PERGAMON

Chemosphere 50 (2003) 201–215

CHEMOSPHERE

www.elsevier.com/locate/chemosphere

Models to predict emissions of health-damaging pollutants and global warming contributions of residential fuel/stove combinations in China

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Received 2 October 2001; received in revised form 6 March 2002; accepted 2 May 2002

Abstract

Residential energy use in developing countries has traditionally been associated with combustion devices of poor energy efficiency, which have been shown to produce substantial health-damaging pollution, contributing significantly to the global burden of disease, and greenhouse gas (GHG) emissions. Precision of these estimates in China has been hampered by limited data on stove use and fuel consumption in residences. In addition limited information is available on variability of emissions of pollutants from different stove/fuel combinations in typical use, as measurement of emission factors requires measurement of multiple chemical species in complex burn cycle tests. Such measurements are too costly and time consuming for application in conjunction with national surveys. Emissions of most of the major health-damaging pollutants (HDP) and many of the gases that contribute to GHG emissions from cooking stoves are the result of the significant portion of fuel carbon that is diverted to products of incomplete combustion (PIC) as a result of poor combustion efficiencies. The approximately linear increase in emissions of PIC with decreasing combustion efficiencies allows development of linear models to predict emissions of GHG and HDP intrinsically linked to CO_2 and PIC production, and ultimately allows the prediction of global warming contributions from residential stove emissions. A comprehensive emissions database of three burn cycles of 23 typical fuel/stove combinations tested in a simulated village house in China has been used to develop models to predict emissions of HDP and global warming commitment (GWC) from cooking stoves in China, that rely on simple survey information on stove and fuel use that may be incorporated into national surveys. Stepwise regression models predicted 66% of the variance in global warming commitment (CO_2, CO, CH_4, NO_x, TNMHC) per 1 MJ delivered energy due to emissions from these stoves if survey information on fuel type was available. Subsequently if stove type is known, stepwise regression models predicted 73% of the variance. Integrated assessment of policies to change stove or fuel type requires that implications for environmental impacts, energy efficiency, global warming and human exposures to HDP emissions can be evaluated. Frequently, this involves measurement of TSP or CO as the major HDPs. Incorporation of this information into models to predict GWC predicted 79% and 78% of the variance respectively. Clearly, however, the complexity of making multiple measurements in conjunction with a national survey would be both expensive and time consuming. Thus, models to predict HDP using simple survey information, and with measurement of either CO/CO_2 or TSP/CO_2 to predict emission factors for the other HDP have been derived. Stepwise regression models predicted 65% of the variance in emissions of total suspended particulate as grams of carbon (TSPC) per 1 MJ delivered if survey information on fuel and stove type

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PII: S0045-6535(02)00478-2

was available and 74% if the CO/CO_2 ratio was measured. Similarly stepwise regression models predicted 76% of the variance in COC emissions per MJ delivered with survey information on stove and fuel type and 85% if the TSPC/CO_2 ratio was measured. Ultimately, with international agreements on emissions trading frameworks, similar models based on extensive databases of the fate of fuel carbon during combustion from representative household stoves would provide a mechanism for computing greenhouse credits in the residential sector as part of clean development mechanism frameworks and monitoring compliance to control regimes.

Keywords: Household fuels; Cook stoves; Global warming commitment; Greenhouse gas emissions; Particulate emissions

1. Introduction

The Chinese government improved biomass stove program is one of the oldest and certainly the largest such program in the world (Smith et al., 1993). The program, run by the Ministry of Agriculture, is credited with introduction of more than 180 million stoves since its inception in 1981 (WEA, 2000). The principal motivation has been to increase fuel efficiency thereby reducing pressure on wood resources and releasing crop residues for more effective uses in rural areas. Since the 1980s, however, two additional issues related to household biomass stoves have come into prominence: emissions of health-damaging pollutants (HDP) and greenhouse gases (GHG). HDP and many of the gases that contribute to GHG emissions are both largely due to the significant portion of fuel carbon that is diverted to products of incomplete combustion (PIC) in simple stoves. Eventually most PICs are oxidized to CO_2, but in the meantime they individually have greater global warming potentials than CO_2 by itself. Thus, even though CO_2 is taken up by vegetation in the next growing season when fuels are renewably harvested, the global warming commitment (GWC) of a meal cooked with renewably harvested biomass may exceed that of one cooked with fossil fuels (Smith et al., 2000). This picture is further complicated as much of the harvesting of both fuel wood and brush wood is currently non-renewable, although increasing the firewood supply has been a priority in rural development in China. Recent work has shown that HDP and GHG emissions vary dramatically among different fuel/stove combinations in China and elsewhere (Smith et al., 2000; Zhang et al., 2000). In addition, these studies have shown that shifts up the energy ladder from biomass to coal, kerosene, or gas leads to significant changes in the emissions profile and emission rates from residential fuel combustion.

Promotion of the proper stove types combined with changes in fuel type, therefore could possibly be effective mechanisms for achieving short-term health benefits through reduction of HDP emissions and also accomplishes longer term goals of GHG reduction (Smith, 1994). Although the household sector accounted for only 14% of Chinese commercial energy consumption, non-commercial biomass fuels including firewood, brushwood, crop residues and some animal dung, accounted for 300 million tons coal equivalent in 1990 (World Bank, 1996) and residential combustion has been characterized by poor total energy efficiencies relative to industrial consumption (which itself has been considerably below that of western industrialized nations). Thus emissions relative to delivered energy for household fuel consumption are high. The cost-effectiveness of control, therefore, may be greater than other sectors, arguing for priority among GHG control measures especially if benefits of reducing health-damaging pollution are also considered (Wang and Smith, 1999). The benefits of each new technology or a change in fuel use need to be clearly evaluated, however, as programs to implement a change in stove type require considerable effort and lead-time for dissemination and adoption in such a large population (Lu, 1993). In addition more accurate evaluation will become essential as national assessment of GHG emissions becomes more important, and actions to limit emissions of greenhouse gases, particularly those that have other positive economic, environmental and health benefits (World Bank, 1996), are desired in accordance with international consensus.

Assessment of the impact of changes in fuel or stove type on GHG or HDP emissions on a national scale has been problematic, however, for the following reasons:

1. Regional and national fuel data have often not been task or stove specific, nor have they been related to average nominal combustion efficiency (NCE) of the stoves. A series of assumptions on fuel use and stove efficiency are therefore implicit in GHG estimates.
2. The emissions of GHG from small-scale combustion of biomass are not well characterized (IPCC, 1997), and studies to measure HDP emissions frequently have not included GHG emissions. Few measurements have been made to develop comprehensive emission factors from household stoves in spite of the large number of household stoves and the high percentage of national fuel consumption in less devel-

oped countries (up to 80–90% in many of the poorest countries (Smith et al., 2000; WEA, 2000)). Often, to obtain an idea of the overall contribution of household stoves, measurements of one or a few gases using different methods in different regions by different investigators have been combined (IPCC, 1997; Streets and Walhoff, 1999; Bhattacharya et al., 2000).

