FROM CLIMATE TO COOKSTOVES:
AN ANALYSIS OF BLACK CARBON REDUCTION POLICIES

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Table of Contents

List of Tables

List of Figures

List of Acronyms and Abbreviations

BC	black carbon
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CNISP	Chinese National Improved Stove Program
EJ	10^{18} joules
GHG	greenhouse gas
Gg	10^9 grams
IPCC	Intergovernmental Panel on Climate Change
KCJ	Kenyan ceramic Jiko
Mt	10^6 tons
N_2O	nitrous oxide
NO_x	nitrogen oxide
O_3	ozone
OC	organic carbon
PJ	10^{15} joules
PM	particulate matter
SO_2	sulfur dioxide
Tg	10^{12} grams
TJ	10^{12} joules
TNMHC	total non-methane hydrocarbon
TSP	total suspended particulates
USD	United States Dollars
WB	World Bank
WHO	World Health Organization

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ABSTRACT

Early climate change studies have focused primarily on greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxides (N_2O). However, various components of particulate matter also contribute to or offset the effects of global warming. In particular, black carbon particulate matter (BC) has been identified as a significant contributor to global warming. BC emissions also pose a significant health risk, particularly in developing countries where coal and biomass are burned residentially over open fires or in inefficient cookstoves. Measures to reduce BC could have important environmental and public health benefits by reducing climate forcing emissions as well as health-related pollutants. Policymakers will need to both encourage dialogue and implement strategies in the future to reduce black carbon, particularly in developing countries. This study evaluates the policy implications of current black carbon research from the perspective of climate and health and identifies the highest priority needs for additional research to perform a credible cost-benefit analysis of black carbon reduction policies. More scientific studies are necessary to better evaluate the climate and health effects of black carbon as well as uncertainties in global inventories of emissions, so that the most cost-effective mitigation measures can be identified and implemented.

1: INTRODUCTION

Let me report then all the god declared.
King Phoebus bids us straitly extirpate
A fell pollution that infests the land,
And no more harbor an inveterate sore
-Creon, Sophocles' Oedipus Rex

This study initially attempted to identify major sources of black carbon (BC) emissions and perform a cost benefit analysis of reducing these sources. However, as the project evolved it became clear that uncertainties associated with BC emissions and their effect on climate change and public health would detract from the credibility of such an analysis. Therefore, this paper identifies scientific uncertainties and areas of research necessary to address the BC problem from a policy perspective to fully analyze specific black carbon reduction policies in terms of cost of such policies and benefits on climate change and public health.

1.1 Radiative Forcing and Climate Change

The term "radiative forcing" denotes an externally imposed perturbation in the radiative energy budget of the earth's climate system. Such perturbations are caused by changes in the concentrations of anthropogenic agents such as carbon dioxide (CO_2) and aerosols, or changes in the solar irradiance incident upon the planet [IPCC 2001]. Radiative forcing is the key driver of the Earth's climate system, governing the temperature and circulation of the atmosphere and ocean, and critically affecting the habitability of the planet. Computer models have been developed to assess how natural and anthropogenic emissions of greenhouse gases and aerosols affect radiative forcing and climate. These climate models, or general circulation models (GCMs), are developed and run in a number of research centers internationally, and offer the best method to estimate future climate change.

Perturbations in the energy budget of the Earth's climate system can result in large-scale climate changes. "Global warming" has become shorthand for a wide range of climate change indicators, but other consequences include cooling in some locations and perturbations in weather patterns such as increased droughts and flooding. These climate changes are of concern because global warming can lead to a rise in sea level and ecosystem disruption, while droughts and floods can result in the immediate loss of crops and damages, causing economic losses and famine.

The Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report [2001] and Hansen et al. [2000] produce different estimations of the contribution of different radiative agents including greenhouse gases (GHGs), aerosols, land-use change, and solar irradiance on global annually averaged estimated forcing (Figure 1). In both estimates, CO_2 is the largest forcing (~1.4 W/m^2), but other non-CO_2 forcings are significant, such as sulfates, tropospheric ozone, and BC. The IPCC estimates that BC has a global mean radiative forcing of 0.2W/m^2 [IPCC 2001], but Hansen et al. [2002] estimate that that BC causes a greater forcing of $0.8 \pm .4$ W/m^2. Similarly, Hansen et al. [2000] estimate that the sum of non-CO_2 forcings such as BC, methane (CH_4), chlorofluoro carbons (CFCs), ozone (O_3), and nitrous oxide (N_2O) is roughly equal to the total CO_2 forcing. The IPCC data, in contrast, illustrates that the forcing effects of non-CO_2 GHGs are negligible compared to that of CO_2.

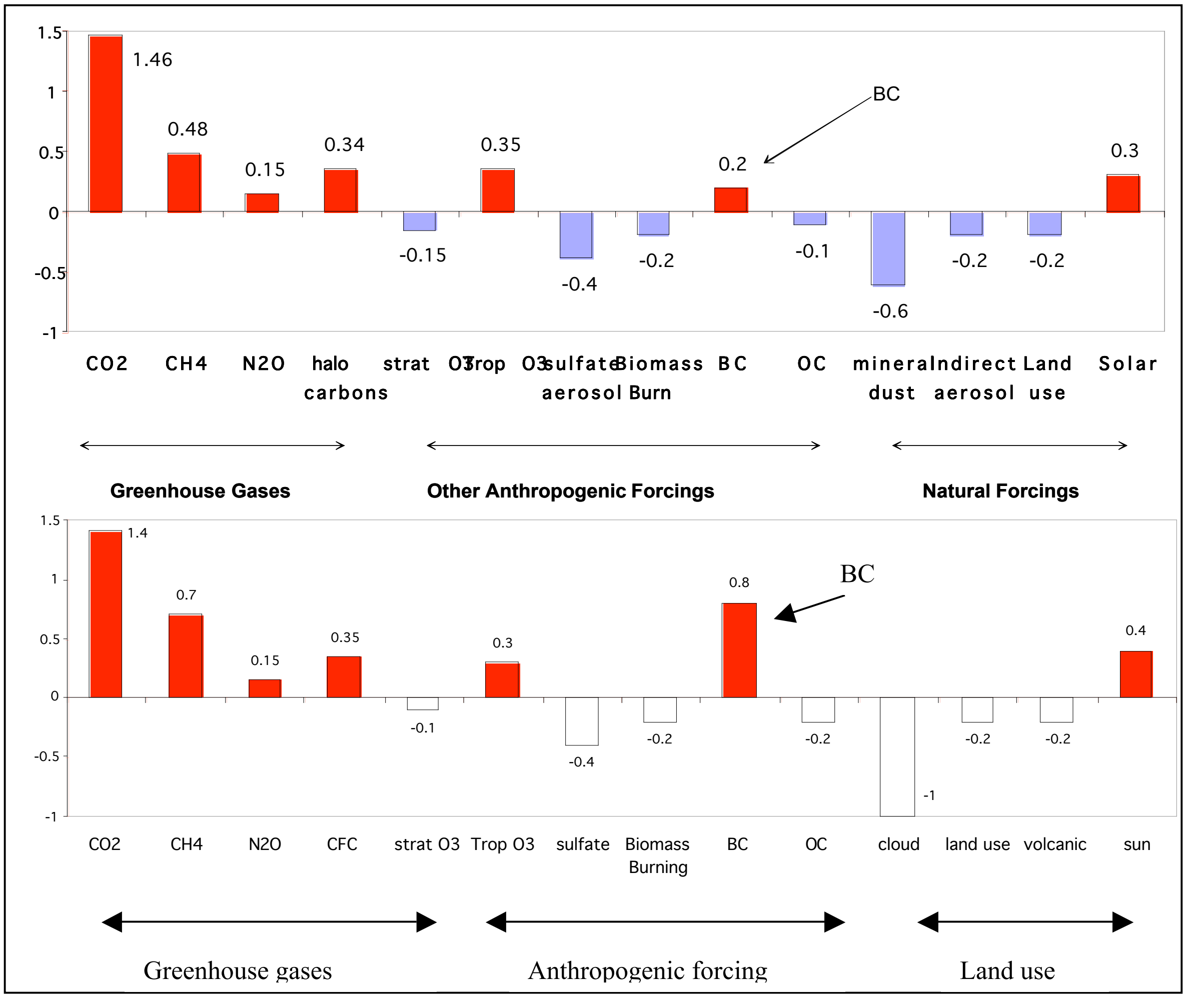

Figure 1. Global annual mean radiative forcing. (a) IPCC estimated global and annual mean radiative forcing 1750-present. (b) Hansen et al.'s estimated climate forcing 1850-2000. Forcing is measured in W/m^2. Note that Hansen et al.'s estimates contain greater forcing of BC. [IPCC 2001, Hansen et al. 2000]

Early climate projections of future emission trends focus on business as usual (BAU) models, where CO_2 emissions will increase based on current rates of growth. This would lead to a doubling of CO_2 by the year 2060 [IPCC 2000]. More recent climate projections consider a range of driving forces such as demographic, social, economic, and technological developments. The IPCC *Special Report on Emissions Scenarios* (SRES) [2000] formulates a set of future emissions scenarios. The scenarios consider a wide range of driving forces of future emissions, from high development and fossil fuel dependency to low development and fossil fuel dependency. SRES accounts for future trends in CO_2, CH_4, N_2O, carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), sulfur dioxide (SO_2) CFCs, hydrofluorocarbons, perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6). However, SRES does not consider effects of particulates containing BC on the future climate [IPCC 2000].

Current climate change strategies focus primarily on reducing CO_2. The Kyoto Protocol is an international agreement for industrialized nations to reduce their collective emissions of greenhouse gases by 5.2% of 1990 levels by the year 2012. As of 2003, the Protocol is not legally binding due to insufficient ratification. The Kyoto Protocol would require countries to make reductions in their GHGs including CO_2, CH_4, N_2O, PFCs and SF_6 [UNFCC 2002]. The US emits roughly 20% of global GHGs [IPCC 2001], and the current administration has deemed compliance with the Protocol too costly and likely resulting in layoffs of workers and price increases for consumers [White House 2001]. As Bush spokesman Ari Fleischer has stated, the protocol “is not in the United States' economic best interest” [CNN 2001].

