissions also result, as NO_x have significant GWC but are not PIC. Thus, the combustion of maize residues in traditional brick stoves has a higher GWC than improved brick stoves due to higher NO_x emissions, even though having lower TSP and CO emissions.

Although emissions of both HDP and GWC are related to combustion efficiency, renewably harvested biomass fuels do not include GWC of CO_2 as equivalent mass of CO_2 will be removed from the atmosphere in subsequent growing seasons. Thus, emissions of HDP relative to GWC were much greater for renewably harvested biomass fuels compared to other fuels. For illustration, TSP emissions from wheat residues were considerably higher than brushwood, but GWC of renewably harvested wheat residues were considerably lower than those of non-renewably harvested brushwood. Similarly, TSP emissions from fuel wood were above all fossils fuels except unprocessed washed coal, while GWCs for renewably harvested fuel wood were lower than both unprocessed and processed coal. Clearly, selection of stove type solely based on global

[3] Although these do not include emissions at other parts of fuel cycle during biogas production e.g., leakage during storage and piping etc. As these emissions contain substantial CH_4, which has a GWP per carbon atom of 22.6 relative to CO_2 over a 20-year time horizon, small leaks can be significant.

[4] Although no pre-cut was made on the size distribution and particulate mass is reported as total suspended particulate (TSP) particulate emissions from incomplete combustion in small scale residential stoves are generally in the sub-micron range. Airflow through residential stoves is usually insufficient to entrain the larger fly ash particles observed in stacks of industrial burners.

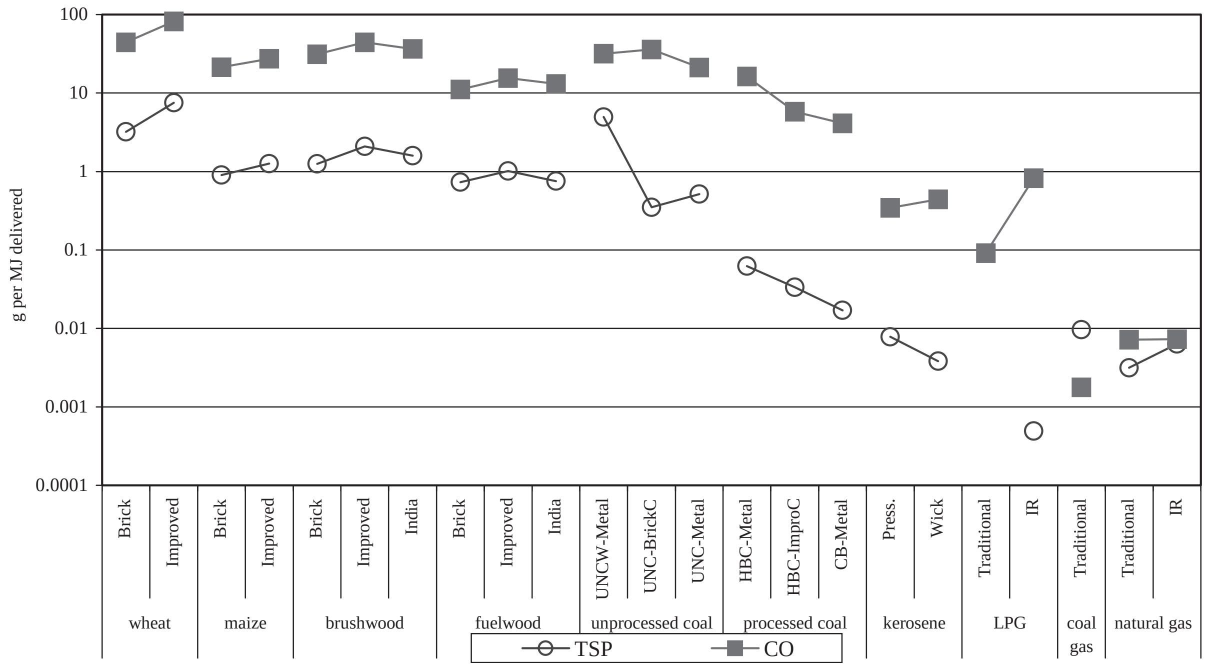

Fig. 3. Emissions of health damaging pollutants different stove/fuel combinations per MJ delivered.

