Testimony for the Hearing on Black Carbon and Climate Change

House Committee on Oversight and Government Reform

United States House of Representatives

The Honorable Henry A. Waxman, Chair

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Chairman Waxman and Ranking Member Davis, and members of the Committee, I am pleased to have this opportunity to share my expertise about black carbon, its origins, and its role in climate change. I commend your committee for continuing this discussion at the national level, and I am honored to participate. Thank you for your invitation and your consideration.

I am Tami Bond, Assistant Professor of Civil and Environmental Engineering at the University of Illinois, Urbana-Champaign. I have spent the last twelve years modeling and measuring sources of black carbon and other aerosols.

1. Scope of testimony

I will be speaking today on the sources of black carbon, on its role in the climate system especially as it compares to greenhouse gases, and on the potential for mitigation based on my understanding of sources and intervention options. Following are the major points of my presentation:

- To the best of our knowledge, black carbon comes from four major source types.
- History shows that black carbon emissions can be reduced rapidly when cleaner alternatives are available.
- When considering mitigation options, black carbon and other products of incomplete combustion should be considered together with greenhouse gases, especially when they contribute a significant fraction of the atmospheric impact.
- Mitigation options that address black carbon, particularly in developed countries, are not always cost-effective compared to greenhouse gases.
- Some mitigation options can quickly and economically reduce warming by eliminating black carbon and other products of incomplete combustion. Some of these offer major co-benefits in terms of human health and local environmental protection. Implementing them will be challenging, but reduction technologies are available.

2. Sources and magnitudes of black carbon emissions

My colleague, Dr. Jacobson, has already reviewed the definitions of black carbon and its radiative forcing relative to that of greenhouse gases. He has also discussed its potential for reducing warming in the immediate future.

2.1. Black carbon comes from four major source types

Black carbon emissions in 2000 (Figure 1, ref 1) resulted mainly from four source categories: (1) diesel engines for transportation or industrial use; (2) residential solid fuels such as wood and coal, burned with traditional technologies; (3) open forest and savanna burning, both natural and initiated by humans for land clearing; and (4) industrial processes, usually from smaller boilers.