3. Limited information is available on variability in emissions of pollutants from different stove/fuel combinations in typical use. Most measurements of emission factors have used only a few stoves in controlled or simulated environments, which are subsequently extrapolated to a national level.
4. Measurement of emissions factors typically requires complex burn cycle tests involving skilled personnel and the measurement of multiple chemical species. Such tests would be prohibitively expensive in many developing countries, and of such complexity to prohibit measurement of the large numbers of households required for application with national surveys. In addition, such a measurement program would involve complicated logistics imposing considerable burden on households and participants.

Even when comprehensive emissions estimates combined with standardization of tasks to reduce operator variability have been made (Zhang et al., 2000), there is considerable natural variation between each combustion event. In addition, considerable variation between average emissions estimates for the wide variety of combinations of stove and fuel types, would lead to a wide range of national emissions estimates, depending on the proportions of different stoves present (Zhang et al., 2000). Reduction of the uncertainties in these estimates would lead to considerable improvement in the confidence of national estimates of indoor air concentrations and exposures of the population in China to HDP. Not only would this enable more sophisticated investigation of the relationship between pollution levels and various forms of ill-health, it would also facilitate monitoring and evaluation of interventions such as improved fuels, stoves, ventilation and enable evaluation of policies for future energy use forecasts. Several mechanisms have the potential to reduce uncertainty including development emission factor estimates that are intrinsically linked to fundamental relationships between pollutants emitted during fuel combustion and combustion efficiencies of individual stoves (rather than averaged point estimates), and collection of national fuel-use survey information on household stove type and consumption of non-commercial fuels (rather than national consumption estimates).

Objectives of the current manuscript are to use the most comprehensive database to date of stove emissions from 28 fuel/stove combinations in common use in China (Zhang et al., 2000), to develop predictive models for HDP and GWC. Initial models are presented that rely on knowledge of stove and fuel use to predict GWC. Subsequently models that include measurement of CO/CO_2 ratio, that may be collected cheaply in association with national surveys on stove and fuel use as a proxy for combustion efficiency are presented.

2. Methods

Before describing the analyses performed on the emissions database, we describe briefly how the emission factors were derived. Full description of methods and quality controls is reported in Zhang et al. (2000). Briefly, 28 fuel/stove combinations were tested, but only 23 are included in the current analysis as one of the coal types tested in two stove types came from a specific mine in Shanxi province and was included in emissions tests because of its high emissions relative to other coal types. In addition the INDIA stove, which was a portable metal non-chimney stove made in India, was not typical of those in use in China and was also not included in regression models. The fuel types represent those commonly used in urban (gaseous fuels, coal and kerosene) and rural households (crop residues, wood, coal and kerosene) in China. All solid fuels were procured in one lot, sun-dried and stored in a large storage room prior to tests. 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 and infrared head designed to convert a portion of the heat released to the surrounding air into infrared radiation to heat the pot bottom. All other fuel/stove combinations were tested in a simulated village house at Tsinghua University (Beijing, China). Fuel stove combinations and fuel composition are shown in Table 1. Coal was burned in metal coal stoves, brick coal stoves and improved coal stoves. Biomass was burned in brick stoves, India stoves and improved stoves. Kerosene was burned in press stoves and wick stoves. 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., 1993). 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.

2.1. Sampling design

Combustion products were collected using a stainless steel sampling probe attached to a filter holder, a pump (SKC Inc. USA) and then a clean Tedlar bag (SKC Inc.

Table 1
Input variables, stoves and fuel types

Fuel variables		Stove variables		Emission factors (g/l MJ delivered)		
Code	Description	Code	Description	Flue	Code	Description
HBC	Honeycomb coal briquette	BRICK	Traditional brick stove	☑	TSPC	Carbon content of combustion particulates
CB	Coal biquette	IMPROVE	Improved brick	☑	CO_2C	Carbon of carbon dioxide
UNC	Unprocessed coal	METAL	Metal coal stove	☑ ×	$COCO_2RA$	Emissions CO/CO_2 ratio
WO1	Fuel wood	IMPROC	Improved metal coal stove	×		
WO2	Brush wood	PRESS	Kerosene pressure stove	×		
WR	Wheat residue	WICK	Kerosene wick stove	×		
MR	Maize residue	TRADITIO	Traditional gas stove	×		
KERO	Kerosene	IR	Gas stove with infrared head	×		
LPG	Liquid petroleum gas	FLUE	Presence or absence of flues			
NG	Natural gas					
CG	Coal gas					

USA). 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 80-l Tedlar bags throughout a whole burn cycle. In the current study the "water boiling test" (VITA, 1985), developed as a standard international method to compare stove efficiencies, was used with slight modification to define the burn cycle that was reasonably close to common cooking practice in residences. Burn cycles were from 35 to 60 min for all fuels except coal burning, which needs a longer cycle especially during the initial phases. Indoor background samples were collected at stove mouth height near the door using the same sampling configuration. Three successful complete burn cycles were measured for each fuel/stove combination. For each fuel type a parallel sampling of flue gas was conducted. Filters used to collect TSP were 37 mm quartz fiber filters (Pallflex Products Co., USA) and the mass of collected particles was determined gravimetrically. Pre- and post-sampling filters were equilibrated in a weighing room at constant humidity and temperature for at least 24 h prior to weighing on an electronic microbalance. One TSP filter for each fuel/stove combination was analyzed for carbon content using a thermal optical carbon analysis technique at Sunset Laboratory Oregon, USA.

2.2. Laboratory analyses

Air samples were removed from the 80-l Tedlar bag using a gas-tight syringe and analyzed for CO_2, CO, CH_4 and TNMHC in an analytical lab adjacent to the simulated kitchen. When immediate analysis was not possible a 4-l Tedlar bag was filled from the 80-l Tedlar bag using a SKC pump and Teflon tubing and analysis within three days of collection (no significant losses were observed during this period by Zhang et al. (2000)). A second aliquot of air sample was removed from the Tedlar bag using a flow rate of 0.2–0.4 $1\,\mathrm{min}^{-1}$ for SO_2 and NO_x and analyzed by standard methods for ambient SO_2 and NO_x (SEPA, 1992). SO_2 was collected using an impinger containing a solution of formaldehyde, potassium bipthalate, and Na_2-CDTA buffer solution. NO_x was collected using a CrO_3 tube and an impinger containing *p*-aminobenzenesulfonic acid, acetic acid, and NEDA (Salztman reagent). Prior to SO_2 analysis sulfuric acid followed by sodium hydroxide and *para*-rosaniline were added sequentially followed by sitting at 20 ± 2 °C for 15 min. NO_x and SO_2 were analysed colorimetrically (540 and 575 nm, respectively). CO, CH_4 and CO_2 were separated using a column packed with carbon spheres and analyzed by gas chromatograph with flame ionization detection–methanizer. TNMHC was measured by subtracting CH_4 from the total hydrocarbon. Two or more injections were made for each sample with RSD $< 10\%$. Calibration curves were measured daily and had $r^2 > 0.99$, and detection limits were 0.7–1.0 ppm.