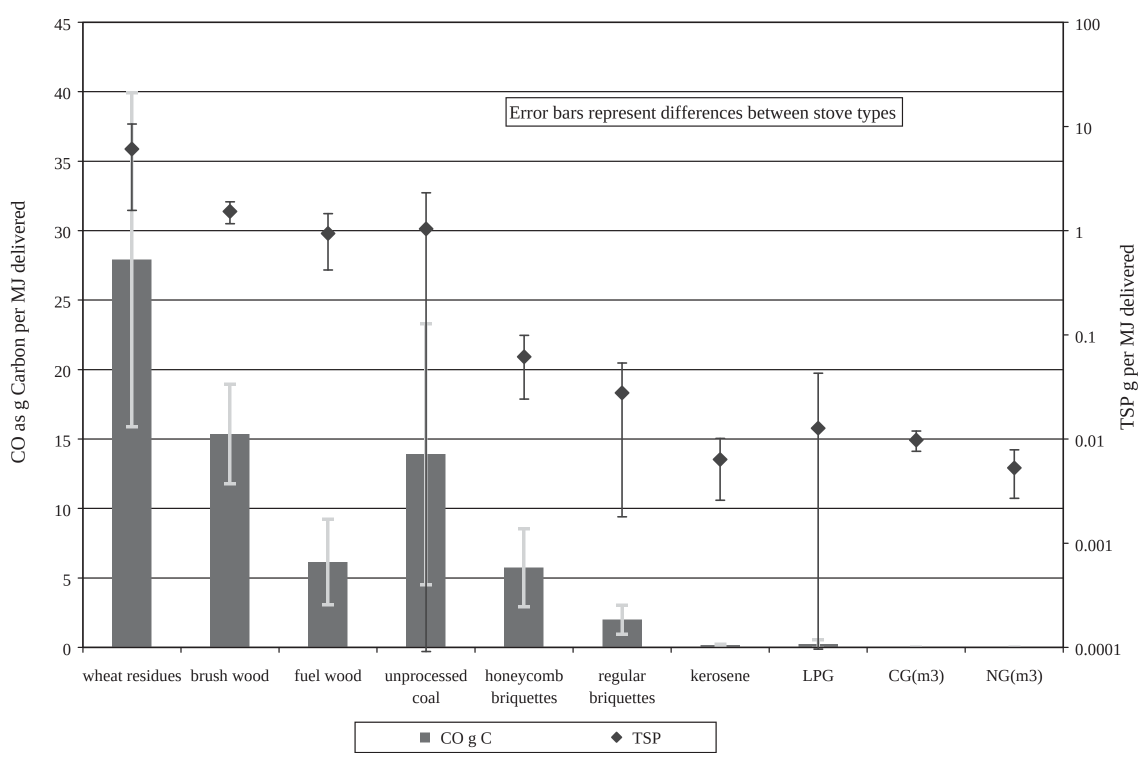

Fig. 4. Reductions in TSP and CO per MJ delivered that may be made by change in stove type for stoves tested as part of the current study.

warming contribution could potentially lead to additional health burdens.

Fig. 4 illustrates the reductions in TSP and CO per MJ delivered that may be made by change in stove type for stoves tested in the current study. This figure demonstrates the potential benefits of changes in stove type and also those of fuel switching. More importantly, however, there is a trade-off as improved biomass stoves are intermediate steps along the ‘‘energy ladder’’ toward eventual provision of clean fuels for all households.

Given the large variety of economic and agro-climatic conditions in China, there are undoubtedly many communities where policies to promote movement to cleaner fuels may be more cost-effective today than improved biomass stoves. Promotion of stoves in such areas, therefore, may well be counterproductive. Conversely, although economic growth rates are substantially greater than the world's average, China is still a developing country and switching to cleaner fuels is out of economic reach of many rural Chinese (Florig, 1997). For these rural Chinese stuck near the bottom of the energy ladder, or who lack access to distribution points of cleaner fuels, promotion of cleaner burning stoves with flues remains an effective measure in reducing indoor levels of HDP. Cost benefit analyses should, therefore, include evaluation of using other fuels compared to installation of improved stoves.