Some climate simulations have concluded that even if fully implemented, the Kyoto Protocol would have little effect in the mitigation of climate change in the 21st century [Malakoff 1997]. The cuts by industrialized countries would be offset by increases in emissions from developing nations, such as China and India, which would not be bound by the Protocol. China, second only to the US in GHG emissions, is expected to overtake the US as the world's leading emitter of carbon dioxide within decades, since it burns massive amounts of coal [Malakoff 2002]. Yet, China was entirely exempted from the requirements of the Kyoto Protocol.

The Kyoto Protocol is estimated to only delay the warming trend by a few decades, and is not a sufficient solution to the problem of climate change. One climate researcher posits that "it might take another 30 Kyotos over the next century" to stabilize global warming [Mahlman, qtd. by Malakoff 1997].

Hansen et al. [2000] offer an "alternative scenario" for addressing the problem of global warming in the 21st century which addresses some deficiencies of the Kyoto Protocol. The scenario calls for a halting of non-CO_2 GHGs as well as BC over the next 50 years. Hansen et al. [2000] still maintain that CO_2 must be limited in addition to BC because of its long lifespan and great effect on global warming. This scenario has high-level administrative support. President Bush expressed disapproval of the Protocol, positing "Kyoto failed to address two major pollutants that have an impact on warming, black soot and tropospheric ozone. Both are proven health hazards. Reducing both would not only address climate change but also dramatically improve people's health" [Bush, qtd. in Jacobsen 2002]. The alternative scenario emphasizes cuts in non-CO_2 GHGs and BC aerosols, which are not regulated under the Kyoto Protocol. These targets are easier and cheaper to achieve than CO_2 emission reductions, since current technologies exist to reduce the non-CO_2 forcing species, whereas large CO_2 emissions reductions would require more extensive restructuring of the global energy infrastructure. Such a strategy would apply globally, and "unite the interests of developed and developing countries" [Hansen et al. 2000].

1.2 Black Carbon Overview

Black carbon is soot formed by incomplete combustion of coal, diesel fuels, and biomass, and can be a product of industrial pollution, traffic, outdoor fires, and residential energy use. Emissions are particularly high in China and India where indoor cooking and heating are done with coal, wood, cow dung, and field residue at low temperatures, which results in incomplete combustion.

Atmospheric aerosols are particles suspended in air. Aerosols may contain sulfates, nitrates, carbonaceous (organic and black carbon) particles, sea salt, and mineral dust [Menon et al. 2002]. Although most aerosols reflect sunlight to cool the atmosphere, aerosols containing BC are of particular concern because they heat the atmosphere by absorbing sunlight, darkening clouds, and darkening snow and sea ice surfaces [Hansen et al. 2000]. Black carbon is the greatest anthropogenic aerosol absorber of solar radiation [Cooke et al. 1996], and this absorption offsets the cooling effects of non-BC aerosols such as sulfate. According to Hansen et al. [2000], BC is the third largest climate forcing, trailing only CO_2 and CH_4.

The lifespan of black carbon is 5.29 days, [Cooke et al. 1996] which is a relatively short lifespan, especially when compared to CO_2, which lingers in the atmosphere for decades to centuries [IPCC 2001]. Because it has a significantly shorter lifespan than other emissions, its global distribution of radiative forcing is vastly different (Figure 2). CO_2 is transported worldwide from major sources by atmospheric transport, and has a relatively even global distribution of forcing. However, BC emissions do not travel far from their source and its forcing effects therefore remain a localized problem. Therefore, regional programs in India and China, where the problem is most acute, could see a dramatic payoff shortly after reduction measures are taken.

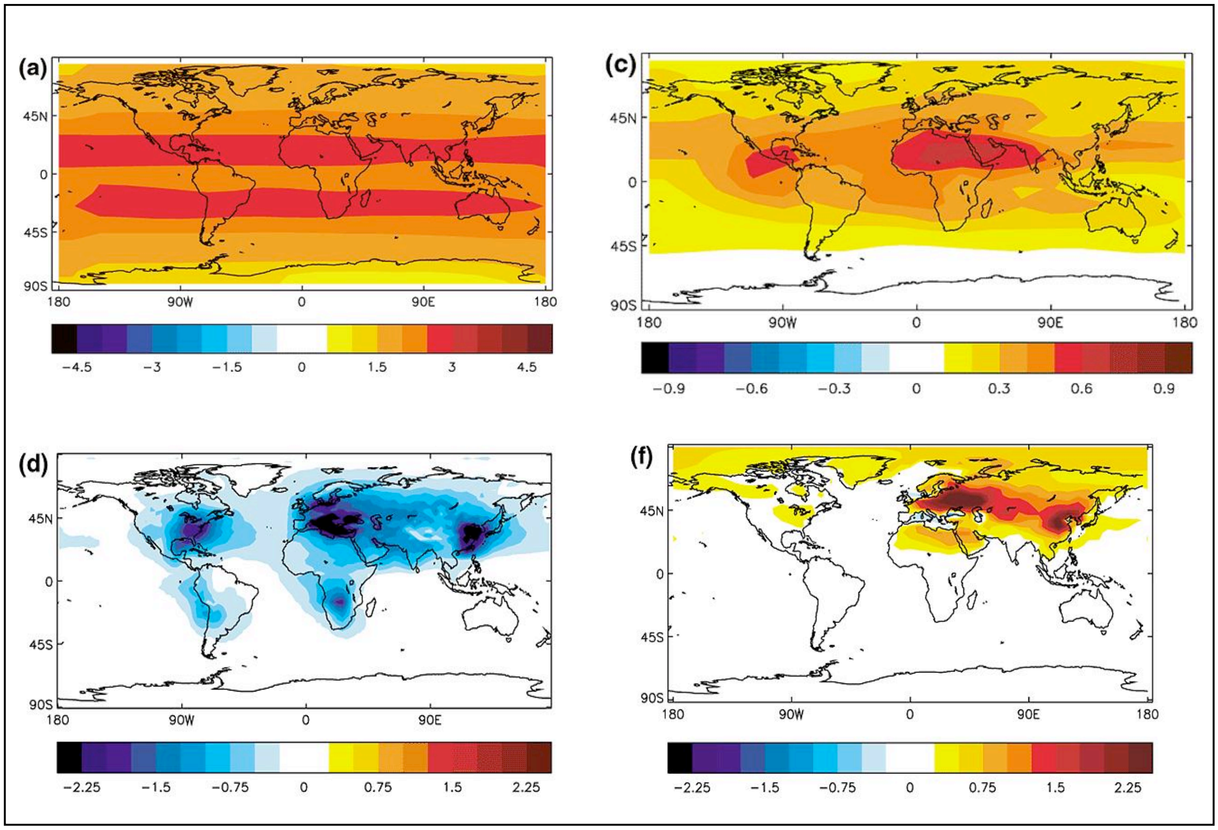

Figure 2. Global distribution of annual-average radiative forcing (1750 to 2000) due to (a) greenhouse gases including CO_2 ,CH_4 ,N_2O, CFC-11 and CFC- 12, (c) increases in tropospheric ozone, (d) sulfate (f) organic carbon and black carbon. Forcing measured in W/m^2 . [IPCC 2001]

1.3 Black Carbon Impacts on Regional Climate

In addition to contributing to global warming, BC aerosols have other regional effects. BC aerosols have significantly contributed to recent changes in weather patterns in China and in India [Menon et al. 2002]. In recent decades, China and India have been experiencing significant changes in precipitation trends. These changes include summer floods in southern China, increased droughts in northern China, and cooling in China and India, while most of the world has been experiencing warming. Menon et al. [2002] used a global climate model to investigate the possible contribution of BC aerosols to these changes. Using the Goddard Institute for Space

Studies (GISS) climate model and aerosol data from 46 ground stations in China, two simulations were conducted. In one simulation, aerosols containing BC were added to the model, and some of the incoming solar radiation was absorbed. In the second simulation, BC was removed from the aerosols so that all incoming solar radiation was reflected. In both simulations, other forcings including GHGs and sea surface temperature (SST) were fixed at the same values as the control run so that the aerosols were the only forcing, and the models were run for 120 years. After running the model with a variety of forcing mechanisms, researchers found that only scenarios including the effects of BC produced results consistent with actual observations of cooling in China but warming in the rest of the world [Menon et al. 2002].

2: AIR POLLUTION AND PUBLIC HEALTH

"Give me your tired, your poor, your huddled masses yearning to breathe free"
-Emma Lazarus

In addition to black carbon's effect on climate, BC aerosols also have significant adverse health effects. Air pollution is a health problem affecting developed and developing countries throughout the world. There has been escalating scientific concern over air quality since the air pollution disasters in London and other highly industrialized cities in the mid-20^{th} century. Indeed, it is believed that the "London smog" resulting from combustion of household fuels killed 4,000 people in 1952 [WHO 1999].

There have been few studies on the effects of BC and public health, and most epidemiological studies which discuss air quality and public health do not specifically mention BC, but rather focus on PM. Particulate matter is a generic term applied to solid suspended particles and includes BC aerosols, sulfates, and other pollutants.[1]. The fraction of BC in PM varies from source of emissions and place, i.e., PM emitted from diesel combustion will have a greater fraction of BC than PM emitted from gasoline [Battye et al. 2002]. Since black carbon comprises a fraction of particulate matter, we can apply these studies to an analysis of the effect of BC on global health.

Particulate matter is a significant contributor to indoor air pollution, especially in developing countries that use coal and biomass fuels in inefficient indoor stoves for cooking and heating. Regional studies have released some estimations of the fraction of BC in particulate matter [Streets et al. 2001, Battye et al. 2002]. Diesel vehicles in China released 1.43 g/kg of $PM_{2.5}$ in 1995, and it is estimated that 52% of these emissions were composed of BC [Streets et al. 2001]. It is expected that this fraction would also be high in residential sectors since burning of coal and biomass for heating and cooking significantly contribute to BC emissions. Similarly, the US Environmental Protection Agency (EPA) also suggests that $PM_{2.5}$ emissions from transportation contain a large fraction of BC [Battye et al. 2002]. However, a more complete analysis of the fraction of BC in PM by sector in developed and developing countries is needed.