2.3. Data analysis

Regression models were performed on a data set of 23 fuel/stove combinations. Duplicate measurements were averaged and three burn cycles for each stove/fuel combination entered regressions with the exception of unprocessed coal in a metal stove with no flue and brush-wood in an improved stove, where only one burn cycle was completed, and NO_x measurement in one burn cycle of fuel wood in a brick stove was not completed. A total of 64 samples, therefore, entered stepwise regressions. SPSS version 10.0 (SPSS Inc., USA) was used for all analyses. Stepwise regression models used an f probability of 0.5 for entry and 1.0 for removal. One burn cycle of wheat residue with exceptionally low combustion efficiency was omitted from models with fuel type and stove type as this single data point disproportionately affected these models, but not those incorporating CO/CO_2 or TSP/CO_2 ratios. Emissions factors for these fuel/stove combinations have been summarized and described in Zhang et al. (2000), including composition of the original fuel. The reader is directed to this manuscript for a more detailed description of carbon balance calculations and emission factor calculations, which will not be described here. Merits and disadvantages of changes in stove and fuel use for energy efficiency, human exposures to HDP emissions and GHG emissions within a common framework, called the "triple carbon balance" approach (Smith, 1994), which involves carefully measuring the fate of fuel carbon in different fuel/stoves to evaluate implications for energy, health, and global warming, has been presented in Smith et al. (2000). Before describing the results, it is useful, however, to make certain terms clear.

3. Definitions

3.1. Combustion efficiency

Combustion efficiency indicates how much energy in the fuel is converted to heat and is a linear combination of two internal efficiencies: NCE and heat transfer efficiency (HTE) (US EPA, 2000). Combustion efficiency and NCE are measured in the burn cycle tests, which involved the measurement of initial weight of the fuel, weight of the lighter, calorific value of the fuel, moisture content of the fuel, duration of test, weight of unburned fuel and gaseous emissions (US EPA, 2000). NCE indicates the percentage of the fuel carbon converted to carbon dioxide. The remaining carbon is released as PIC, which, if they had been burned, would have released additional heat in converting completely to carbon dioxide. PIC are defined as CO, CH_4, TNMHC (total non-methane hydrocarbons as g carbon) and TSP-C (total suspended particulates as g carbon where m.w. = 12 for TSP-C). Included in the PIC are nearly all the HDP and GHG of interest.

3.2. GHG and GWC

GHG emissions have become a focus not only for the scientific community but also for responsible governments all over the world. Energy consumption is the largest source of anthropogenic GHG emissions worldwide, and China accounts for 10% of global energy use (World Bank, 1996). More importantly, Chinese economic growth rates are substantially greater than the world average and China is likely to maintain rapid rates of economic growth well into the current century (World Bank, 1996). China will therefore play an increasing role in the balance of global emissions, particularly as Chinese energy supply relies heavily on fossil fuels.

Since there are several GHGs emitted from residential fuel/stove combinations in different absolute and relative amounts, it is necessary to use the following aggregate index for comparisons (Smith et al., 2000):

$$\mathrm{GWC} = \sum_i \mathrm{GHG}_i \times \mathrm{GWP}_i$$

where GHG_i is the quantity of the ith GHG in question, and GWP_i is the 20-year global warming potential per molecule of that particular GWP relative to CO_2. GWP were taken from IPCC (1990), although it is acknowledged that there are a number of uncertainties in their estimation. In the current analysis GWC are expressed in per unit energy delivered to the pot, as it gives the most relevant information about the impact of stove and fuel substitution on GHG emissions. Models to predict GWC of various combinations of GHG may be derived from database depending on the purpose of the models. For example although many gases from combustion have direct global warming effects or have an indirect global warming effects 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). In the current analysis we derive models to predict the combined GWC of CO_2, CO, CH_4, TNMHC (total non-methane hydrocarbon as g carbon) representing a more comprehensive list of gases that have significant global warming effects (henceforward referred to as 'GWC (CO_2, CO, CH_4, TNMHC)'). Nitrous oxide (N_2O) was not included in this analysis, but contributed an average of only 1% of the renewable GWC for fuel wood combustion per 1 MJ delivered energy in similar emissions tests of fuel stove combinations in India (Smith et al., 2000).

4. Results and discussion

Current methods to assess global warming contributions of residential stove emissions in China rely on national estimates of fuel consumption usually from government statistical publications. Regional and national fuel data in China, therefore, have not been household, task or stove specific. Subsequently, national fuel consumption data have been combined with IPCC coefficients to calculate national emission inventories according to a standard methodology in the IPCC country inventory handbook (1997). IPCC coefficients were averaged point estimates produced by combining scattered measurements of one or a few gases at a time made using different methods by different investigators in different regions, due to relatively few emission factor measurements for small-scale, semi-enclosed combustion. Streets and Walhoff (1999) and Bhattacharya et al. (2000) for example used this method to derive emission factors to estimate inventories of GHG emissions from biofuel combustion in Asia. Coefficients used for this calculation may overstate emissions from fuel consumption by as much as 10% for coal due to inefficient fuel combustion in small industrial and commercial boilers and residential stoves, which leaves unburned coal and char not accounted for in estimates of fuel consumption (World Bank, 1996).

The RAINS-ASIA model of emissions does not include data for non-commercial sector biofuels (fuelwood, crop residues and animal waste) and the CHINA-MAP program extrapolates per capita estimates of fuel consumption for several years from 1990 to 1995 to estimate emissions profiles for CO, NO_x and SO_2 using averaged point emissions factors for each fuel and pollutant (Streets and Walhoff, 2000). A similar approach is used in the EDGAR model (Olivier et al., 1996) with differing estimates of emissions factors for the domestic sector. Each of these models does not cover the range of pollutants measured in the burn cycle tests used as a basis for models in the current studies, nor are the domestic components intrinsically linked to stove efficiencies, as their objectives were different.

The emissions database on which the current models are based, was made in a simulated rural kitchen with a series of trial runs prior to the actual tests to reduce variability due to differences in operator behavior to achieve a method precision of <20% for major parameters. Subsequent emissions tests were performed by the same investigators, in the same location, using identical equipment, analyses, calibration and quality assurance, representing the most comprehensive database of residential fuel use in China available. Thus, emission factors reported from this study (Zhang et al., 2000) already represent a considerable increase in confidence over previous estimates. Models for the prediction of emissions of GHG and HDP that are intrinsically linked to CO_2 and PIC production are linked to the individual efficiencies of the stoves, and account for variability of different stoves found in rural environments as the models are intrinsically linked to the physics of the com-bustion process. Not only would this allow for variability of different stove designs affecting NCE, but also allow for variability in fuel combustion as a result of slight differences in fuel type and fire construction etc.