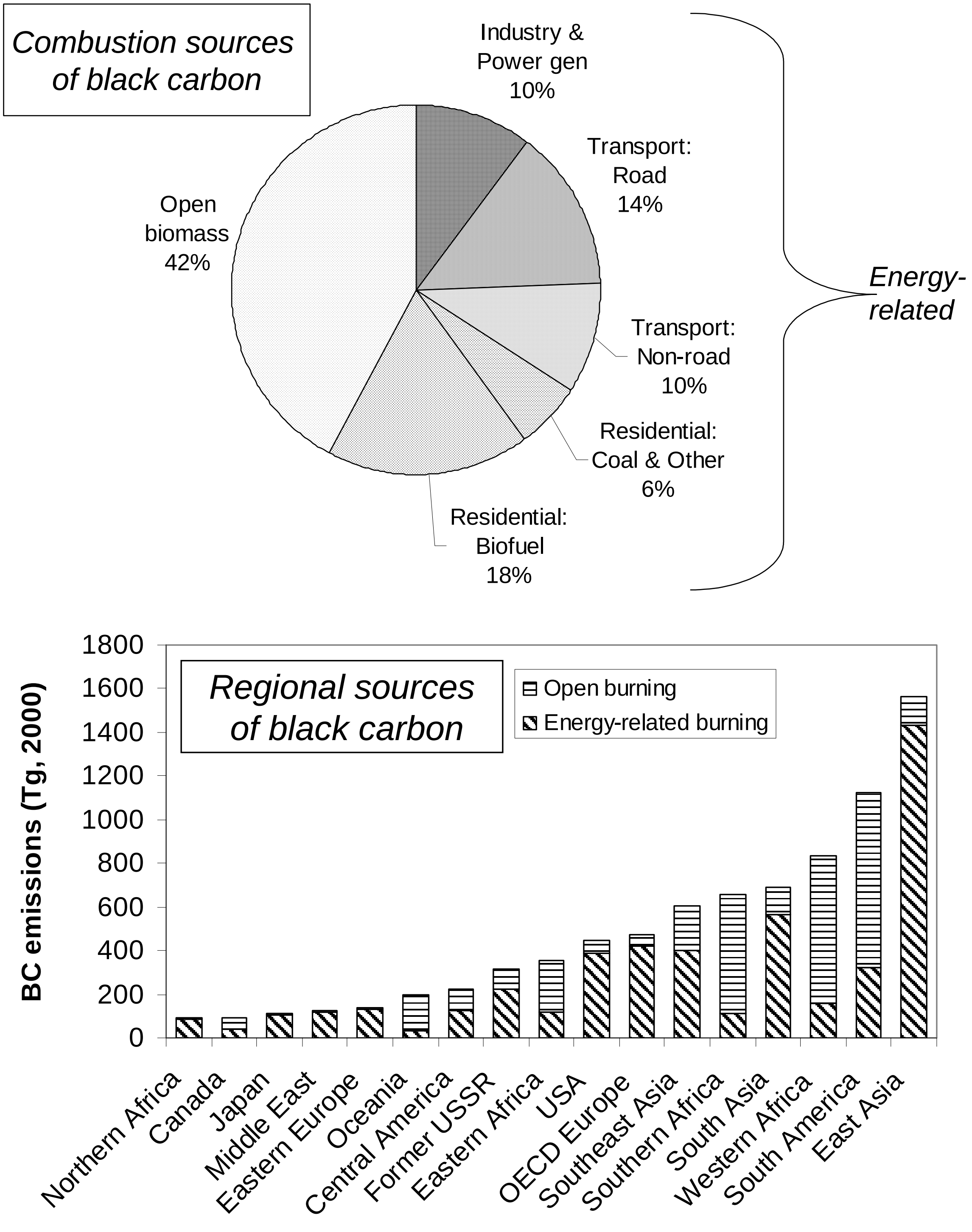


Figure 1. Sources of black carbon: combustion type and region.
From ref 1, updated to year 2000 data.

I have summarized only emissions of black carbon, although they are also emitted with organic carbon, cooling particles, and many gaseous chemicals. The values I present here are compatible with those in Dr. Jacobson's testimony, but they are tabulated differently. My approach is to ask first, "Where does the black carbon come from?" and then, when discussing each source, "If these sources are mitigated, how likely is it that warming will be reduced?"

These estimates are necessarily imprecise, especially when compared with carbon dioxide emissions. That is mainly because: (1) For black carbon, emissions from the same *fuel* can vary by orders of magnitude, depending on the quality of the burning. (2) Within a particular source *type*, black carbon can come from millions of individual combustion units, resulting in a wide range of emission levels. For example, 10-20% of a vehicle fleet can produce half the total emissions [2, 3]. (3) Finally, if the process or combustion fluctuates, emissions from the same *source* vary with time, and fluctuating conditions can result in large emission puffs [4].

In order to produce the emission estimates in Figure 1, we estimate the types of technology used in each world region, often based on sparse data. There are thousands or millions of sources of each type, none of which is continuously monitored. We have to assume that a few measurements can be used to characterize these emissions. Because pollution is undesirable, the worst emitters usually do not want to be detected, and do not offer themselves for emission testing. Emission estimates are biased low if this limitation is not considered. Representing these and other issues on a global basis is a real challenge.

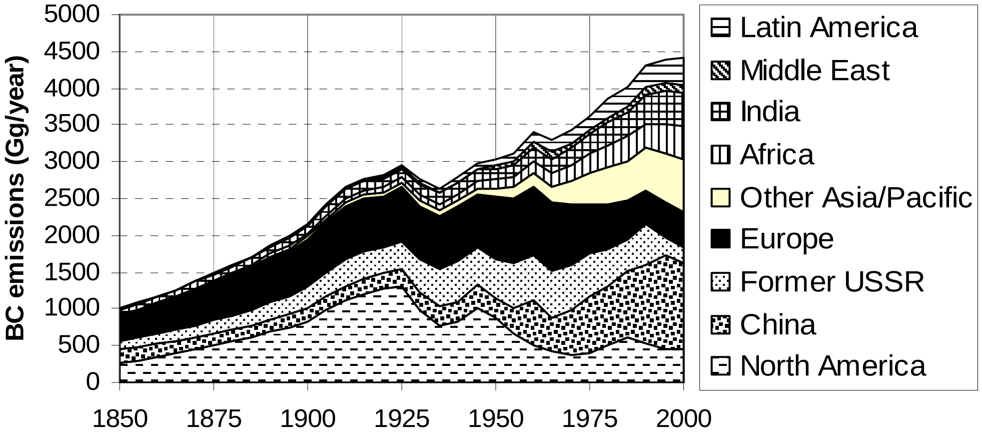
Despite the uncertainties, these estimates identify the major contributors to black carbon emissions. As estimates improve, the magnitude of each sectoral contribution may change. However, these major contributors will neither vanish, nor grow to dominate the entire picture. This last statement is based on an uncertainty analysis included in the development of the global emission estimate [1].