2.1 Indoor Air Quality

Generally, people spend most of their time indoors, which makes indoor air pollution a significant health risk [WHO 1999]. Indoor air pollution is a particularly large problem in developing countries (Table 1). In developed countries, pollutant concentrations indoors are similar to those outdoors, with the ratio of indoor to outdoor concentration falling in the range 0.7-1.3 [WHO 1999]. However, in developing countries when indoor heating and cooking appliances are fueled by coal and biomass, concentrations of combustion products in indoor air

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[1] PM_{10} refers to particles with a median diameter less than 10 μm and $PM_{2.5}$ refers to a median diameter less than 2.5 μm.

are substantially higher than those outdoors. Roughly half of the world's households use these fuels in open fires or leaking stoves which contributes to a large fraction of BC emissions [WHO 1999]. High indoor concentrations of PM containing BC can contribute to respiratory disease and cancer [WHO 1999]. $PM_{2.5}$ emissions are so small that they can penetrate deep into the lungs and remain for extended periods of time, contributing to serious impacts on public health [Nielsen et al. 1998]. Policies directed towards BC reduction would benefit developing countries such as China, which are exposed to high levels of indoor air pollution and ensuing health risks.

	Concentrations			Exposure		
Region	Indoor	Outdoor		Indoor	Outdoor	Total
	($\mu g/m^3$)	($\mu g/m^3$)		(%)	(%)	(%)
Developed						
Urban	100	70		7	1	7
Rural	80	40		2	0	2
Developing						
Urban	250	280		25	9	34
Rural	400	70		52	5	57
TOTAL=				86	14	100

Table 1. Global particulate concentration and exposures in urban and rural indoor and outdoor environments. PM (including BC) is a significantly larger problem in developing countries than developed. Population exposures are expressed as percentage of world total. Exposure is defined as number of people exposed multiplied by duration of exposure and concentration inhaled during that time. Particulate concentrations include PM_{10} and $PM_{2.5}$. [Smith 1996]

It is now widely recognized that household use of fuels such as coal and biomass used for indoor heating and cooking in developing countries pose a serious health risk. In developing countries, respiratory diseases are a leading cause of morbidity and mortality in children and adults. Acute respiratory infections (ARI) are the leading cause of death in children under 5 years of age worldwide [Murray et al. 1996]. Between 3 and 5 million children 5 years and younger die each year from ARIs, and 99% of these deaths occur in developing countries [Murray et al. 1996]. A 1993 World Bank report estimates that indoor air pollution is responsible for almost

50% of the burden of total disease resulting from poor household environments in developing countries, due to the association between indoor air pollution and ARIs [World Bank 1993].

Relatively few studies have been conducted to study the health effects of indoor air pollution in the developing world; however, available data has shown that indoor air pollution is associated with adverse health effects. Smith et al. [1994] found that the use of coal for cooking and heating in China increases the risk of lung cancer in the exposed population by a factor of 3 to 9. Pandey et al. [1989] determined that children in Asia and Africa are 2 to 6 times more likely to develop acute respiratory disease with the indoor use of fuels for cooking [Pandey et al. 1989]. Additionally, Smith [2000] estimates that 270,000 Indian children under the age of five die each year from acute respiratory infections arising from particulate air pollution caused by inefficient indoor burning of coal and biomass for cooking and heating [Smith 2000].

Studies in the developed world have also linked outdoor particulate air pollution including BC emissions with an increased risk of adverse health effects [Pope et al. 2002, Kunzli et al. 2000]. In the developed world, air pollution is emitted mostly from industrial sources, power generation, and traffic, rather than from domestic sources. Pope et al. [2002] determined that fine particulate matter and SO_2 pollution are linked with lung cancer, cardiopulmonary, and all-cause mortality in metropolitan areas throughout the U.S. A 10_g/m^3 increase in daily fine particulate air pollution was associated with an 8% increase in the risk of cardiopulmonary mortality, a 6% increase in the risk of lung cancer mortality, and a 4% increase in the risk of all-cause mortality [Pope et al. 2002]. Similarly, a study conducted in Europe estimated that air pollution caused 6% of total mortality in France, Switzerland and Austria, with 40,000 deaths, 500,000 asthma attacks, 25,000 new cases of chronic bronchitis, and 290,000 episodes of bronchitis in children annually [Kunzli et al. 2001].

The global health effects of particulates such as BC as well as the climate effects provide reason to reduce particulate air pollution. These effects are expected to be even greater in developing countries. Greater attention should be focused on reducing air pollution in developing countries where pollution exposure is higher and healthcare is limited. There is a growing body of evidence indicating that particulates including BC may be particularly harmful substances [Menon et al. 2002, Kunzli et al. 2001, Pope et al. 2002, Smith 2000], but further analysis is needed on the costs and benefits of reducing such particulates and the methods for such reductions to be included in international climate change treaties.

3: METHODS

This paper reviews the current scientific knowledge of black carbon for the purpose of deriving and evaluating policy options for the mitigation of global BC emissions. The following three analyses were performed by synthesizing the literature on BC distribution and forcing. These analyses, in turn, were used in the overall evaluation of the feasibility of a global BC reduction policy.

1. Emissions factors were used to evaluate the BC contribution of different fuel and cookstove combinations in the residential sector.
2. Various cookstove/fuel combinations in China and Kenya were analyzed.
3. Uncertainties and areas of necessary research for a cost-benefit analysis of BC reductions were identified.

Using existent BC inventories, the global distribution of BC was mapped using Geographical Information System software (ArcGIS), and a BC emissions inventory from Cooke et al. [1999].

Current models simulating the climate effect of BC chiefly use the Cooke et al. [1999] BC emission inventories. While the Cooke et al. [1999] emissions inventory contains the best currently available data on BC emissions, there is still a considerable amount of uncertainty over exactly how much BC is emitted globally. A new BC inventory will be released in the coming months by Bond et al. which correlates BC emissions to technology used, and yields smaller global emissions of BC than does Cooke et al.'s estimate. For future research, the Bond et al. emission inventory should be compared with Cooke et al. [1999].

4: RESULTS

4.1 Black Carbon Emission Sources

Cooke et al. [1999] estimate the total global BC emissions at 15.2 Tg/yr. While most countries emit relatively little BC, there are BC "hotspots" in China, India, and Europe with emissions ranging from 1.01-2.89 Tg/yr per year. North America and particularly the eastern US also emit large amounts of BC (.95 Tg/yr) but they are on average lower in comparison to those "hotspots" (Figure 3).

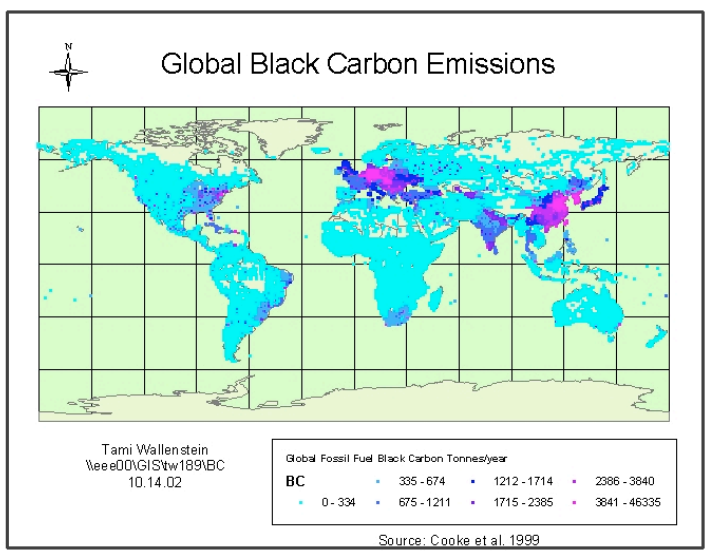

Figure 3. Global distribution of black carbon. Emissions measured in tons/yr. Note the hotspots over China, India, and Eastern Europe. Data taken from Cooke et al. 1999.

Region	BC Cooke et al.1999	BC Bond 2002
North America	.95	.39(.33-1.56)
Latin America	2.41	.99 (.73-2.51)
Europe	1.01	.44 (.33-1.20)
Former USSR	.87	.36 (.22-1.24)
Africa/MidEast	3.78	1.90 (1.38-4.07)
China	2.80	1.19 (.78-3.91)
India	1.45	.53 (.40-1.78)
Other Asia	.52	.33 (.26-.8)
Pacific	1.43	.5 (.26-1.06)
Total	**15.2**	**6.62 (4.68-18.1)**

Table 2. Comparison of estimates of contributions of global BC by country Emissions measured in Tg/yr. Low/high estimates given in brackets. [Cooke et al. 1999, Bond 2002].

The two biggest sources of BC are residential burning of coal and biomass and the commercial burning of diesel. BC emissions are associated with fuel type and combustion technology [Cooke et al. 1999, Streets et al. 2001]. Emission factors are often used to estimate emissions from different fuels and are defined as the estimated average emission rate of a given pollutant for a fuel, relative to the mass of the fuel or energy output. There are several differences between the emission factors of domestic and industrial combustion practices. Domestic fuels are burned under relatively poor conditions at low temperatures, which favor the production of particulates. In addition to the difference in particulate emissions between sectors, there are also variations in energy efficiencies within the industrial sector. While the developed world has seen improvements in energy efficiency, the utilization efficiency of energy in China is 30% less than that of the developed world [Cooke et al. 1999]. The lower efficiencies of equipment in developing countries lead to higher emission factors. Residential coal combustion in developing countries and diesel combustion associated with transportation have the largest emission factors, consistent with being the two greatest sources of global BC emissions (Figure 4).

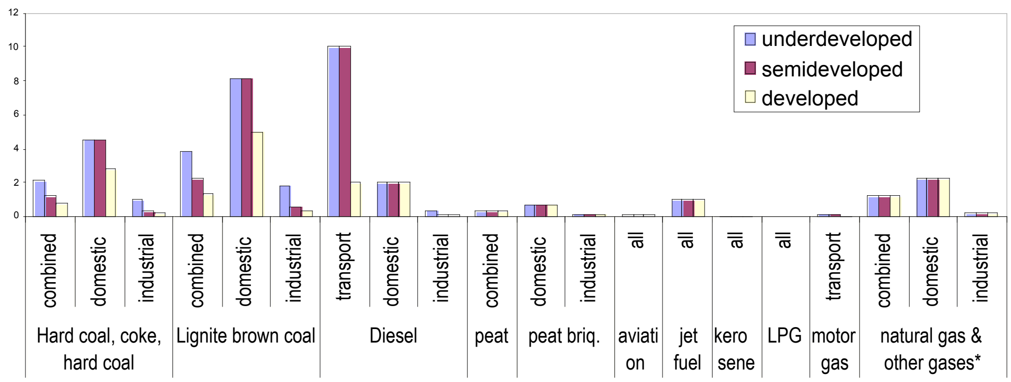

Figure 4. Black carbon emission factors for fuel type and sector for developed, semi-developed, and developed countries. Black carbon emission factors for fuel type and sector for developed, semi- developed, and developed countries. Emission factors are defined as the estimated average emission rate of a given pollutant for a fuel, relative to the mass of the fuel or energy output. Emissions factors measured in g/kg * Emissions factors for natural gas and other gases are given in g TJ^{-1}.[Cooke et al. 1999] .