Recent energy consumption in rural areas was 14.7% fuel wood, 18.2% agricultural residues and 44.4% coal in 1998 (CERS and CAREI, 2000). If differences between these stove types are weighted by fuel consumption in rural China, emissions of TSP using stoves with higher combustion efficiencies for each fuel type would represent a potential 87% reduction compared to the least efficient stoves. Clearly, however, this figure is merely illustrative as conditions in the millions of rural Chinese households are likely to be much more variable. Combustion conditions are likely to be less controlled, there are more stove types in actual use than measured in the study, and there are a number of other factors that may affect stove performance in residential settings including: wind speed, dampening patterns, preheated stoves and indoor/outdoor temperature differences. A number of interesting issues arise, however, in that in many cases the stoves that produced the lowest emissions per MJ delivered were not the stoves that have been promoted as improved stoves due to greater fuel efficiencies.

4.3. Improved biomass stoves

A wide variety of stoves have been developed and disseminated throughout Asia, Africa, and Latin America and whose diversity and complexity is summarized by Westhoff and Germann (1995). Although many have been effective in achieving greater thermal efficiency, these stoves were not systematically evaluated in terms of emissions of harmful pollutants, contribution to greenhouse gas emissions and environmental impacts compared to other options in residential fuel/energy provision. Such analyses are essential in developing a complete rationale behind policies for residential energy provision especially considering the tremendous effort and lead-time required for implementation of such programs.

Table 2
Comparison of geometric mean residential biomass stove emissions per 1 MJ delivered

Geometric mean emissions per MJ delivered						
Fuel	Stove	TSP	CO	GWCALL	NCE	PIC
Wheat residue[a]	Brick	3.2	44	160	0.92	24
	improved	7.5	82	219	0.78	46
	% change	134	85	36	−15	90
Maize residue[a]	Brick	0.9	21	94	0.94	11
	improved	1.3	27	87	0.88	14
	% change	40	28	−8	−6	26
Brush wood	Brick	1.3	31	104	0.93	15
	improved	2.1	44	159	0.89	24
	% change	66	43	54	−4	57
Fuel wood	Brick	0.7	11	28	0.97	6
	improved	1.0	15	53	0.92	9
	% change	39	40	87	−5	63

[a] Burning of agricultural residues was highly variable.

Indeed, our measurements indicate that in many cases greater thermal efficiency was achieved by improving heat transfer efficiency between the combustion source and the pot bottom, but at the expense of a decrease in combustion efficiency. This led in many cases to lower demand for fuel and hence less time spent looking for fuel or spent on purchasing fuel per meal cooked, but increased HDP and GHP. Table 2 shows geometric mean emissions per 1 MJ delivered of TSP, CO, GWC, nominal combustion efficiency and PIC, from fuel wood, brush wood, maize and wheat residues burnt in traditional brick and improved stoves. The percentage increases in emissions and other parameters when moving from a traditional to an improved stove are presented under each fuel type. For all biomass fuel types emissions of TSP and CO were increased in improved stoves. Although these improved stoves have flues that vent part of the emissions outside of the residence, resulting in improved indoor air quality immediately around the stove, the overall emissions are considerably higher. Without a comprehensive "triple-carbon balance" approach it is possible, therefore, to implement policies with the best intentions for alleviating the burden of collecting fuel, which may actually result in increased emissions of health damaging pollutants and increased global warming contributions. Similarly, if only nominal combustion efficiency were improved, emissions of health damaging pollutants would be reduced but the overall efficiency of the stove would remain quite similar. Ideally the most advantageous are stoves that manage to increase heat transfer efficiency, whilst also maintaining high nominal combustion efficiencies. There are such improved stoves for biomass in use in India, which rely on ceramic combustion chambers to improve combustion efficiency whilst improving heat transfer efficiencies. These stoves conserve fuel, reduce indoor air pollution and achieve lower GWC (Smith et al., 2000). It is unlikely, however, that one stove type will meet the needs of all the diverse conditions and people in China and other parts of the world, and the above example serves just as an illustration that such stoves can be designed. There is a clear need for the development, health, and environment sectors to work together towards win–win outcomes in future stove programs where the full range of options for energy provision are evaluated, and stoves are scientifically designed with an understanding of the mechanisms by which fuel efficiency is improved and the resultant effects on levels of HDP, GHP and environmental impacts. Design of stoves for such programs would also necessarily include appreciation of cultural practices and traditional food preparation techniques so that the stoves can be incorporated into rural economical development. As a further incentive and mechanism to defray some of the costs of improved stoves or fuel switching there is a need for mechanisms that allow the inclusion of the household energy sector in international carbon trading agreements. Although individually the stoves are quite small, this sector accounts for a significant portion of primary energy consumption in China and other developing countries. With the concomitant benefits due to reduction in levels of HDP these present truly no regret scenarios.