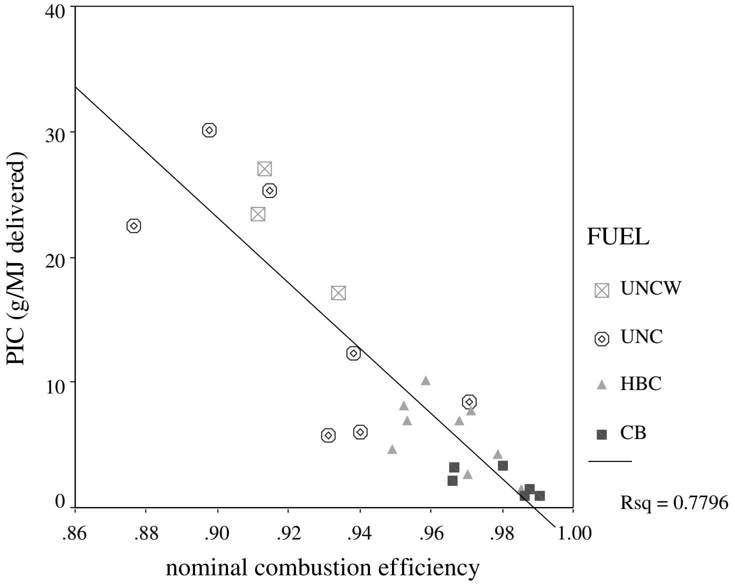
4.1. Efficiencies and products of incomplete combustion emissions

A stove's fuel usage can be reduced by improving the efficiency of combustion of the fuel (NCE) or by improving the transfer of heat (HTE) between combustion gases and the pot. Frequently improvements in the latter involve reducing the distance between the pot and the combustion source, and by reducing the space around the edges of the pot, while increasing the surface area of the pot over which the hot gases have to travel. Unfortunately, in many cases ventilation of the stove is decreased during this process, resulting in reduced NCEs. Fig. 1 shows the effect of reduction of NCEs on the production of PIC per 1 MJ delivered energy, for both biomass (Fig. 1a) and coal (Fig. 1b). It is clear that as NCEs are decreased there is an approximately linear increase in emission of PIC ($r^2 = 0.78$ and 0.79 respectively) across different stoves and fuel types. This general association, therefore, allows development of linear predictive models for the prediction of emissions of GHG and HDP intrinsically linked to CO_2 and PIC production, and ultimately allows the prediction of GWC from residential stove emissions. Such models are not appropriate, however, for prediction of emissions of HDP that are related to inherent properties of the fuel and not the combustion process such as SO_2 emissions, which are dependent on the sulfur content of the fuel.

Emissions of HDP (TSP and CO) are also related to the combustion process. Fig. 2 show the relationship between NCE and TSP-C (total suspended particulate matter as g carbon where m.w. = 12 for TSP-C) emissions per 1 MJ delivered energy. It is immediately apparent that reductions in NCE lead to exponentially increased TSP-C emissions. This general relationship has fundamental health and air quality implications for any change in stove type.

Prediction of NO_x is more complex as NO_x is formed from the nitrogen in the air rather than in the fuel, and emissions are dependent on peak temperatures during combustion. As a result increased NCEs were associated with increased NO_x levels for each fuel as increased combustion efficiencies are associated with higher overall temperatures, but burning of different fuels showed characteristically different NO_x emissions due to their ease of combustion. Thus, for biomass fuels the temperature of combustion was strongly influenced by fuel type, whereas burning of processed and unprocessed coals was strongly influenced by stove type.

a. Coal types



b. biomass

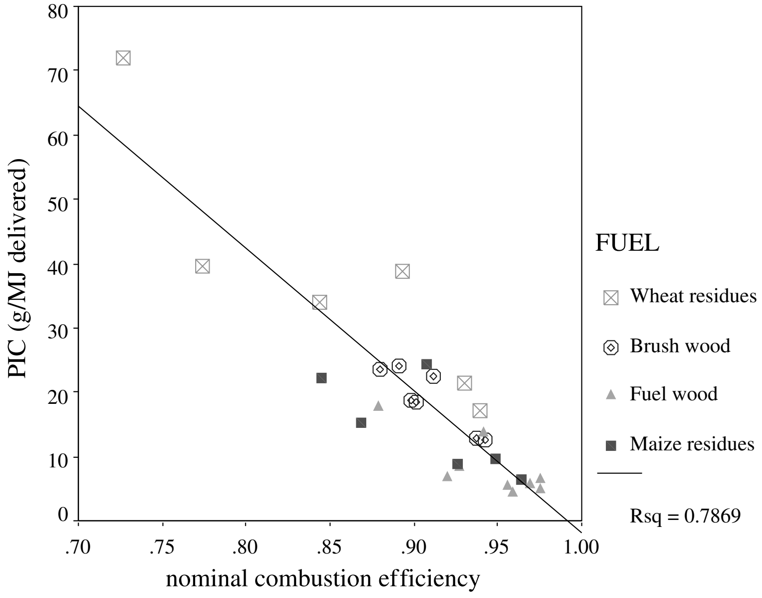


Fig. 1. Increase in PIC as a result of decreased NCE: (a) coal types, (b) biomass.

4.2. Predictive models

The utility of current models to predict HDP and GWC emissions from household stoves is determined by availability and access to information on independent variables. Thus, models using the most detailed information as predictor variables may account for the greatest percentage of the variance, but such models may have little application as such information is not routinely available or is expensive and time consuming to collect. [1] This is important if application is on

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[1] For example, methane is an important greenhouse gas but measurement of methane at these concentrations is difficult and expensive, especially in developing world settings.

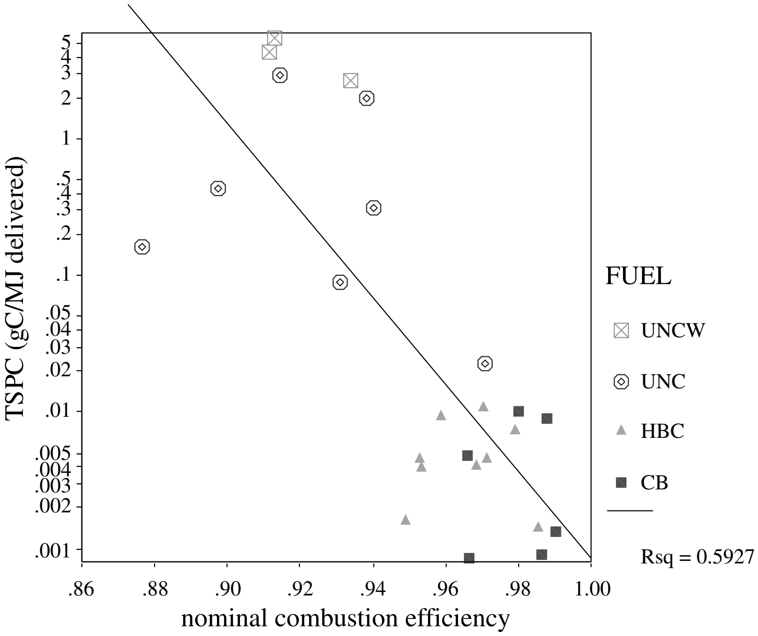

Fig. 2. Increase in TSP-C as a result of decreased NCE.

regional or national levels where large numbers of houses would be required, especially in developing world contexts where funds are usually very limited. For example, NCEs allow prediction of levels of PIC, but require measurement of multiple chemical species. CO/CO_2 ratios, however, are good proxies for NCEs, are easily measured and a more practical choice. Similarly measurement of TSP emission factors would be preferable, but would require all emissions from the stove to be captured while TSP/CO_2 ratios are more easily measured. The current manuscript, therefore, presents a series of models ordered by increasing complexity, which enables a range of available information to be used. In addition, the current manuscript has focused on those parameters that can be easily monitored in the field and thus allows assessment of the relative importance of each field parameter in future investigations. Table 1 shows the range of independent input variables and their codes used in the current analysis.