4.2 Sources of Black Carbon Emissions in China

China emits 2.80 Tg BC/yr, or 18% of global black carbon emissions, and contributes to global BC emissions more than any other country. Therefore, this study will concentrate on sources of emissions in China and policies for their reduction. China suffers from severe energy-related environmental problems, largely in part due to the country's heavy use of unwashed coal, yielding large emissions of sulfur dioxide and PM containing BC [DOE 2002]. One study of particulates in five large cities in China revealed that PM concentrations were 2 to 5 times the daily maximum acceptable particulate standards set by the WHO (70 _g/m^3 daily) [Xu 1998]. Dirty coal combustion is one of the biggest contributors to BC emissions. Coal makes up the bulk, over 63%, of China's primary energy consumption, and China is both the largest consumer and producer of coal in the world [DOE 2002]. China's coal consumption in 2000 was 1.27 billion short tons, over 24% of the world total [DOE 2002]. Moreover, China’s coal consumption is expected to experience an average annual 4.3% increase from 1999-2020 [DOE 2002].

In comparison, developed countries generally rely more heavily on cleaner forms of energy, including natural gas, oil, and cleaner coal. The US uses oil for about 39% of its total primary energy requirements, 23% natural gas, and 22% coal [DOE 2002]. Coal consumption in the US is expected to experience a 1.3% increase from 1999-2020 [EIA 2002], which is significantly less than the expected increase in China (Figure 5).

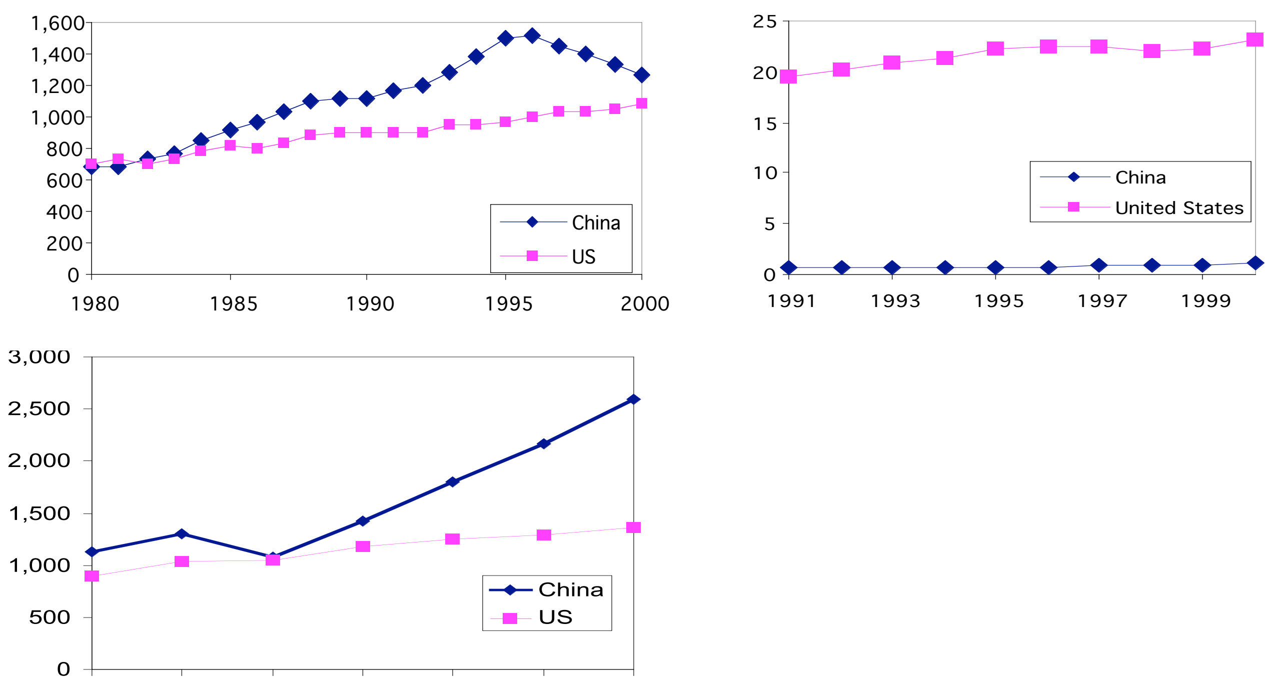

Figure 5. Fuel use in China and US (a) China v. US coal consumption 1980-2000. Decrease in the late 90's due to East Asian economic crisis. Coal consumption measured in short tons (b) China v. US natural gas consumption 1991-2001. Natural gas measured in 10^{15} BTU. (c) China v. US projected future coal consumption 1990-2020. Coal consumption measured in million short tons. [EIA 2002]

4.3 BC Emissions in China By Sector

BC emissions are distributed by sectors as follows: residential 83.3%, industry 7.2%, field combustion 5.6%, transport 3.2%, and power generation 0.6% (Figure 6) [Streets et al.

2001]. The distribution by fuel type is: coal 51.6%, biofuels and fuel combustion 44%, and oil 4.4% (Table 3) [Streets et al. 2001].

Sector	Fuel	Energy use (PJ)		BC emissions (Gg)	
		1995	2020	1995	2020
Residential	Coal	3872	4848	605.4	534.8
	Oil	432	2088	1.0	5.5
	Biofuel	7939	6016	512.0	386.8
	Subtotal	12, 243	12, 952	1118.4	927.1
Industry	Coal	13, 171	18, 257	82.5	80.6
	Oil	2040	2513	11.1	14.5
	Biofuel	600	482	3.6	1.4
	Subtotal	15, 811	21, 252	97.2	96.5
Power generation	Coal	10, 080	18, 054	1.5	0.1
	Oil	731	607	6.1	4.8
	Biofuel	89	226	0.7	0.5
	Subtotal	10, 900	18, 887	8.3	5.4
Transport: road	Gasoline	1208	4047	2.3	7.6
	Diesel	508	2798	13.3	73.3
Transport: other vehicles	Gasoline	100	139	0.2	0.3
	Diesel	764	1644	20.0	43.1
	Coal	234	277	3.2	3.7
Transport: ships	Diesel	138	328	3.6	8.6
	Heavy fuel oil	87	308	0.8	2.7
	Subtotal	3039	9541	43.4	139.3
Field combustion	Crop residue	N/A	N/A	74.7	56.1
Total		41, 993	62, 632	1342.0	1224.4

Table 3. Energy use and BC emission factors for China, 1995 and 2020 (projected). [Streets et al. 2001]

4.3.1 Residential Sector

The overwhelming majority of BC emissions in China are generated from the residential sector. The population of China is roughly one and a quarter billion and the population density of China is 133.82 persons/km^2, roughly four times that of the US [CIA 2002]. Streets et al. [2001] estimate that 83% of BC emissions in China are caused by residential use of coal and biofuels. These fuels are burned in domestic cooking stoves and heaters without

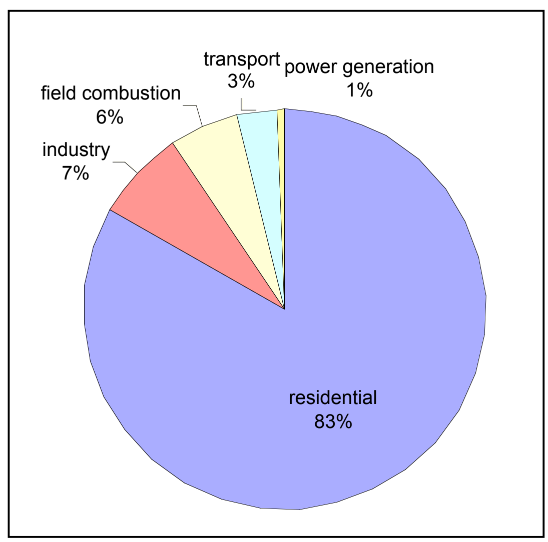

Figure 6. Emissions by sector in China. The overwhelming majority of BC emissions originate from the residential sector. [Streets et al. 2001].

any emission controls. Streets et al. [2001] estimate that in 1995, the Chinese residential sector consumed 3630 PJ of completely unrefined raw coal and only 241 PJ of “cleaner” coal briquettes. Households use a wide array of fuels for energy use, varying from low quality fuels such as animal dung and crop residues to more efficient coal, oil and gas. In general, rural households use more low quality fuels such as dung and biomass, while urban households rely on more modern coal and gas [Smith et al. 1993].

4.3.2 Industrial Sector

While China has an industrial growth rate of nearly 10% (compared to -4% in the US) [CIA 2001], industrial fuel combustion produces significantly less BC than the residential sector, due to more complete combustion of fuels at higher temperatures and greater emission controls [Streets et al. 2001]. Industry in China is less technologically advanced than in developed countries and includes iron, steel, coal, machine building, armaments, textiles and apparel, petroleum, cement, chemical fertilizers, footwear, toys, food processing, automobiles, consumer electronics, and telecommunications [CIA 2001]. The total energy used in the industrial sector in 1995 was 15.8 EJ, and 83% of this energy was provided by coal. The industrial sector produced 97.2 Gg of BC in 1995, primarily from uncontrolled coal-fired stokers and the production and use of coke in the iron and steel industry [Streets et al. 2001]. Industrial BC emissions are not expected to change significantly from 1995-2020, since increasing oil usage will offset a decline in the use of coal.

4.3.3 Field Combustion of Crop Residues

The burning of biomass as a means of waste disposal after harvesting is another significant source of BC emissions (75 Gg). Efforts are underway to give incentives to farmers in China to plow under more of these wastes to increase the fertility of the soil. Assuming these efforts are successful, the amount of crop residue could be significantly reduced and yield smaller BC emissions (56 Gg by 2020) [Streets et al. 2001].