4.4. Improved coal stove, unprocessed and processed coal

Table 3 shows geometric mean emissions per 1 MJ delivered of TSP, CO, GWC, fuel use, PIC, nominal combustion efficiency and overall efficiency, from coal stoves in China. The improved metal stove using honeycomb briquettes results in the highest overall efficiency of 47% and clearly reduced emissions: 50% for TSP, 70% for CO and 70% for NO_x compared to metal stoves with flues. Interestingly the presence of a flue dramatically decreased the overall efficiency for both honeycomb briquettes and coal briquettes, resulting in higher emissions of TSP, CO and NO_x, and ultimately leading to higher global warming contributions for these stoves. Clearly there is a trade-off as the flue removes much of the health damaging pollution from the immediate vicinity around the stove, and inside the home, where women and children may be exposed to extremely high concentrations of health damaging pollutants when un-vented. While this reduces dramatically peak concentrations of exposure, as with biomass emissions, the increased emissions in urban areas, villages and slums penetrate indoor environments, exposing the population to consistently elevated background levels.

Emissions from stoves using unprocessed coal were much more variable between burn cycles, as fuel distribution and combustion efficiencies of unprocessed coal were much more uneven. As a result specific conclusions about the merits of different stove types should not be made. Not surprisingly, emissions of NO_x were higher for the processed compared to unprocessed coals reflecting higher combustion temperatures and improved combustion efficiencies. An additional component of the 1987 air pollution prevention act required those residences still using coal to burn coal briquettes and shaped coal instead of unprocessed coal (UNEP/WHO, 1992). Although the number of measurements for each fuel and stove combination was small, coal briquettes appeared to have lower emissions than honeycomb coal briquettes. A reduction in emissions was only seen for SO_2, which is absent in the honeycomb

Table 3
Comparison of residential stove emissions for unprocessed and processed coal per 1 MJ delivered

Geometric mean emissions per MJ delivered								
Fuel	Stove	TSP	CO	NO_x	GWCALL	PIC	NCE	OE (%)
Honeycomb briquettes	Metal with the flue	0.07	8.04	0.14	266	8.1	0.97	16
	Metal no flue	0.06	6.02	0.10	188	6.0	0.96	23
	Improved metal	0.03	2.48	0.04	97	2.5	0.97	47
Metal with flue to improved	% change	−49	−69	−69	−63	−69	0	
Unprocessed coal	Traditioonal brick	0.35	15.4	0.48	229	15.8	0.90	16
	Metal with flue	0.31	9.5	0.09	249	10.9	0.94	15
Traditional brick to metal with flue	% change	−10	−38	−82	9	−31	4	
Coal briquettes	Metal with flue	0.05	2.2	0.06	117	2.2	0.98	26
	Metal no flue	0.01	1.4	0.17	100	1.4	0.98	37
Unprocessed to coal briquette (metal with flue)	% change	−85	−77	−30	−53	−80	4	

briquettes (not shown). For both traditional brick stoves and metal stoves with flues, however, emissions from the use of unprocessed coal ranged from being equivalent to honeycomb briquettes to being 4–6 times higher for CO, 5–9 times higher for TSP, and global warming contributions were up to 3 times higher. Changes in the use of unprocessed coal to the use of coal briquettes in metal stoves with flues would result in reductions of 85% TSP, 77% CO, 53% GWC on a geometric mean basis as a result of 80% reduction in PIC, while also achieving higher overall efficiency.