4.3. Prediction of global warming commitment

Table 2 presents a summary of stepwise regression models to predict the GWC (CO_2, CO, CH_4, NO_x, TNMHC) per 1 MJ delivered energy of Chinese residential cooking stoves. If survey information on fuel type is available, stepwise regression models accounted for 66% of the variance in GWC across all stove and fuel types, as a function of their NCE. Predictor variables were unprocessed coal, followed sequentially by honeycomb coal briquettes, wheat residues, coal briquettes, brushwood and maize residues. Subsequently, stepwise regression models accounted for 73% of the variance if stove type was known, and predictors were unprocessed coal, honeycomb coal briquettes, wheat residues, improved coal stoves, metal coal stoves, brush wood, maize residues and coal briquettes. Input information for the above models is currently being collected as components of a national survey of fuel use, stove use and health, as part of re-assessment of the Chinese improved stove program. Survey tools, however, do not provide information on levels of HDP, which are essential for making informed assessments of policies to change stoves or fuel types on a regional or national basis. Such integrated assessments would involve simultaneous evaluation of environmental impacts, energy efficiency, human exposures to HDP emissions and global warming by tracing the fate of fuel carbon in the ‘triple carbon balance’ framework (Smith, 1994). If measurements of TSP or CO as the major HDPs were available, such information could be incorporated into models to predict GWC allowing prediction of 79% and 78% of the variance respectively. Although the increase in predictive ability within this dataset is small, greater variability would be expected from the millions of stoves in use in China due to variation in construction, use, housing ventilation, indoor vs outdoor temperature differences discussed below. These factors would result in alteration of the efficiency of the stove, of which the CO/CO_2 ratio is a good surrogate. Thus increased predictive ability would be expected for models including CO/CO_2 ratio relative to models that rely on the survey instrument alone.

Table 2
Prediction of GWC

Input variables	Dependent variable	Adjusted r^2	Predictor variables[a]
Fuel type	GWC (CO_2, CO, CH_4, NO_x, TNMHC)	0.66	(Constant), UNC, HBC, WR, CB, WO2, MR
Fuel type, stove type	GWC (CO_2, CO, CH_4, NO_x, TNMHC)	0.73	(Constant), UNC, HBC, WR, IMPROC, METAL, WO_2, MR, CB
Fuel type, stove type, TSPC/CO_2C ratio	GWC (CO_2, CO, CH_4, NO_x, TNMHC)	0.79	(Constant), UNC, TSPC/CO_2C ratio, HBC, IMPROC, CB, BRICK, WO1, METAL
Fuel type, stove type, COC/CO_2C ratio	GWC (CO_2, CO, CH_4, NO_x, TNMHC)	0.78	(Constant), COC/CO_2C ratio, METAL, UNC, HBC, IMPROVED, IMPROC

[a] UNC = unprocessed coal, HBC = honey comb briquette, WR = wheat residues, CB = coal briquette, WO2 = brush wood, MR = maize residue, WO1 = fuel wood, COC = CO as g carbon, CO_2C = CO_2 as g carbon, TSPC = total suspended particulate as g carbon, Stoves: IMPROC = improved coal, METAL = metal coal stove, BRICK = traditional brick stove (biomass), IMPROVED = improved brick stove (biomass).

In reality, however, the driving factor for these measurements would be information on emission of HDP. The importance of this factor is demonstrated by the standardized betas, included to make regression coefficients of different independent variables comparable, and *t* statistics, which provide a measure of the relative importance, or predictive ability of each independent variable in the model (Table 3). The relative importance of the CO/CO_2 ratio in the models is clearly demonstrated with a *t* statistic of 8.4 compared to a maximum of 5.3 for other independent variables in the model. In addition the relative strength of the regression coefficients are demonstrated by a beta of 0.7 compared to 0.2–0.4 for other predictors in the model. Thus, when the CO/CO_2 ratio is included as an independent variable it is the best single indicator of combustion efficiency, which is the stove performance parameter of most relevance to health and GHG impacts.

Fig. 3 shows GWC (CO_2, CO, CH_4, NO_x, TNMHC) from measurement of the different fuel stove combinations and the GWC (CO_2, CO, CH_4, NO_x, TNMHC) calculated using stepwise regression models with (1) fuel

Table 3
Stepwise regression coefficients and collinearity statistics for regression models of GWC

Dependent variable	Model input	Unstandardizied coefficients			Standardized beta	*t* statistic	Collinearity statistics	
		Predictors	*B*	Standard error			Tolerance	Condition index
GWC (CO_2, CO, CH_4, NO_x, TNMHC)	Fuel type	(Constant)	42.1	10.6		4.0		1.0
		UNC	226.7	23.0	0.8	9.9	0.89	1.3
		HBC	142.3	20.9	0.5	6.8	0.87	1.3
		WR	124.0	26.4	0.4	4.7	0.91	1.3
		CB	71.7	24.5	0.2	2.9	0.90	1.3
		WO2	78.0	29.0	0.2	2.7	0.93	1.3
		MR	55.8	24.5	0.2	2.3	0.90	2.8
GWC (CO_2, CO, CH_4, NO_x, TNMHC)	Fuel, stove	(Constant)	42.1	9.3		4.5		1.0
		UNC	209.5	22.3	0.7	9.4	0.73	1.2
		HBC	165.7	24.1	0.6	6.9	0.50	1.4
		WR	124.0	23.2	0.4	5.3	0.91	1.5
		IMPROC	−110.4	35.3	−0.3	−3.1	0.63	1.5
		METAL	40.1	21.9	0.2	1.8	0.61	1.5
		WO2	78.0	25.5	0.2	3.1	0.93	2.0
		MR	55.8	21.5	0.2	2.6	0.90	2.6
		CB	51.6	24.1	0.2	2.1	0.71	3.5
GWC (CO_2, CO, CH_4, NO_x, TNMHC)	Fuel, stove CO/CO_2 ratio	(Constant)	44.83	8.2		5.5		1.0
		COC/CO_2C	978.8	117.0	0.7	8.4	0.49	1.3
		METAL	66.33	19.1	0.2	3.5	0.77	1.4
		UNC	114.8	21.7	0.4	5.3	0.74	1.9
		HBC	111.5	22.2	0.4	5.0	0.57	2.5
		IMPROVED	−66.9	23.3	−0.2	−2.9	0.48	2.9
		IMPROC	−92.66	34.4	−0.2	−2.7	0.64	3.7