4.3.4 Transportation Sector

Black carbon emissions from transportation were relatively low in 1995 (43 Gg), but are expected to triple by 2020 due to large increases in vehicle ownership. Streets et al.[2001] expect transportation to contribute 11% of BC emissions in China by 2020. Diesel fueled vehicles have much higher PM emissions than gasoline-fueled vehicles, and while it is likely that the US will enact stricter emission controls on diesel, it is unlikely that China will enact such controls in the next 20 years [Streets et al. 2001].

4.4 Future Black Carbon Emissions in China

Raw coal is now being phased out or banned in large cities throughout China and is being replaced with coal briquettes, which produce less BC [Streets et al. 2001]. The outlook is also good in terms of population growth, with an expected growth rate of 0.87% [CIA 2002], a small change in comparison to other developing countries. It has been estimated that BC emissions in China could decrease by 9% by the year 2020 to 1224 Gg through the use of more advanced combustion, emission controls, and the replacement of raw coal with coal briquettes in the residential sector [Streets et al. 2001]. Given the health and climate benefits that can accrue from a reduction in BC, it would be wise to accelerate the transition to cleaner fuels. Some of this work is already underway, from the improvement of cookstoves in China [Smith et al. 1993] to stricter industrial emission controls in industrial centers [Wang et al. 1998].

5: Discussion: Residential BC Emission Controls

"Implacable November weather... Smoke lowering down from chimney-pots,
making a soft black drizzle, with flakes of soot in it as big as full-grown snowflakes—
gone into mourning, one might imagine, for the death of the sun."— Dickens, Bleak House[2]

The most effective approach to reducing black carbon emissions globally would target residential emissions in developing countries and diesel emissions in developed countries. This section will focus on the largest source of BC—residential emissions of coal and biomass burning. Since residential emissions contribute 83% of the BC emissions in China, a BC reduction policy targeting residential coal and biomass consumption would reduce China's extensive contribution to global inventories of BC and reduce the burden of domestic air pollution and respiratory disease.

5.1 Residential Emissions

Half the world's population and 90% of households in developing countries rely on biomass fuel such as wood, dung, and crop residues for household cooking and heating [Kammen 1995]. In many developing countries, these fuels are often burned in inefficient open fires. Approximately two billion kilograms of biomass are burned indoors daily in developing countries [Ezzati et al. 2000]. Such inefficient combustion of biomass fuels at low temperatures results in the highest indoor air pollution concentrations in the world [Albalak et al. 1999].

Biofuels are primarily used in developing countries, predominantly in rural areas. The general pattern in developing countries is that with increasing income people tend to move up the energy ladder from firewood to charcoal or kerosene and then to liquefied petroleum gas (LPG), natural gas, or electricity for cooking [Barnes et al. 1994]. This shift occurs most often in urban areas, because in rural areas, less income and more freely available biomass resource lead to

[2] Quote taken from Bond 2000.

continued reliance on biomass for cooking. Indeed, when firewood is scarce in rural areas, residents typically move down the ladder, using crop residues and dung for cooking fuel energy. Another significant factor impeding many rural populations from moving up the energy ladder towards more modern fuels is poor distribution and lack of an infrastructure for modern fuels such as natural gas.

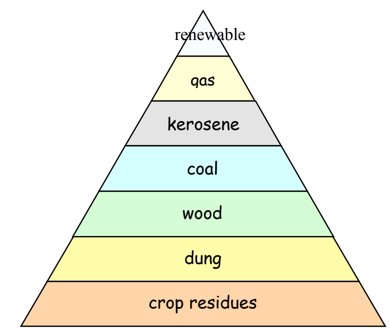

Figure 7. The energy ladder. Fuels increase in efficiency and cleanliness from bottom up. [Smith 1987]

As discussed in Section 2, incomplete combustion of traditional fuels such as wood and biomass releases large concentrations of black carbon and is associated with respiratory disease [Saatkamp et al. 2000]. The smoke from cooking fuels can result in exposures to particulates such as black carbon at 20 times the level that the WHO considers a serious health risk [Kammen 1995]. In rural areas, women and children spend a disproportionate number of hours per day exposed to the smoke from indoor fires and exhibit a significantly higher rate of respiratory disease [Kammen 1995, Smith 1987, Ellegard 1996].

Most developing countries rely heavily on traditional "three stone" biomass stoves, which have energy efficiencies as low as 5-10% [Barnes et al. 1994]. Initial cookstove programs estimated that relatively simple design changes in traditional stoves, such as flues, could create improved biomass cookstoves that are 3-6 times more efficient [Barnes et al. 1994].

Since the energy crisis of the 1970s, international aid organizations have implemented improved cookstove programs in developing countries. With the oil price shocks of the 1970s, households in developing countries were less able to move up the energy ladder to fossil fuels and had to rely more heavily on biomass [Barnes et al. 1994]. Improved cookstove programs were of interest to the international community because of a desire to mitigate and reduce deforestation that resulted from increased reliance on biomass after the oil crisis [Ezzati et al. 2000]. The public health benefits from such reductions in exposure to indoor pollutants were not widely recognized until after many plans for improved cookstoves were already underway [Ezzati et al. 2000]. This double benefit of improved cookstoves—improvement in public health as well as mitigating adverse environmental impacts—gave additional impetus to the cause of design and implementation of improved stoves.

Grassroots women's organizations also played a role in the implementation of improved cookstove programs. In Gujarat, India, women belonging to self-help groups are trained to build stoves. In Haryana, India, a network of 7,000 women's groups supported by the Government of India's Department of Women and Child Development implement improved stove programs at the village level. The groups identify beneficiaries, motivate households and supervise stove building [World Bank/UNDP 2001]. In Guatemala, women's groups work with development aid organizations to address the needs of women in the indigenous community and to improve their conditions [Guatemala Stove Program 2003].

Improved stove programs are faced with the challenge of developing practical programs that address health, environment, and economic concerns associated with stove and fuel combinations at various steps of the energy ladder. The health benefits from reduced reliance on biomass fuels create an incentive for developing countries to shift towards more modern energy sources such as natural gas and electrification. Nonetheless, these options are expensive to both the government and to households in the absence of large sums of international aid and subsidies. Additionally, electrification or modern fuel projects require building a centralized system to distribute such energy, and are often difficult or prohibitively expensive in rural areas. Therefore, this discussion will not focus on these options, desirable as they may be; rather, the scope of this discussion will be limited to domestic fuels burned locally.

5.2: Fuels

Several studies in developing countries have examined the relative benefits of coal and biofuels using efficiencies, emissions, and cost factors that can be described as follows:

Emissions factor(E_f): E_f= E/F or E/n

Cost factor (C_f): C_f= c/F

Energy factor (N_f): N_f =n /F

Where E is emissions produced, F is amount of fuel, c is cost, and n is energy. The types of emissions which are often used to evaluate a given fuel's effect on public health and the environment are particulates (which contain BC), SO_2, N_2O, hydrocarbons, CO, and CO_2. Emissions and efficiency data using traditional cooking and heating stoves with no flue in rural India estimate that crop residues such as coconut husk emit the most particulates containing black carbon, followed by cow dung, wood, and coal (Table 4) [Smith 1987]. A negative correlation exists between emission levels and efficiencies of these fuels, and the more inefficient fuels such as cow dung emit the most particulates [Smith 1987].

Fuel	Particulates	SO_x	NO_x	HC	CO	CO_2**
Wood	3,800	250	300	3200	34,000	581,000
Cowdung	10,000	3200			44,000	
Indian coal	289	2200	460	2200	27,000	628,000***
Crop residue (coconut)	17000	-			54,000	609,000****
Natural gas	0.5	-	10	5	250	20,000

Table 4. Emission factors of 6 pollutants for different fuels. Emissions measured in kg /TJ delivered under Indian rural cooking conditions-no flue. Fuel equivalent measured in metric tons.
* measured in cubic meters
** CO_2 data from Zhang et al. 2000 and measured under conditions in rural China
*** Chinese coal
****crop residue (maize and wheat)
[Smith 1987, Zhang et al. 2000]

Since the impacts of pollution on climate change as well as public health are of concern, the carbon dioxide emissions of residential fuels should also be considered in this analysis. Only 28% of CO_2 emissions in China originate from the residential sector [EIA 2002], compared to 83% of the country's black carbon emissions [Streets et al. 2001]. Therefore, fuels with low BC emission factors but high CO_2 emission factors are still preferable because of the comparatively low existing residential CO_2 emissions. In fact, emissions data from a 2000 study that tested 28 fuel/stove combinations in China reveals that overall, a reduction in TSP will correlate with a reduction in CO_2 [Zhang et al. 2000]. There is a slight positive correlation between particulates and CO_2 emissions, and reducing one would often tend to decrease the other. Among the fuels tested, this positive correlation is especially strong for coal, indicating that a reduction in coal burning would yield a double benefit of CO_2 reductions to mitigate climate change, as well as TSP reductions to improve public health (Figure 8). While coal is still considered a "dirty" fuel, a shift up the energy ladder from wood or biomass to coal would benefit the climate and public health.

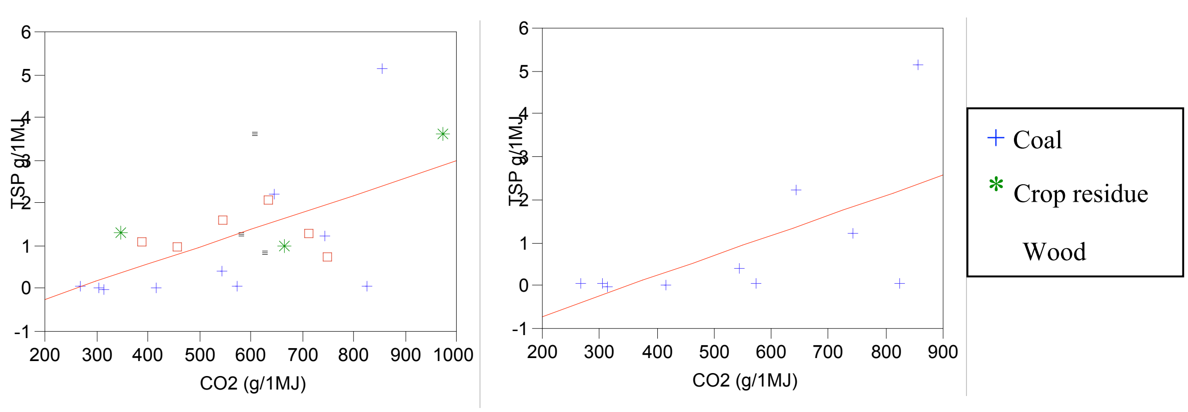

Figure 8. CO_2 v. TSP emission factors for (a) coal, crop residues, and wood (b) coal only. Note the positive correlation between TSP and CO_2. R values are .57 and .62, respectively. Data taken from Zhang et al. 2000.