Additional support comes from Zhang et al. (2001), who reported results of an integrated analysis of energy, greenhouse gas and air quality implications from use of a new type of boiler briquette coal compared to raw coal from which it was formulated. Use of the boiler briquette coal resulted in multiple benefits including amongst others: 37% increase in thermal efficiency and corresponding 25% reduction in fuel demand, 26% reduction in CO_2 emission, 17% reduction in CO emission, 63% reduction in SO_2 emission, 22% reduction in $PM_{2.5}$ mass emission. The larger reductions in emissions from unprocessed coal to coal briquettes in the current study compared to those of Zhang et al. (2001) were probably due to poorer combustion efficiencies of burning unprocessed coal in small scale residential cook stoves compared to coal fired boilers. Combined with higher total residential coal consumption in rural households on a national basis, this implies that greater or equivalent emissions reductions could therefore be achieved through improvement of fuels in household stoves.

Reduction in health damaging pollution and greenhouse emissions can also be achieved through district heating via co-generating power plants in urban environments. In this case cooking is electric and heating is through high-pressure hot water pipes and emissions sources are removed from the residence, removing high population exposures, to the power plant where effective emission controls can be implemented. Reduction in greenhouse emissions and ultimately energy conservation is achieved through elimination of many of the thousands of inefficient and uncontrolled household and industrial boilers.

4.5. Dissemination of improved stoves in China and GWC from rural residential biomass burning

Fig. 5 shows the dissemination of improved stoves in China with the number of rural households demonstrating the impact of the largest and most successful improved stove program worldwide with current estimates of 90% coverage in the rural population. Such a feat is unprecedented especially in the light of often poor dissemination of improved stoves elsewhere in the world. The primary motivation, at least for the first generation of these improved stoves, was a desire for greater fuel efficiency in accordance with the strong Chinese emphasis on conservation, often referred to as China's 'fifth energy source' (Lu, 1993). From this

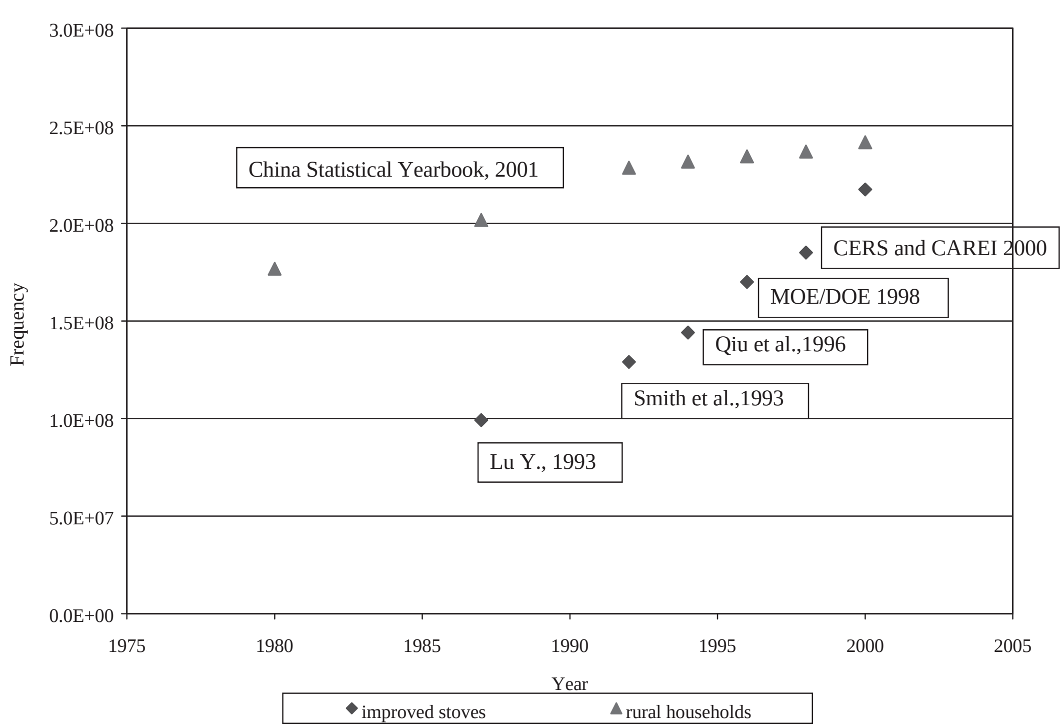

Fig. 5. Dissemination of improved stoves in rural China and number of rural households. (CERS and CAREI, 2000; China Statistical Yearbook, 2001; Lu, 1993; MOE/DOE, 1998; Qiu et al., 1996; Smith et al., 1993).