2.2. Black carbon emissions can be reduced quickly by improving fuels or combustion

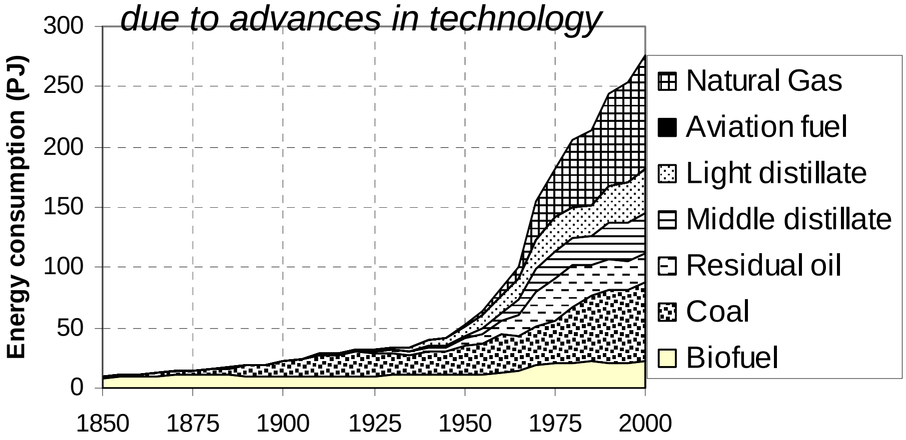
Engineers and regulatory agencies have long experience with reducing particulate matter [5], from metering shovelfuls of coal [6] to the Clean Air Acts. This means that tools are available for reducing black carbon, a component of that particulate matter.

In 1932, an engineer described a coal heater as "…simply a device for stewing off tars and vapors of inconceivable variety as to composition, odor and filth for the effective work of polluting the atmosphere." [7] Enter the pulverized coal boiler, whose emissions contain little black carbon [8]. Temperatures were high, and particles were suspended and better mixed. Due to vastly improved combustion, black carbon emissions in the United States decreased (Figure 2a, ref 9) despite phenomenal growth in coal use. Estimates of the North American emission trend [9, 10] are broadly consistent with the Arctic record [11]. Because of improvements in combustion, global black carbon emissions have

Estimate of historical BC emissions



Energy increases faster than BC due to advances in technology



Estimated changes in diesel emission factor

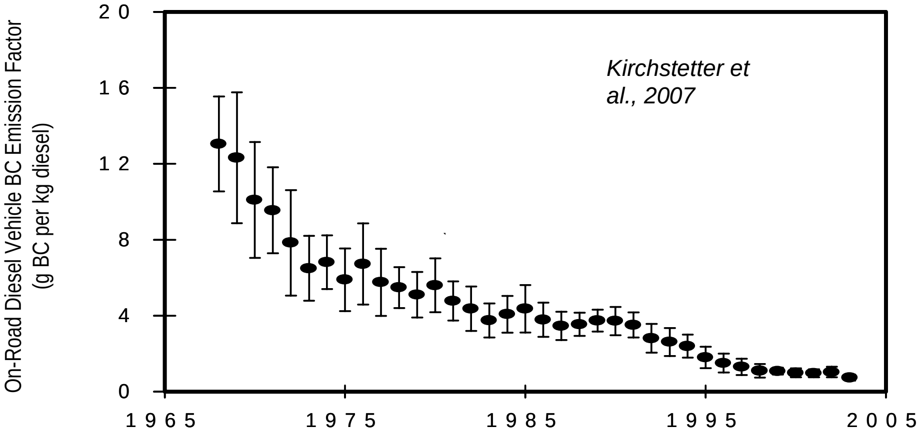


Figure 2. Historical changes in black carbon, energy, and emission intensity.
Top two figures from ref 9; bottom figure from ref 12.

increased at a much slower rate than global fuel consumption (Figure 2b). This is true even if one considers only the increase in the dirtiest fuels (coal and middle to heavy distillate oil). Diesel emission rates have decreased just as dramatically in response to regulation (Figure 2c, ref 12).