Another fuel of interest is charcoal. Many improved cookstove programs in developing countries have begun to use charcoal as a cooking fuel. Charcoal has low emission factors for PM including black carbon, making homes cleaner and less smoky. A 1996 study examined the association between exposure to cooking fuel emissions and health in Maputo, Mozambique [Ellegard 1996]. The measure of health was cough symptoms among women cooks, and the fuels used were wood, coal, charcoal, electricity, and liquid petroleum gas (LPG). Wood users were exposed to significantly higher levels of particulate emissions, including black carbon, than users of coal or modern fuels (Table 5), but there was no reported difference in cough symptoms between charcoal and modern fuels users [Ellegard 1996]. This would suggest that charcoal use should be encouraged over wood to a greater degree, but more research is needed in this area.

	Mean particulate concentration $\mu g/m^3$
Wood	1200
Charcoal	540
LPG	200
Kerosene	760
Coal	940

Table 5. Concentrations of particulates measured while cooking with different fuels. Particulate emissions from charcoal are lower than wood and coal and are therefore an attractive option from the perspective of reducing BC. LPG and electricity are not considered feasible options at this point. [Ellegard 1996]

While charcoal is a quick and inexpensive method of reducing health impacts of indoor cookstoves, high emission factors of carbon monoxide COand CO_2 must be addressed. Since CO cannot be detected by human senses, indoor levels of CO can rise to lethal levels without the corresponding warning signs such as irritation and cough that would be created from wood smoke. Therefore, charcoal could be responsible for more acute CO poisonings than other biofuels. This will be discussed further in the upcoming sections.

In summary, fuel transitions up the energy ladder can reduce the burden of indoor pollution. However, fuels are also increasingly expensive up the energy ladder. Technology exists to reduce indoor air pollution, but the price and availability of many fuels often pose an insurmountable obstacle. However, using the most efficient and clean available fuel a household can comfortably afford in combination with an improved cookstove can mitigate indoor air pollution.

5.3 Stoves

While a switch to cleaner fuel is the most effective long-term solution to large residential emissions of black carbon, more efficient use of certain biofuels is an effective solution in the medium term. The relationship between the amount of fuel used and indoor pollution concentration is not direct, and depends in part on the stove used and ventilation available. With close attention to designs that accomplish both objectives, more efficient cookstoves could yield less exposure to indoor air pollution.

Traditional cook stoves are indoor open fires contained by three stones, with no flue or means of ventilation. Open fires are extremely inefficient and transfer as little as 10% of the heat generated to the cooking utensil, and the rest is released into the indoor environment [Kammen 1995]. Significant decreases in particulate emissions can be achieved by some form of ventilation, such as a flue to remove smoke from the room. As new housing units are built, consideration should be given to improving ventilation in cooking areas. Increased air exchange during cooking can result in lower concentrations of black carbon and other particulates (Figure 9). Additionally, improved cookstoves are generally smaller than traditional stoves and use less wood. These stoves are often portable and can be placed outside the home during the smoldering period when the fire is extinguished. This can decrease household emission concentrations by 77% during the smoldering period [Ezzati et al. 2000].

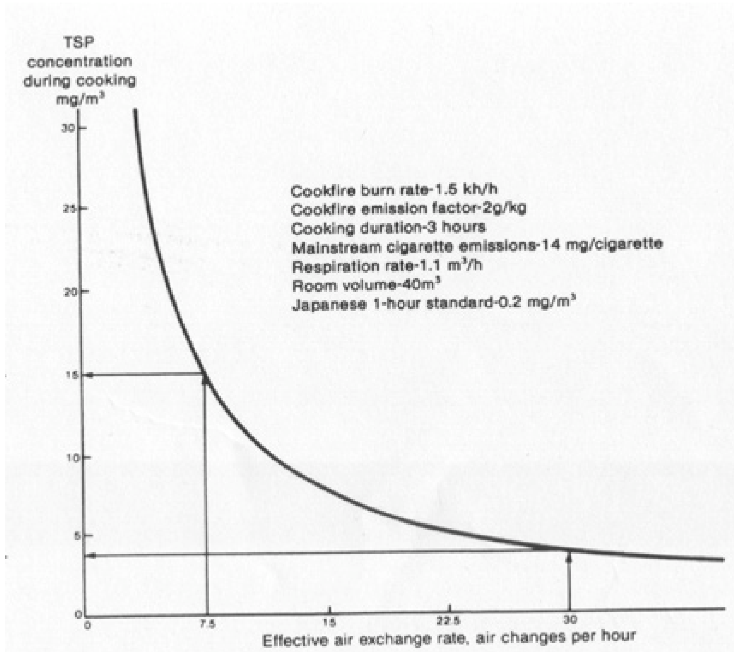

Figure 9. Hypothetical steady-state concentrations of total suspended particulates (TSP) according to air exchange rates. Increases in air exchange rates will yield reductions in TSP including BC. Assumptions used to reflect typical conditions in village households. [Smith 1987]

5.4 Improved Cookstove Programs in China

Since the 1970s, government programs, international development assistant organizations, and community-based efforts have studied and developed improved stove programs. China has the world's most extensive cookstove program, with improved cookstoves in 7 out of 10 rural households [Kammen 1995]. While the types of stoves vary throughout different provinces to meet different needs, most improved Chinese stoves burn crop residues, wood, and coal, and consist of a chimney as well as insulating material. Before the introduction of a widespread improved cookstove program in the early 1980s, farmers in rural villages would report burning their furniture so that they could have one hot meal per day because of shortages in wood or biomass [Smith et al. 1993]. Fortunately, by the early 1990s, the Chinese National Improved Stove Program (CNISP) had installed improved biomass cookstoves in 50% of rural households [Smith et al. 1993].

This effort came about as a result of a growing concern over the extent of rural household fuel shortages and degradation of forests. CNISP was perhaps more successful than improved stove programs in other countries because it encouraged local county governments to adopt policies to offer economic incentives for the use of improved stoves. In the Guangdong province, only households using improved stoves are allowed to cut fuel wood from forests at reduced prices; monetary awards are given to towns that met the checking criteria for improved stoves; and a craftsperson who persists in making traditional stoves is fined and has his license revoked [Smith et al.1993]. The cost per household of improved stoves was $10.99, which is .5% of the average Chinese rural household’s annual income [Smith et al. 1993, Lim 2002]. Roughly 10% of this cost was subsidized through a combination of national, province, and local governments [Smith et al. 1993].

China's cookstove program accounts for roughly 70-80% of the total number of improved cookstoves installed worldwide [FAO 1993]. The number of stoves installed, as well as the variety of models to suit the diverse geographical conditions and users' needs and preferences serves as a model to programs in other developing countries.

5.5 Improved Cookstove Programs in Kenya

Another successful stove improvement case study worth noting is in Kenya, where by 1995 almost one million people (over 10% of rural households) cook with the Kenyan ceramic Jiko (KCJ) [Smith et al. 1993]. While Kenya emits relatively little BC and would not be a key target in a strategic plan to reduce global BC, the Kenyan improved cookstove program is used in this paper as a case study for the development of improved cookstove programs in countries with higher BC emissions.

The ceramic Jiko improves stove efficiency through the addition of an insulating ceramic liner which allows 25-40% of the heat to be delivered to the pot. The stone walls absorb 20-40% of the heat, and 10-30% is released as flue gases such as carbon monoxide and methane [Kammen 1995]. More than half of urban households in Kenya use the ceramic Jiko, which saves on average 1,300 pounds of fuel per year over the open fire method and results in savings of $65 per house—often up to a fifth of a household's annual income [Kammen 1995]. Many have invested these savings into education for their children. Users of the Jiko range from very poor to wealthy; however, demand for these stoves is concentrated in urban areas. Demand does not seem comparable in rural areas, since the $5 stove price of the Jiko is often too expensive for lower income households, who often prefer to collect their own firewood and dung and cook over open fires. However, residents in rural areas may be willing to spend something less than that amount for a slightly less efficient improved stove, since there are clear benefits of improved stoves on the daily lives of residents, including reducing the burden of collecting wood and reducing the acrid smoke in cooking huts. Despite its price, many other African countries have adopted the Kenyan Jiko, and it is widely used in Tanzania, Sudan, Uganda, Zambia, and Burundi [Kammen 1995].

Stove	Body	Liner	Fuel	Price USD
Three stone	n/a	n/a	wood	0
Kuni Mbili	metal	ceramic	wood	6
Upesi	metal	ceramic	wood	6
Lira	metal	ceramic	wood	6
Metal Jiko	metal	n/a	charcoal	1.5
Kenya Ceramic Jiko	metal	ceramic	charcoal	5
Loketto	metal	metal	charcoal	6

Table 6 Household stove/fuel combination and prices for the Kenyan Improved Cookstove Program. Note that these stoves have a lifetime of 2-3 years [Ezzati personal correspondence 2003] so it is a one-time cost for this amount of time. [Ezzati et al. 2000]

5.6 Other Cookstove Designs

Many improved cookstoves throughout the world employ simple design changes such as the addition of a flue in order to significantly reduce particulate emissions. Many households in Jaracuaro, Mexico use the improved efficiency Lorena stove with chimneys. The use of the Lorena correlates to reductions in indoor concentrations of particulates and adverse health effects such as acute respiratory infections [Saatkamp et al. 2000].

The benefits of improved cookstoves have led to efforts towards a more radical shift from traditional technologies to renewable sources such as solar energy. Solar cookstoves are used sparsely in Africa and Latin America. Designs vary, but the most common solar stove is the "box cooker," with a metal plate to absorb sunlight, walls made of reflective materials such as an aluminum sheet, and a glass sheet to trap the heat [Kammen 1995]. While these stoves require supplemental cookstoves for nighttime and cloudy days, they emit no smoke and can reduce fuel expenditures significantly.