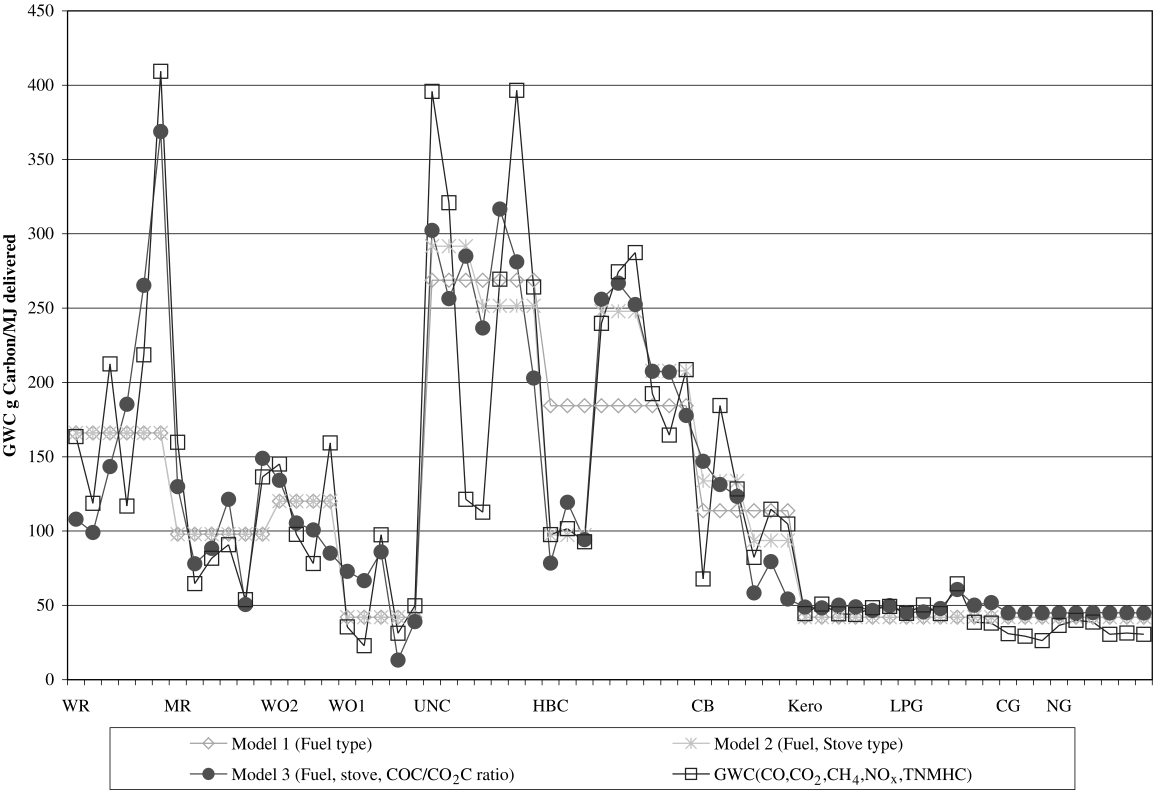

Fig. 3. Comparison of Models 1–3 with GWC from emissions measurements.

type, (2) fuel type and stove type, and (3) fuel type, stove type and CO/CO$_2$ ratio as independent variables. The large variability in measurements of coal and biomass within each stove type are not fully accounted for by the CO/CO$_2$ ratio as a proxy for efficiency, and the fit of the model is clearly hampered by high variability in the combustion of unprocessed coal. Otherwise this model appears to be better fit to the data as a result of inclusion of the CO/CO$_2$ ratio as a proxy for combustion efficiency. Clearly however an expanded database would greatly aid in the estimation of coefficients for this model, and would probably result in greater predictive ability with better estimates of emissions factors for each fuel stove type.

Models 1–3 assume renewable harvesting. Much of the harvesting of fuel wood and brush wood is currently non-renewable, however, although increasing renewable harvesting has been a priority for China in rural development. Increasing the firewood supply was considered a strategic necessity, including firewood planting of six million out of an available 30 million hectares for afforestation under the Sixth Five Year Plan (Lu, 1993). The GWC of non-renewable harvested biomass burning is considerably higher than those in the current models as CO$_2$ emissions are not taken up by the next growing season and have a net warming effect. The extent of renewable and non-renewable harvesting of fuel wood and brush wood would be a highly desirable addition to models to predict GWC but are currently very uncertain due to the non-commercial nature of much of the fuel.

Another concern over using current models to predict GWC (CO$_2$, CO, CH$_4$, NO$_x$, TNMHC) for large areas or on a national basis is that the distribution of actual fuel/stove combinations in the field may be quite different from those in the emissions database, and that high correlations for models in the emissions database may not reflect the predictive ability for current distributions of fuel/stove combinations in China. Coal and biomass use are well represented in current models and account for the majority of fuel use in rural areas. Current estimates of Chinese rural energy consumption in 1998 were 33% biomass and 44% coal (CERS and CAREI, 1999) and the ratio of biomass energy consumption to commercial energy use for rural China in 1996 was 0.15 (Sinton and Friedly, 2000). While different proportions of fuel/stove types and potential differences in predictive ability should always be considered very carefully when applying such models, the standard errors for the B coefficients in the model (Table 3), which measure the spread of the residuals about the fitted line and are expressed in units of the dependent variable, were very similar for different fuel types, suggesting that different proportions of each fuel type would not unduly affect the fit of the models.

There are also a number of other factors that may affect computation of GWC including wind speed, dampening patterns, and indoor/outdoor temperature differences. In addition many cooking stoves are also heating stoves in the winter, and emissions factors per MJ delivered for cooking will be different if the stove is preheated (from continuously burning) due to heating requirements. For coal stoves especially, coal emissions per cooking event will be smaller with a preheated than with a cold stove. Indeed, current surveys try to assess this parameter both in the questionnaire and the time activity portion, including whether different fuels are used, so that the heating component may be treated separately. Variability arising from these factors is not included in the dataset but would result in alteration of the efficiency of the stove, of which the CO/CO_2 ratio is a good surrogate. Thus as the models are intrinsically linked to the stove efficiencies these variables are indirectly accounted for in the dataset. Clearly, however, these would only provide a point estimate when the survey and CO/CO_2 measurements are implemented and do not provide information on variability over time. Investigation of the effects of such variables on emission factors would provide an important dimension in estimates of GWC (CO_2, CO, CH_4, NO_x, TNMHC).

Although the current database is currently the most comprehensive database of emissions factors from residential fuel combustion in China, it does not, of course, cover all fuel/stove combinations in use by the 1.3 billion people in China. It represents, however, two dozen of the most common. What we present in the paper is an example of how such data can be used. It shows that a carefully designed set of measurements can inform a larger problem, although of course not completely delineate it. The fact that correlations work reasonably well for this set provides confidence, but not assurance, that a larger set would similarly do so. Further accuracy and extension to other fuel/stove combinations would require further measurements as would dealing with the many other variations involved, such as local cooking practices, variations in construction techniques, differences in fuel quality, etc. Although the models presented here illustrate an approach that may have considerable application in this field, development of a more detailed and extensive database would be recommended prior to making decisions that may have such wide reaching impact. Development of an expanded database not only would allow us greater confidence in coefficients and predictions, and allow more comprehensive validation, but also would enable development of models according to fuel type and models that incorporate the renewable status of biomass fuels.