History also suggests an approximate development path, as shown in Figure 3. The large emissions from developing regions (Figure 1) are mostly from open biomass burning and from small-scale traditional combustion of solid fuels such as wood and coal. A plausible hypothesis is that in countries which have limited infrastructure and availability of clean fuels, black carbon emissions come mainly from solid fuels for heating and cooking. Over time, cleaner fuels and devices are adopted, and transportation becomes the main source. Some countries may also show increases in industry and transport, depending on the availability of local coal.

Given proper conditions and incentives, polluting technologies can be quickly phased out. In some small-scale applications (such as domestic cooking in developing countries), health and convenience will drive such a transition when affordable, reliable alternatives are available. For other sources, such as vehicles or coal boilers, regulatory approaches may be required to nudge either the transition to existing technology or the development of new technology.

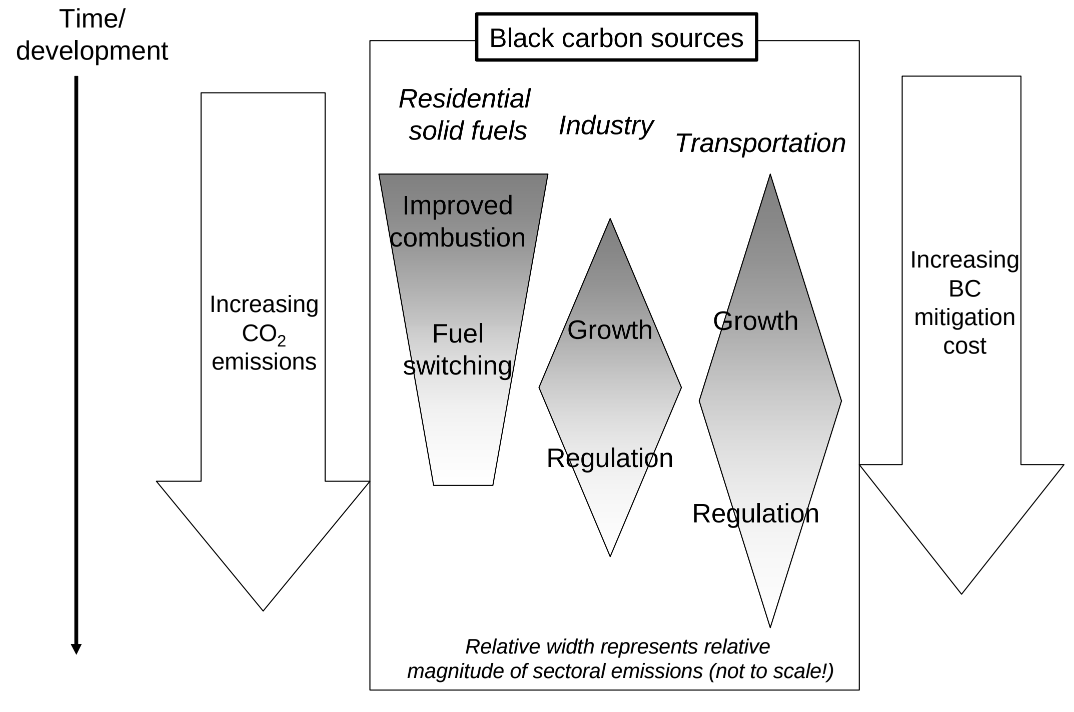


Figure 3. Development path of black carbon emissions.

Figure 1 shows large contributions from developing regions. The course of history in the United States and Europe suggests that these contributions will decrease. A key question is how quickly this transition will occur. Health concerns, air quality concerns, technology development, and potential greenhouse gas mitigation policies could all accelerate the transition.