Based on current studies, the most cost effective approach would be a larger scale cookstove program, promoting the use of charcoal burned in a stove similar to the Kenyan Jiko or Loketto with a ceramic lining and with good ventilation. Residential emissions from combustion of fuels in cookstoves are the largest source of BC worldwide, and would be the cheapest to reduce compared to diesel or industrial emissions. In Kenya, for example, as noted above, the ceramic Jiko charcoal stove costs $5, and saves 1,300 pounds of fuel annually. Since the cost of the fuel is about 5 cents per pound, the annual fuel savings would be $65 annually, and thus the payback period for the initial investment would be recouped in less than one month. Therefore, in the case of the Jiko, the benefits of the stove outweigh the cost. However, the potential unintended consequences of cookstove programs that promote charcoal need additional research.

5.7 Analysis of Charcoal Use

Could widespread charcoal use be the best option to reduce BC emissions? Cookstove programs have often been successful through the use of improved cookstoves burning charcoal. Improved stoves in Kenya such as the metal Jiko, ceramic Jiko, and Loketto burn charcoal and emit the least PM concentrations (Figure 10).

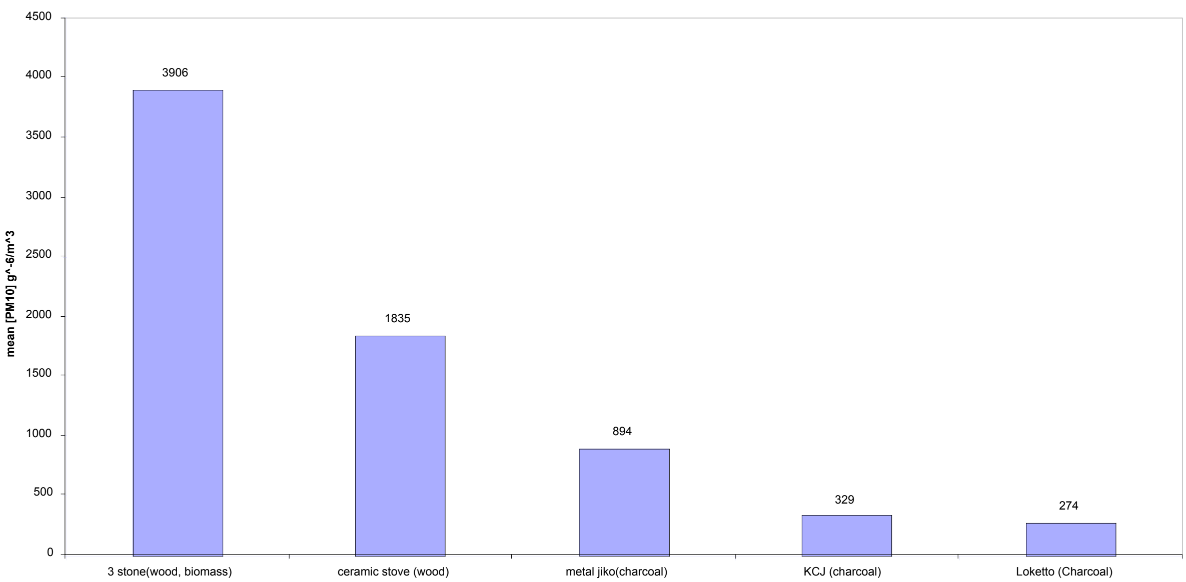

Figure 10. Emissions of PM during actual burning conditions in Kenya for charcoal and wood stoves. [Ezzati et al. 2002a]

From the perspective of reducing black carbon, a transition to charcoal in developing countries is worthy of future policy consideration. However, the use of charcoal results in other forms of environmental degradation, including elevated CO_2 and CH_4 emissions and deforestation, as well as adverse effects on public health from carbon monoxide. In order to fully determine whether charcoal use should be encouraged in developing countries, three types of charcoal emissions were examined—CO_2, CO, and PM including black carbon (Figure 11).

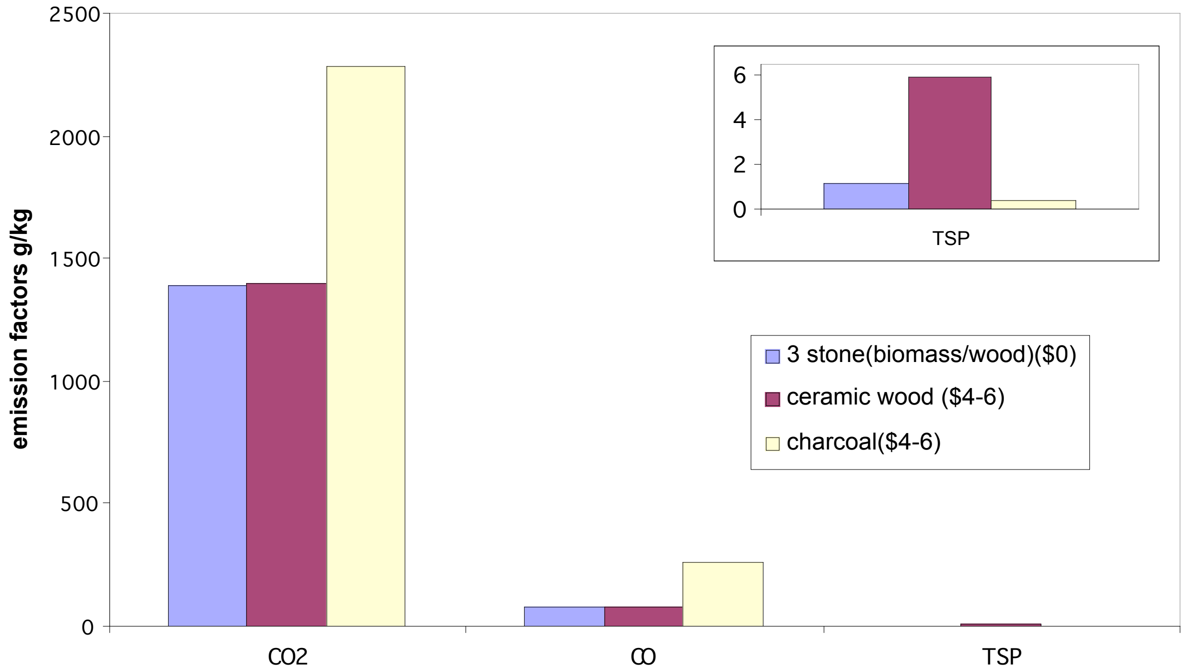

Figure 11. Comparison of emissions by stove. Stoves used in study were three stone fire, ceramic lined cookstoves including Upesi, Kuni Mbili, and Lira, all $6. Charcoal stoves included Kenyan Ceramic Jiko and Loketto, also $4-6. Therefore, price should not be a factor in deciding between charcoal and wood use based on this figure, and only emissions should be considered. The height of each bar shows the average emission factor for each pollutant reported in g/kg. Because of the large scale of emissions, TSP is reported in g carbon only and is shown separately since its emission factor for different stoves is much smaller than that of CO_2. The three stone fire burns wood less efficiently than the ceramic wood stoves. Data from 29 days of measurements of conditions of actual use in 19 rural Kenyan households. [Bailis et al. forthcoming]

5.7.1 Carbon Dioxide

While it was stated earlier that for most fuels, there is little tradeoff between BC emissions and CO_2 emissions, charcoal is one fuel that is most certainly faced with this tradeoff, and one concern that should be addressed with respect to the increased use of charcoal in developing countries is elevated greenhouse gas emissions. In order to compare the effects of GHG emissions on future climate change, Global Warming Potentials (GWP) are used. Global warming potentials are defined as the ratio of radiative forcing of a compound to an equivalent quantity of CO_2 on a mass or molar basis, and are used to compare the radiative forcing of different compounds. Although GHG emissions from charcoal are lower than GHG emissions from wood, high CO_2 and CH_4 levels in charcoal remain in the atmosphere longer and therefore charcoal stoves emit more GHGs than wood stoves when emissions for both types of stove were weighted using a 20 year GWP. Therefore the climate change potential from charcoal stoves is greater than the GWP for wood stoves. However, emissions from charcoal burning in developing countries contribute little to global GHG emissions compared to emissions from fossil fuels in developing countries, and their impact on global climate change is likely negligible (Table 7).

	CO_2	CO	CH_4	TNMHC	NOx	N_2O
Kenyan charcoal production	3.9	0.49	0.097	0.2	0.00014	0.00032
Kenyan fossil fuel use	6.7	-	-	-	-	-
US fossil fuel use	5940	68.66	10.09	9.62	21.09	0.269

Table 7. Estimated annual GHG emissions from charcoal production in Kenya (1996), compared to emissions from fossil fuel use in Kenya, and the United States. Emissions measured in Mt. Total production of charcoal of 2.2 Mt in Kenya [Pennise et al. 2001]

5.7.2 PM_{10} Containing Black Carbon

While emissions from charcoal stoves can be associated with high GHG emissions compared to wood stoves, charcoal offers significant public health benefits over wood through reduced PM_{10} emissions. A transition from burning wood in a three stone fire to charcoal can reduce PM_{10} exposure of household users by 75-95%, resulting in a 45% reduction in childhood lower respiratory infections, the leading cause of global morbidity and mortality [Ezzati et al. 2002, Murray et al. 1996].

5.7.3 Carbon Monoxide

Charcoal is manufactured by heating biomass in the absence of air. The manufacturing process of charcoal separates and eliminates most of the particulate and other hydrocarbon emissions, but never eliminates carbon monoxide, and therefore CO emission factors for charcoal are relatively high [Smith 1987]. The comparison of wood and charcoal stoves has therefore long been considered a tradeoff between efficiency and safety. While wood presents a risk of chronic disease, charcoal presents a risk of acute poisoning and death. Because charcoal sources emit CO directly into the home at the time of human occupancy (mealtime) exposures are often very large. People using coal and biomass cookstoves are often exposed to daily CO exposures higher than health based national standards and WHO guidelines [Zhang et al 1999], and these exposures are even greater with charcoal stoves that have higher CO emission factors. The WHO one-hour standard for CO concentration is 40 mg m^{-3}. When charcoal is burned under conditions typical to a rural home (40 m^3 kitchen, 1.7 kg fuel with emission factor of 74 g/kg, air exchange rate of 5-20 exchanges/hr), the estimated one-hour average concentration during indoor charcoal burning is 528 mg m^{-3}, 13 times higher than the WHO guideline [Zhang et al. 1999].