4.4. Prediction of health-damaging pollutants

In addition to indoor contamination (Sinton et al., 1996), household fuels contribute to neighborhood (Smith et al., 1992), urban, regional (Streets and Walhoff, 1999), and global (Lelieveld et al., 2000) health-damaging pollution. Indoors, however, such emissions have large exposure effectiveness factors, i.e., produce a large exposure/dose per unit emissions (Smith, 1993). Estimates range from 200 000 (World Bank, 1997) to a million (Florig, 1997) premature deaths annually from exposures to household fuel smoke in China. Other health endpoints e.g. reduced mobility and productivity, may result in a loss of 7.4 million work years due to health damages related to air pollution (World Bank, 1997). Prediction of concentrations of health-damaging pollution and more importantly measures to reduce these levels remains a high priority in order to reduce large human and economic damage from such exposures.

Integrated assessment of policies to change stove or fuel type requires that implications for environmental impacts, energy efficiency, global warming and human exposures to HDP emissions can be evaluated. Frequently, this involves measurement of TSP or CO as the major HDPs. Clearly, however, the complexity of making multiple measurements in conjunction with a national survey would be both expensive and time consuming. Thus, models to predict HDP using simple survey information, and with measurement of either CO/CO_2 or TSP/CO_2 to predict emission factors for the other HDP have been derived below. Table 4 presents a summary of stepwise regression models to predict NO_x, TSP and natural log transformed TSP levels per 1 MJ delivered energy. Stepwise regression models predicted 65% of the variance in emissions TSPC per 1 MJ delivered if survey information on fuel and stove type was available and 74% if the CO/CO_2 ratio was measured. Similarly stepwise regression models predicted 76% of the variance in COC emissions per MJ delivered with survey information on stove and fuel type and 85% if the $TSPC/CO_2$ ratio was measured.

If natural log transformed TSP levels were used as the dependent variable, stepwise regression models accounted for 90% of the variance in natural log transformed TSP concentrations across all stove and fuel types if survey information on fuel type was available. Interestingly, this model accounted for such a high percentage of the variance that little added explanation of variance (<1%) was added by including stove type or measurement of the CO/CO_2 ratio as independent variables, although this may well increase with a larger and more comprehensive database.

Table 4
Prediction of HDP

Input variables	Dependent variable	Adjusted R^2	Predictor variables[a]
Fuel type	TSPC	0.581	(Constant), WR, WO2, UNC, WO1
Fuel type, stove type	TSPC	0.651	(Constant), WR, IMPROVED, UNC, WO2, WO1
Fuel type, stove type, COC/CO_2C ratio	TSPC	0.742	(Constant), COC/CO_2C ratio, WR, MR
Fuel type	COC	0.708	(Constant), WR, UNC, WO2, MR, HBC, WO1
Fuel type, stove type	COC	0.762	(Constant), WR, UNC, IMPROVED, BRICK, WO1, HBC
Fuel type, stove type $TSPC/CO_2C$ ratio	COC	0.853	(Constant), $TSPC/CO_2C$ ratio, BRICK, WO1, IMPROVED, METAL, MR, CB, WO2
Fuel type	ln TSPC	0.894	(Constant), LPG, WR, WO1, WO2, UNC, MR, HBC
Fuel type, stove type	ln TSPC	0.900	(Constant), METAL, UNC, LPG, WR, WO2, WO1, MR, HBC
Fuel type, stove type, COC/CO_2C ratio	ln TSPC	0.910	(Constant), COC/CO_2C ratio, BRICK, IMPROVED, METAL, CB, LPG, HBC, IMPROC, UNC, MR
Fuel type, stove type	NO_x	0.693	(Constant), BRICK, WO2

[a] WR = wheat residues, UNC = unprocessed coal, MR = maize residue, WO1 = fuel wood, WO2 = brush wood, LPG = liquid petroleum gas, HBC = honey comb briquette, CB = coal briquette, Stoves: IMPROVED = improved brick, BRICK = traditional brick, METAL = metal coal stove, IMPROC = improved coal stove.

Stepwise regression models accounted for 69% of the variance of NO_x per 1 MJ delivered energy. Lower prediction for NO_x was expected, as emissions are dependent on peak temperatures during combustion, rather than efficiency of the combustion process. Consequently, considerable caution should be used in conjunction with these estimates, as operator variability can lead to dramatic differences in emissions estimates.

4.5. Coefficients and stability

The stepwise regression procedure includes post-hoc assessment of collinearity with each predictor variable entered in the procedure, and tests variables already in the model for removal at each step. This method is used especially when there are correlations among the independent variables (SPSS 10.0 Applications guide, SPSS, Chicago, IL, USA). Correlation between predictor variables was assessed using a Pearson two-tailed correlation matrix. Correlation between predictor variables that entered stepwise regression models and variables that did not enter the models (and could be prevented from entering the models as a result) were moderate between wheat residues and COC/CO_2C ratio (0.61) and $TSPC/CO_2C$ ratio (0.62). This may well explain why wheat residues do not appear as a predictor variable in models that include these ratios as input variable, but are a strong predictor for models that do not. Correlations between other variables did not present problems with current models.

Tables 3 and 5 present summaries of unstandardized coefficients, standard error of the coefficients, tolerance statistics and condition indexes for stepwise regression models based on prior knowledge of fuel type, and knowledge of fuel type, stove type and CO/CO_2 ratio. Tolerance statistics are defined as:

$$\text{Tolerance} = 1 - R_i^2$$

where R_i^2 is the squared multiple correlation of that variable with the other independent variables in the model (SPSS 10.0 Applications guide, SPSS, Chicago, IL, USA), and the dependent variable is ignored. Thus, values of tolerance range from 0 to 1, and small values indicate that the variable is almost a linear combination of other independent variables. The tolerance statistic is therefore indicative of the stability of the model. The condition indexes are the square roots of the largest eigenvalue to each successive eigenvalue. Condition indexes greater than 15 indicate possible problems with collinearity and greater than 30 indicate a serious problem with collinearity of the independent variables (SPSS 10.0 Applications guide, SPSS, Chicago, IL, USA). Condition indexes for models to predict GWC (CO_2, CO, CH_4, NO_x, TNMHC) did not exceed 3.7 and tolerance statistics had a minimum of 0.477, indicating considerable stability and that collinearity was not a problem within the models. Condition indeces for models to predict TSPC did not exceed 3.1 and tolerance statistics had a minimum of 0.56. Condition indexes for models to predict ln TSPC that included fuel type as independent variables did not exceed 3.2 and tolerance statistics had a minimum of 0.815. For the more complex models to predict ln TSPC including stove type and COC/CO_2C ratio as independent variables (which did not significantly increase the predictive ability) the models were less

Table 5
Stepwise regression coefficients and collinearity statistics of regression models for HDP