3. Radiative forcing by sector or source

3.1. Each source affects many chemical species

In discussing black carbon mitigation options, two biases are inherent in conventional representations and accounting procedures: (1) assignment of forcing by species rather than by process, and (2) almost exclusive attention to longer-lived species, such as carbon dioxide or methane, and neglect of shorter-lived species, such as black or organic carbon, although their impacts are not limited to their environments. The practical implication of these biases is neglect of promising mitigation options that may increase carbon dioxide emissions but achieve over-compensating reductions in the emissions of other species, e.g., black carbon. If rapid changes become necessary, such as in response to Arctic warming, including short-lived species with very high short-term warming impacts may be warranted.

The Intergovernmental Panel on Climate Change, as well as much scientific research, quantifies how individual chemical species affect the climate system. A typical presentation identifies the contributions of greenhouse gases, sulfate particles, or carbon particles. (For example, see Figure SPM-2 in ref 13.) However, it is rarely possible to reduce greenhouse gases alone, aerosols alone, or black carbon alone. A more comprehensive way to assess climate impact is by combining all contributions from an individual source. For example, sectors such as power generation, industry, transportation, or households affect greenhouse gases, aerosols, and ozone precursors. A few studies have quantified net effects from sources such as open biomass burning, or total forcing by of aerosols from individual sectors [14].

3.2. Considering all emissions opens possibilities

The source-specific approach is particularly important when black carbon and other products of incomplete combustion are a significant part of radiative forcing. That is the case for each of the four major contributors to black carbon emissions. Forcing from all emissions must be counted in order to identify whether these actions have the intended effect. Limiting attention to traditional[i] greenhouse gases alone has two dangers:

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[i] I use the term *traditional* greenhouse gases to refer to the species listed in the Kyoto Protocol: carbon dioxide, methane, and nitrous oxide. Other greenhouse gases listed in the Kyoto Protocol (hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride) are emitted from industrial processes and are not products of incomplete combustion. The Framework Convention on Climate Change (FCCC) lists many other greenhouse gases. Non-gaseous warming agents such as black carbon are not mentioned there, but the principle of comprehensiveness is enshrined in the text.

- **Missed opportunities** occur if radiative forcing could be reduced economically, but these sources were ignored because their primary contribution (products of incomplete combustion) is not included in the list of species for mitigation.

- **Misinformation about net benefits** of a choice may result when black carbon and other products of incomplete combustion are a significant part of radiative forcing. Table 1 summarizes two classic studies demonstrating this principle. The quote by Kirk Smith (box) is not intended to advocate for CO_2 emissions. Rather, it suggests that sources with incomplete combustion should clean up the combustion first, and then transition to a low-carbon pathway.

As this Committee has already acknowledged the potential importance of short-lived species by holding this hearing, emphasis on this point may be unnecessary. However, it should be clear that existing international agreements, and all current efforts on climate mitigation actions, are *not* evaluated with a comprehensive approach.

> *"If one is going to put carbon gases into the atmosphere, the least damaging from a global warming standpoint is CO_2; most [products of incomplete combustion] have a higher impact per carbon atom."*
>
> *-- Kirk R. Smith, Annual Reviews of Energy & the Environment [17]*

4. Black carbon reduction as a climate solution

4.1. There are preliminary measures to compare black carbon and CO_2

Because greenhouse gases and aerosols affect the climate system on different spatial and temporal scales, it is difficult to compare them in the same framework. However, we must invoke some basic measure of equivalence in order to evaluate whether addressing black carbon is cost-effective. One such measure is the amount of warming caused after

Table 1. Two studies demonstrate the need to consider total emissions in evaluating climate change

Source	*Conclusion from Greenhouse-gas forcing*	*Conclusion from total forcing*	*Citation*
Vehicles	Diesel vehicles produce less CO_2 than gasoline vehicles	Black carbon plus CO_2 emissions cause diesel vehicles to warm climate in the near term	Jacobson [15, 16]
Domestic cooking	Distilled fossil fuels (kerosene, LPG) release CO_2, while renewably harvested wood does not	Wood may cause more warming due to thermal inefficiency and products of incomplete combustion	Smith et al. [17]

one kilogram of the chemical species of interest is emitted. To compare chemical species with different lifetimes, the warming is integrated over a time frame of interest.[ii]