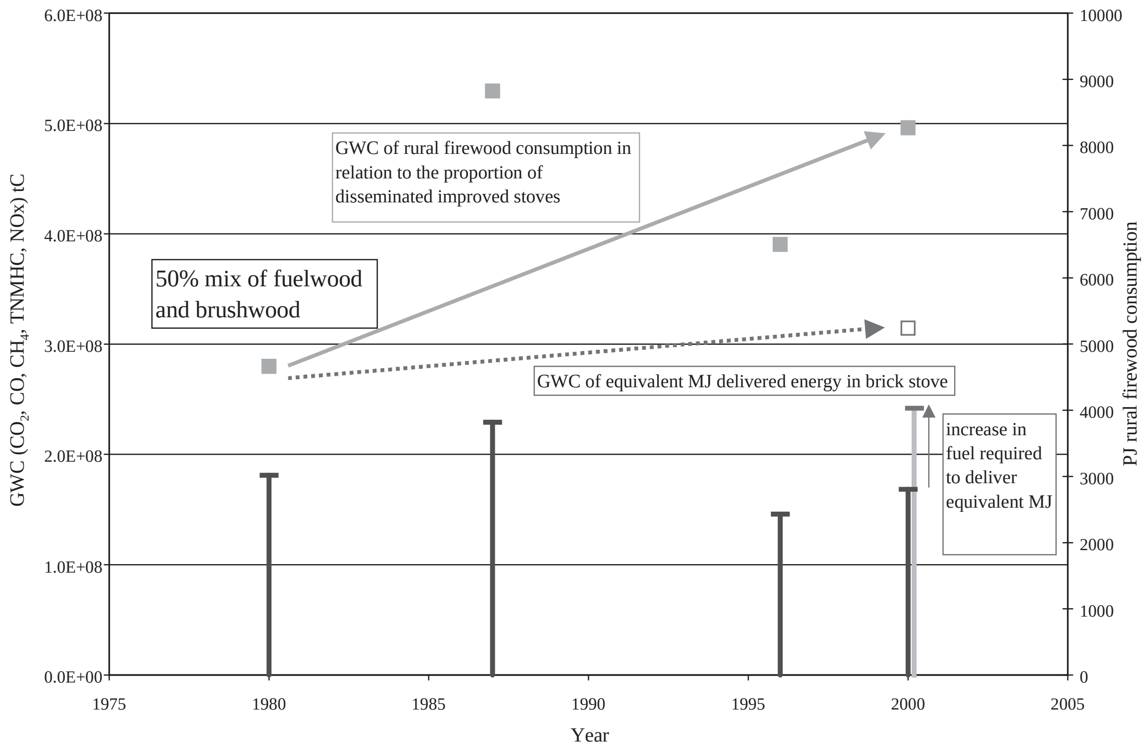

Fig. 6. GWC and firewood consumption of traditional and improved stoves in rural China.