Dependent variable	Model input	Unstandardized coefficients			Standardized beta	*t* statistic	Collinearity statistics	
		Predictors	*B*	Standard error			Tolerance	Condition index
TSPC	Fuel, stove CO/CO_2 ratio	(Constant)	−0.1	0.1		−1.3		1.0
		COC/CO_2C	13.4	1.5	0.7	8.7	0.56	1.5
		WR	0.9	0.4	0.2	2.5	0.58	1.9
		MR	−0.7	0.3	−0.2	−2.2	0.89	3.1
Ln TSPC	Fuel type	(Constant)	−6.6	0.2		−27.8		1.0
		LPG	−1.9	0.5	−0.2	−3.4	0.88	1.3
		WR	7.2	0.5	0.6	13.4	0.88	1.3
		WO1	6.3	0.5	0.6	12.5	0.86	1.3
		WO2	6.7	0.6	0.5	11.3	0.90	1.3
		UNC	5.4	0.5	0.5	11.4	0.84	1.3
		MR	5.6	0.5	0.5	11.1	0.86	1.3
		HBC	1.1	0.4	0.1	2.6	0.82	3.1

stable with condition indexes up to 4.0 and several low tolerance statistics with a minimum of 0.44.

The initial stepwise regression for Model 1, with fuel types as independent variables, was derived from three burn cycles of stove/fuel combinations (with the exception of unprocessed coal in a metal stove with no flue ($n = 1$), brush wood in an improved stove ($n = 1$), fuel wood in a brick stove ($n = 2$), and wheat residues in an improved stove ($n = 2$)). When the third burn cycle of stove fuel combinations was removed from the analysis, and stepwise regression performed on the remaining two burn cycles, the model had similar adjusted r^2 values to the model with three burn cycles ($r^2 = 0.656$ for three burn cycles and 0.659 for two burn cycles, respectively) but the order of brush wood (WO2) and coal briquettes (CB) was reversed and maize residues did not pass criteria for entry due to the sample reduction. Other predictors were the same for both models and change in coefficients was <18% for all predictors and 27% for the constant, indicating considerable stability of the coefficients for this model. When the third burn cycle was removed from stepwise regression models with both fuel types and stove type as independent variables, metal coal stoves and maize residues did not enter the model due to the sample reduction. Other predictors were similar for both models. Coefficients that appeared in both models differed by <18% for all predictors and 27% for the constant. Adjusted r^2 values for these models were very similar and were 0.734 and for three burn cycles and 0.714 for two burn cycles, respectively. Similar analysis for more complex models was hampered by the limited nature of the data set once one-third of the data points were eliminated.

4.6. Application in greenhouse gas reductions

The residential sector has traditionally been overlooked in evaluating least-cost options and no-regret policies options for reducing GHG emissions mainly because residential stoves are individually small and are not perceived as emitting large quantities of greenhouse gases. While this is true, it does not take into account the huge numbers of these devices in China and the developing world, the number of people that rely on these devices as a primary energy source and the poor total energy efficiencies of these devices. Thus emissions relative to delivered energy are high, while the cost of improvements in stove design are relatively low compared to industrial measures. Although understanding the processes of combustion that occur within them is complex, household stoves are generally simple devices and are not perceived as an area where technological invention to reduce GHG emission can be applied. Indeed designs for many improved stoves have improved fuel efficiency as their sole criteria, and have not assessed emissions of greenhouse gases or HDP. Consequently a counter-intuitive result has been achieved with some improved biomass stoves, which have increased fuel efficiency but actually result in increased emissions of GHG and HDP per MJ energy delivered (Smith et al., 2000). GHG formed as PIC have radiative forcings considerably higher than that of CO_2 (Smith et al., 2000). In addition several GHG formed as PIC are also HDP. Thus from both health and global warming perspective it would be beneficial if a greater proportion of emissions were CO_2 relative to PIC. As seen in Figs. 1–3 this would entail increasing NCEs.

One of the most contentious issues before the international community is 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. While such debates should be based upon the best available scientific information, these decisions remain the domain of policy makers and those that represent the national interest. If small-scale devices such as stoves are ever to be part of international GHG negotiations, such as in the clean development mechanism, validation methods will need to be developed to show that, e.g., a new widely disseminated stove has actually achieved the GHG reductions that it was designed to do. Since it will never be possible to measure all emissions from all stoves for verification, some sort of sampling scheme of a few gases will be needed. This paper is a start in that direction. The predictive models presented here combined with survey information form a mechanism for computing greenhouse credits in the residential sector, and monitoring compliance with a control regime. Not only would this allow assessment of stoves that have already been disseminated, and policies for fuel switching, potential merits of improved stoves and fuel switching can easily be compared prior to implementation for those communities involved. Incentives and financial interest in greenhouse credit would also have a secondary benefit of concurrent reduction of HDP, making them truly no regret scenarios.

Clearly such emissions models, in association with information on stove and fuel use, have considerable potential as a tool for assessing impacts of different stove and fuel use policies for both health and global warming endpoints. Reduction in health effects alone would result in considerable economic benefit in terms of reduced health cost and lost work years, in addition to addressing a morally compelling social problem. With international agreement on emissions trading frameworks, models to assess greenhouse reductions could also result in considerable economic benefit on a national level. Expansion of the database from which these initial models have been derived to improve confidence in coefficients would be highly desirable, therefore, considering potential economic impacts. An expanded database based on comprehensive measurement of the fate of fuel carbon during combustion from representative household stoves would allow separate models for assessment of non-renewable and renewable fuels. In addition it would allow development of models for biomass combustion that would incorporate the extent of non-renewable and renewable harvesting as an integral component.

5. Conclusions

- Decrease in NCE was associated with exponentially increased TSP-C emissions, which has fundamental health and air quality implications for any change in stove type.
- If survey information on fuel type is available, stepwise regression models accounted for 66% of the variance in GWC per 1 MJ delivered energy across stove and fuel types. Subsequently if stove type was known, stepwise regression models accounted for 73% of the variance.
- Stepwise regression models predicted 65% of the variance in emissions of total suspended particulate as grams of carbon (TSPC) per 1 MJ delivered if survey information on fuel and stove type was available and 74% if the CO/CO_2 ratio was measured. Similarly stepwise regression models predicted 76% of the variance in COC emissions per MJ delivered with survey information on stove and fuel type and 85% if the $TSPC/CO_2$ ratio was measured.
- Stepwise regression models predicted 90% of the variance in natural log transformed TSP concentrations per 1 MJ delivered energy across stove and fuel types if survey information on fuel type was available.
- Ultimately, with international agreements on emissions trading frameworks, similar models based on comprehensive measurement of the fate of fuel carbon during combustion from representative household stoves would provide a mechanism for computing greenhouse credits in the residential sector, and financial interest in greenhouse credit may provide additional impetus for concurrent reduction of HDP.

Acknowledgements

We would like to thank Dr H. Keith Florig, Department of Engineering and Public Policy, Carnegie Mellon University for his helpful comments during review of this manuscript. This work was supported by the Sustainable Energy Program of the Shell Foundation. A US EPA cooperative agreement with the East–West Center, Honolulu, supported the gathering of the original data. This paper has not gone through official EPA review procedures and official endorsement is not inferred.

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