Estimates suggest that 1 kg of black carbon absorbs about **500-700 times** more energy in 100 years than 1 kg of CO_2 when only direct interaction with sunlight is considered [18, 19]. This range is lower than the global warming potential (GWP) in Dr. Jacobson's testimony. It includes *only* atmospheric forcing, for compatibility with the definition presented by the Intergovernmental Panel on Climate Change (IPCC, ref 20). Although our values differ because of the impacts considered, the major finding is not in question: **black carbon adds 2-3 orders of magnitude more energy to the climate system than an equivalent mass of CO_2.**

The time frame over which the warming impact is to be measured for the purpose of establishing 'equivalence' is of critical importance. Short-term impacts are naturally the highest for short-lived species such as black carbon: 1 kg of black carbon, emitted today, adds about **2000 times** as much energy to the Earth system over 20 years as 1 kg of carbon dioxide.

There are debates surrounding the validity of the comparison between long-lived gases like CO_2 and short-lived species like black carbon [21, 22, 23, 24, 25]. These will not be discussed here. Later, the comparison will be used only for a preliminary comparison of feasibility and cost-effectiveness. The recent synthesis by the IPCC [20] also presents integrated forcing for CO_2 and black carbon, providing some justification for this comparison.

Black carbon affects the climate system in many more ways than just direct interaction with sunlight. Changes in snow and ice albedo increase black carbon warming relative to CO_2 [26]. Changes such as cloud brightening (known as "the indirect effect") will decrease this relative warming [27]. The magnitudes of these changes are not well known. Efforts targeted toward estimating the incremental change in these both snow and clouds due to individual actions should be pursued.

4.2. Black carbon can be a short-term solution

Such a large warming may be hard to fathom. It occurs because black carbon is an extremely good absorber of visible light. Carbon dioxide stays in the atmosphere for decades, but it absorbs just a small amount of infrared radiation. One gram of black carbon in the atmosphere adds about 1800 watts to the Earth system as long as it is in the atmosphere [18]. That is about the amount of power consumed by eighteen bright light

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[ii] *Forcing* as commonly shown by IPCC is the rate of energy input. For an analogy, the rate at which a household uses electricity is similar to forcing. *Integrated forcing* is similar to an electric bill which totals all use over a specific period of time.

bulbs or a large barbecue grill. One gram of black carbon is emitted from about half a gallon of diesel fuel in a mid-1990s engine, or a lump of bituminous coal (if it is burned badly) that is the size of a large potato. Fortunately, black carbon is washed out of the atmosphere in a few days [28,29]. This large warming and rapid removal suggests the ability to make a difference quickly.

Both Hansen [30, 31] and Jacobson [32] suggested that black carbon emission reductions could form a viable component of reducing anthropogenic climate effects. This proposal has been taken up in other climate strategies [33], but always as part of a portfolio. It is generally recognized that black carbon cannot provide sufficient warming reduction to counteract CO_2 increases, and that greenhouse gases will dominate forcing by the end of the twenty-first century [34, 35]. However, addressing black carbon is a promising time-buying strategy to keep temperature increases below a critical value, or to take rapid action if sensitive systems are approaching a tipping point.

4.3. There is growing confidence that some sources warm climate

Despite the uncertainties, there is growing measurement evidence that some of the major sources (Figure 1) of black carbon contribute to warming. Carbon dioxide and ozone precursors cause warming. Thus, if the particles themselves contribute net warming, the total emissions from a source are most likely warming as well.

> *"Ramping up mitigation efforts quickly enough to avoid an increase of 2°C to 2.5°C… would require very rapid success in reducing emissions of CH_4 and black soot worldwide, and it would require that global CO_2 emissions level off by 2015 or 2020 at not much above their current amount…"*
>
> *-- Scientific Expert Group on Climate Change and Sustainable Development, 2007* [ref 33]

Measurements of absorption, scattering, and chemical composition from diesel engines [36, 37] and cookstoves [38, 39] show that these particles are strongly light-absorbing and therefore warming, despite the presence of non-absorbing aerosols. Organic carbon particles do not swell as much as sulfate in moist air [40], reducing their cooling potential. Organic carbon particles from solid-fuel burning also absorb a small amount of light [41, 42], making them less cooling or even warming.