conservation standpoint the improved stove program was indeed successful with installation of stoves with reported efficiencies of 20–30% compared to the no more than 10% achieved with traditional stoves (CERS and CAREI, 2000). Evaluation of the effects of improved biomass stove programs in regard to GWC and available fuel supplies is more complex, however, and requires much more information on which stove models are currently in use, combined with detailed information on combustion performance over the lifetime of each stove. In addition, more information is needed on the quality and type of fuel used (brush wood, stem wood, species etc) including the fraction renewably harvested. As such information is not readily available we assume the fractions of traditional to improved stoves for rural biomass stoves were similar to the total fractions of traditional to improved stoves during the same periods (Fig. 5). In most developing countries, the wood burnt in residential stoves comprises a mixture of smaller branches, large branches and trunk wood. Thus we assume that approximately 50% of the firewood is burnt as fuel wood and 50% as brushwood for computation of the GWC for rural residential firewood consumption. Xu (1995) reports that for forest species the ratio of total to stem wood biomass is 1.21 in northeast, 1.56 in southwest, 1.44 in southern and 1.56 for agro-forestry and managed forest in northern and northwestern China. Clearly a ratio of 50:50 for brushwood compared to fuel wood in the current paper does not account for wood diverted into paper and lumber industries, but may be reasonable for four sides wood and fuel wood plantations.

Another important aspect of estimating the GWC from this sector is the appropriate emissions factors for the stoves used to burn the wood. These studies do not, of course, cover all fuel/stove combinations in use by the 1.3 billion people in China and many other variations such as local cooking practices, stoves that are also used for heating, variations in construction techniques, differences in fuel quality, wind speed, and indoor/outdoor temperature differences may effect emission factors. The stoves measured in this study do represent some of the most commonly available, however, and are used to compute GWC for this sector.

Rural household energy use in China including firewood consumption was reported as 3018 PJ for 1980, 3818 PJ for 1987, 2432 PJ for 1996 and 2806 PJ for 2000, respectively (Jingjing et al., 2001). In 1996 firewood consumption dropped, presumably due to a combination of increased fuel efficiency of improved biomass stoves and the adoption of cleaner burning fuels (LPG) and increased coal consumption. The GWC for rural firewood consumption for biomass stoves (Fig. 6) increased substantially between 1980 and 1987 with the increase in fuel consumption and subsequently dropped significantly from 1987 levels and then again increased slightly by 2000. Fig. 6 also shows the GWC emissions that would have resulted for the same delivered energy (same number of households and meals) if the traditional stoves had been used. Clearly the traditional stoves would have resulted in considerably lower emissions from this sector than the 90% dissemination of improved stoves, but this is only a partial picture as it is not clear that the wood consumption patterns shown in 1987 and that which would have been required by traditional stoves to deliver the same energy as the improved stoves in 2000, would have been sustainable over the intervening period without substantial environmental degradation necessitating the use of lower quality fuels. Such a shift would have resulted in increased emissions. Concurrently it is possible that the higher fuel wood requirements of the traditional stoves if they resulted in environmental degradation would have decreased the CO_2 sequestration capacity of those areas in future growing seasons. This illustrates the need for a more holistic, or full fuel cycle approach to biomass burning, in a similar manner to that required for fossil fuel burning, that considers both the production of the fuel wood, the burning of the fuel, sequestration of gases during the next growing season and the environmental degradation and shift in fuels that may occur due to mining of the resource.

5. Conclusions and recommendations

Here we summarize the major findings of our work and recommend actions to reduce the remaining uncertainties that need to be addressed if household combustion devices can be included systematically in pollution control policies, such as those represented by the clean development mechanism (CDM).

5.1. Conclusions

- The relative benefits of different biomass and fossil fuel/stove combinations are dependent on which combustion products are considered. Comprehensive evaluation would require all major radiative forcing agents to be considered, even though at present there are uncertainties in some of global warming potentials. Choice of time horizon (20 or 100 years, for example) or adoption of a discount rate also affects the relative GWPs.
- The difference between global warming commitments for renewable and non-renewable harvesting are of such magnitude, especially compared to differences between improved and brick stoves, that the extent of renewable harvesting of biomass fuels has profound implications for global accounting of carbon emissions.
- Emissions of PIC including TSP and CO were increased in improved stoves with flues for all biomass fuel types in this study. Understanding the mechanism by which fuel efficiency is improved in improved biomass stoves is essential to determine the effects of these stoves on levels of HDP, global warming implications and environmental impact. Similarly the presence of a flue dramatically decreased the overall efficiency for both honeycomb briquettes and coal briquettes, resulting in higher emissions of TSP, CO and NO_x, and ultimately leading to higher global warming contributions for these stoves. Clearly, however, there is a trade-off as the flue removes much of the health damaging pollution from the immediate vicinity around the stove, and inside the home, where women and children may be exposed to extremely high concentrations of health damaging pollutants when unvented. Although this likely reduces peak exposure concentrations, emissions in neighborhood, community and regional environments are increased and may re-penetrate indoor environments, exposing the population to consistently elevated background levels. In isolated rural households the air quality improvement in the vicinity of the stove may vastly outweigh relatively small increases in background concentrations due to large dilution, but in village and slum environments, the increase in background may pose significant heath problems and deterioration in air quality.
- Improved coal stoves result in large reductions in emission of health damaging pollutants and greenhouse gases, while also achieving higher overall efficiency and changes in the use of unprocessed coal to the use of coal briquettes in metal stoves with flues would result in reductions of 85% TSP, 77% CO, 53% GWC on a geometric mean basis as a result of 80% reduction in PIC, while also achieving higher overall efficiency.