CO concentrations in a rural kitchen depend on the volume of the room and air exchange and can be calculated as:

$$\frac{dC(t)}{dt} = \frac{F*E_f}{V} - S*C(t)$$

where C=CO concentration, F=fuel burn rate (kg/h), E_f=CO emission factor (g/kg), t=time (h), V=volume of kitchen (m^3), S=air exchange rate (h^{-1}) [Zhang et al. 1999].

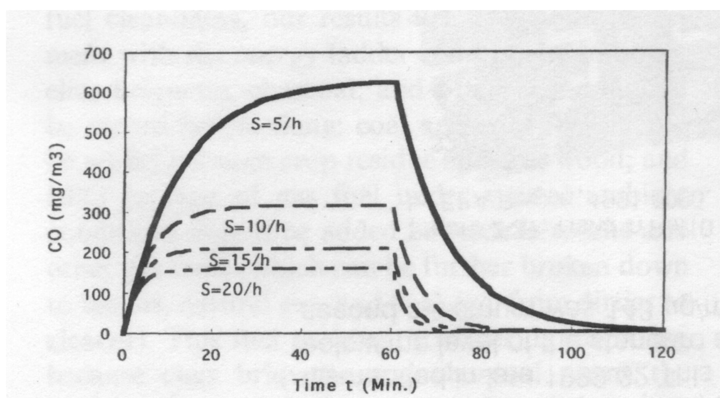

Figure 12. Calculated CO concentrations in a well mixed room where fuel wood was burned in a stove without a flue. S is equal to air exchange rate (h^{-1}). t=0, fire started, t=60, fire extinguished. [Source: Zhang et al. 1999]

Because rural households are poorly constructed, they are likely to have cracks in their infrastructure which increases ventilation. The greater the air exchange rate, the lower the CO concentrations (Figure 12). Air exchange rates are slower in colder environments while at the same time more charcoal is burned indoors for heating, resulting in greater indoor CO emissions. Therefore, CO exposure could be a greater problem in colder climates or in the winter in rural homes.

There has been little data examining carbon monoxide poisoning associated with charcoal combustion in cookstoves in developing countries. Adverse health effects of CO can be classified into acute and chronic CO poisoning. Acute poisoning is a significant risk in parts of the world using fuels such as charcoal [Zhang et al. 1999]. Though no studies have estimated deaths from CO poisoning from charcoal cookstove emissions, anecdotal evidence suggests cases of persons or entire families dying as a result of CO poisoning after a charcoal stove was used to heat a small, poorly ventilated room through the night [Bailis, Zhang Personal Communication 2003]. As village houses usually have large ventilation rates, acute CO poisoning is perhaps less severe in villages than in urban residences which use coal or charcoal stoves. In China, numerous deaths from coal stove CO poisoning have been reported each year, especially during winter months. However, it is likely that many CO related deaths are unreported.

Results of a Zhang et al. [1999] study suggest that at the concentrations of CO reported from charcoal burning under the conditions of the study are typically not high enough to cause acute poisonings, but if certain conditions change such as air exchange rate, volume of the kitchen, and the time the fuel is burned, emissions could rise to fatal levels. However, under the conditions of the Zhang et al. 1999 study we can assume that residents are indeed exposed to CO levels high enough to produce chronic poisoning (concentrations over 29 mg m^{-3} for 8 hours), which can also have significant detrimental health effects. Health effects of chronic exposure to CO include cognitive and memory impairments, physical symptoms such as headache and nausea, emotional and personality effects, sensory and motor disorders, and gross neurological disorders including seizures [Penney 2000].

Despite lack of data on the effects of high CO emissions from charcoal stoves, it is clear that the magnitude of the exposure and health effects will depend on air circulation. The tradeoff between the efficiency and low PM exposure offered by charcoal and health problems associated with CO poisonings can be minimized through changes in cookstove design and the way they are used. Increasing air exchange rates is recommended for reducing CO in indoor environments and could drastically reduce CO concentrations. Therefore, cooking near an open window or a better ventilated part of the house could greatly reduce exposure. Additionally, if improved cookstoves that burn charcoal such as the metal and ceramic Jiko and Loketto were built to contain flues, exposures could be significantly decreased, if not eliminated completely. Additionally, before encouraging use of charcoal in populations that are likely unfamiliar with the dangers of carbon monoxide poisoning, there must be an educational component to the program to familiarize people of the dangers and symptoms of CO poisoning and preventative measures.

5.8 Conclusion

If issues of concern related to CO such as ventilation and education can be successfully addressed, the widespread implementation of improved charcoal cookstoves should be strongly considered. Steps need to be taken, however, to clean up production of charcoal and ensure sustainable harvesting of wood used for charcoal. The public health benefits of reduced particulates including BC are great and would reduce the global burden of disease associated with acute respiratory infection. Additionally, while the $4-6 price of charcoal stoves may be quite costly for some households, it is no more expensive than less efficient wood cookstoves that are more damaging to public health. The added efficiency will save fuel and a portion of household income spent on fuel. Therefore, with appropriate ventilation and education, the use of charcoal in developing countries should be considered where the fuel is available and reasonably priced.

6: RECOMMENDATIONS

Recent scientific studies suggest a need for a detailed policy analysis on the practicality, cost, and benefits of reducing BC emissions. However, current scientific research does not provide enough support or data to conduct a reliable cost benefit analysis. There are several areas of uncertainty or areas where future research is needed before a cost benefit analysis can be conducted from a policy perspective, which will be briefly discussed below. These include:

- Uncertainty in the radiative forcing of BC;
- Uncertainty in BC Emissions;
- Uncertainty in the relative importance of BC in PM for health effects;
- Limited epidemiological studies on indoor air pollution in developing countries;
- and Uncertainly in health effects of CO from charcoal burning.

Uncertainty in Radiative forcing of BC: There are several different estimates of global mean radiative forcing due to BC. The IPCC estimates a forcing of $0.2 W/m^2$, while others, such as Hansen [2002] and Jacobsen [2002] have higher estimates of 0.8 ± 0.4 W/m^2 and 0.5 W/m^2, respectively. Even among the different estimations, the level of understanding of climate forcing due to BC aerosols is low. The IPCC gives a “very low” level of reliability for its BC forcing estimates. In general, non-well mixed GHGs such as aerosols and O_3 have low levels of reliability for their forcing estimates because they depend on model-simulated concentrations, as opposed to well-mixed greenhouse gases such as CO_2 whose global concentrations are well quantified.

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Uncertainty in global BC emissions: The global BC estimates used in this paper are from Cooke et al. [1999]. These estimates were derived from the quantity of fuel consumed and emission factors for specific sectors and countries. A new inventory by Bond et al. [forthcoming] is expected to measure global BC emissions by applying emission factors to fuel use data for different combustion technologies as opposed to country and sector-specific emission factors. This data is not currently available but is expected to be published within the coming months. This estimate contains a lower overall estimation of global BC emissions. In addition to the disparity between the two models of BC emissions, there is uncertainty within each estimate, since both rely on government data on fuel use. Underreporting of fuel use will often occur when a portion of the fuel supply is not officially accounted for or when certain fuels, such as wood cut from forests or household wastes are not accounted for at all. Emission factors may also be inaccurate if they are not measured under typical conditions or if they are measured from better technology than average [Bond 2002].

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Uncertainty in the relative importance of BC for health effects: How much of the health effects indoor air pollution is due to BC emissions? The combustion of coal and biomass releases a host of other pollutants besides BC. Sulfur oxides, among others, are emitted along with BC and pose serious health risks. Exposure to sulfur oxides can result in decreased lung function and cause respiratory disease and premature death [WB 1998]. The emission factors of BC for wood are greater than that of sulfur oxides, and more BC is emitted per kg of wood used. However, coal has a greater emission factor for sulfur oxides than BC and more sulfur oxides are emitted per kg of coal used [Cooke et al. 1999, Smith 1987]. Regardless of which fuel emits more BC, it is necessary to determine whether the respiratory symptoms of indoor air pollution from burning of coal and biomass are a result of BC exposure or exposure to other emissions such as sulfur oxides.

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Limited epidemiological studies on indoor air pollution in developing countries: Many studies examine the effects of air pollution and health in developed countries. However, studies in the developing world have been scarce. Many areas of developing countries have indoor emissions exceeding WHO standards, and the overwhelming majority of worldwide deaths from air pollution occur in developing countries. Despite these compelling reasons to examine the health effects of high levels of exposure to air pollution in developing countries, few studies have examined the health effects associated with such exposure.

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Uncertainty in health effects of CO from charcoal burning: Before it can be concluded whether charcoal use should be encouraged in developing countries, further research needs to be conducted to determine the frequency of acute CO poisonings in rural villages where charcoal is used for heat or cooking fuel. Studies on the long term effects of chronic CO poisonings would also be helpful, though more difficult for several reasons. There is a less direct relationship between exposure and health effects for chronic CO poisonings than acute poisonings that result in death. It would be difficult to relate any symptoms or illnesses specifically to chronic CO exposure, because charcoal smoke is a complex mixture of particulate and gaseous chemical species[3].

This analysis of the policy implications of current black carbon research has been directed from both a climate and health perspective. It has identified the highest priority needs for additional research to perform a credible cost-benefit analysis of black carbon reduction policies. Further studies that address these uncertainties can lead to a more complete understanding of the black carbon problem. Ultimately, by better understanding the climate and health effects of black carbon and the uncertainties in global inventories of emissions, the most cost-effective mitigation measures can be identified, which would have important environmental and public health benefits. Policymakers need to take on a pro-active approach in encouraging dialogue and implementation of strategies to reduce black carbon, particularly in developing countries. An international treaty or protocol to an existing treaty that has provisions for reducing BC would mitigate climate change and lead to improvements in public health.

[3] A 2002 study conducted in the developed world found that after a woman had been exposed to low levels of CO for 1 year, symptoms of CO poisoning persisted for almost 3 years, and she is still being monitored. Many symptoms disappeared after the first 5 days, but 29 months later, the women is still reporting symptoms of CO poisonings and an MRI confirms neurological abnormalities consistent with chronic CO poisoning [Devine et al. 2002]. More studies such as this one should be conducted in the developing world to try to determine the chronic effects of exposure to CO from charcoal cookstoves.

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