5.2. Recommendations

- There is clearly a continued need for an index by which the relative contributions of the various greenhouse pollutants can be summed and compared. In spite of uncertainty in their estimation such indexes provide an essential tool to enable comparison of global warming implications between different options in residential energy provision. As a result of uncertainties it may be useful to express GWP as ranges for use in probabilistic analyses. The utility of such indexes and policy recommendations are hampered, however, unless all radiative forcing agents are considered. In addition as the magnitude of each GWP is dependent on the time horizon considered, agreement on common time horizons and reporting of GWPs would be desirable.

- There is a clear need for tools and information that allow inclusion of household stoves and residential energy provision in the clean development mechanism (CDM) or similar mechanisms. Although stoves are important in total energy use, GHP and HDP, their small-scale, wide distribution, and variability in designs makes it difficult to include in such agreements. Such tools would provide ways to reliably estimate HDP, GWP, and fuel efficiency using parameters that can be easily monitored in the field, enabling computation of carbon credit for communities and regions without measurement of multiple pollutants in complex burn cycles which are too costly for incorporation in large scale surveys. Such an approach for application with residential stoves in China is presented in Edwards et al. (2003).
- There is a clear need for better accounting and estimation of the fraction of biomass fuel harvested renewably. Due to the non-commercial nature of much biomass used in household stoves such a task presents considerable difficulty. Conceivably such information can be obtained through questionnaires in large surveys, combined with accounting of newly planted trees for fuel wood use. Other options would involve more detailed interpretation of high-resolution photographs etc.
- With increasing attention paid to the importance of black carbon (BC) in global warming implications, there is an immediate need for assessment of emissions factors for both heating and cooking of black carbon from different fuels and the many different types of household stove in typical use in rural communities. Further the fate of BC downwind of the source, and in the plumes transported large distances around the globe need to be assessed in order to relate point emissions to warming contributions.
- One of the major drawbacks of studies to assess health impacts from stove emissions in less-developed countries is that measurements of emission factors have not been related to indoor air pollution levels and personal exposures. Similarly measurement of indoor air pollution levels and personal exposures have not been task or stove specific or related to the combustion efficiency of the stoves and energy delivered to the pot. Thus although it is possible to assess relative emissions of these fuel and stove combinations, the relationships to personal exposures and health effects are less clear, especially when some use flues and others don't, and the construction and sealed nature of the stoves are not similar. There is a clear need to develop links between combustion efficiencies of solid fuels in household stoves and personal exposures through investigation of the mass of pollutants from household stoves entering the breathing zone of exposed individuals during a cooking task, or per delivered energy, ultimately defining distributions of personal exposures per energy delivered.
- Populations in less-developed countries that live in 'slum' environments have the misfortune of being exposed to significant modern risks from the large number of excessively polluting vehicles and unregulated industries, while the traditional risks from solid fuel use have not been reduced as a high proportion of houses still use solid fuels. This is not only compounded by the increased emissions from the poor quality fuels and older vehicle fleets usually present in these environments, but these populations are also some of the poorest and most disenfranchised, with high unemployment, poor nutrition and sanitation, and lack of access to adequate health care. There is a clear policy value in understanding where the biggest reduction in exposure could be achieved for these especially vulnerable populations in risk overlap situations.

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