Measurements also indicate that particles from open biomass burning [43] are either cooling or on the border between cooling and warming. There are no good "control technologies" for the prevention of open biomass burning; the interventions have to be adopted via changes in land use policies and the time to achieve the desired impacts can be quite long. Because of these uncertainty, this source—a large fraction of black carbon emissions— will not be considered in the analysis that follows.

5. Mitigation opportunities

Addressing black carbon appears to be a good idea. It results only from suboptimal combustion. It affects climate, visibility, and health negatively. It has the potential to reduce warming rapidly. However, as with greenhouse gases, cost is one of the main obstacles to action. This is no less true for black carbon than it is for carbon dioxide. Despite the fact that black carbon is unwanted, removing it is not free.

5.1. Only a few measures are cost-effective when climate alone is considered

The comparison between black carbon and carbon dioxide discussed above was necessary to discuss climate benefits on a CO_2-equivalent basis. Acceptable costs, if *only* climate benefits are considered, are typically a few dollars to a few tens of dollars per tonne of CO_2 equivalent.

Table 2 presents an estimate of climate benefit for several sources. Here, I will discuss only methods to eliminate *existing* black carbon emissions, since these actions will be required to reduce present-day climate impact. This cost assessment is quite preliminary. Because black carbon is fairly new on the climate stage, deep investigations of black carbon mitigation have not yet occurred, as they have for carbon dioxide. Thus, only the most readily available solutions are listed in the table.

Many of these sources appear inexpensive under a 20-year assessment, and only a few approach cost-effectiveness with 100-year values.[iii] Many of the least expensive mitigation actions are appropriate for developing countries. In accordance with Figure 3, countries undergo many of the least expensive aerosol reductions as they develop. As a country emits more CO_2, the remaining black carbon becomes harder to remove and more expensive. Thus, internal reductions of black carbon are unlikely to detract developed countries from reducing greenhouse gas emissions.

Table 2 supports both optimism and caution.

Optimism is fitting because the costs are close to worthwhile from a climate protection perspective. These costs are likely to decrease as solutions are explored. Furthermore, because each of these solutions will yield human health benefits by improving outdoor or indoor air quality, ancillary benefits may decrease the effective cost. There is a wealth of knowledge in both urban air quality management[iv] and in mitigation of indoor air pollution which should be tapped to suggest more robust solutions and more realistic cost estimates.

[iii] Note that these calculations assume no discounting of benefits. If any discounting is included, then the attractiveness of reducing short-lived species with high short-term warming impacts becomes much greater.

[iv] For example, the Clean Air Initiative for Asian Cities (“cai-asia”), http://www.cleanairnet.org/caiasia/

Table 2. Comparison of possible CO_2-equivalent reductions for eliminating all black carbon from several technologies, from ref 18.

emitting technology	**abatement technology**	**EF-BC (g/kg)**	**fuel (kg/yr)**	**lifetime (yr)**	**lifetime BC (kg)**	**equiv CO2 (t)**		**cost ($/t CO2 eq)**	
						100-yr	**20-yr**	**100-yr**	**20-yr**
diesel engines									
Current light vehicle	particle trap ($250-500)	0.9	1500	10	14	10	31	25-50	8-16
Superemitting light vehicle	repair ($500-1000+); vehicle turnover (several $k)	3	1500	5	23	15	50	30-130	10-40
Pre-regulation truck	particle trap ($5k-10k)	2	10000	10	200	140	440	36-71	11-23
residential solid fuel									
Wood cookstove	cleaner stoves, fuel switching ($3-100)	0.7	2000	3	4.2	2.9	9.2	1-34	0.3-11
Coal cookstove	same as wood stove	8	1000	3	24	16	53	0.2-6	0.1-2
other transport									
gasoline: 2-stroke engine	education, engine switching	1	300	5	1.5	1.1	3.3	not estimated	
industry & power									
coal: low-tech brick kiln	switch kiln type *	5	500000	1	2500	1750	5500	18-35	5.5-11

<u>*Caution*</u> is necessary because black carbon reductions may be much more difficult to achieve despite strong economic justification.[v] The two measures that appear most promising, reducing diesel emissions and improving cooking fuels, each deserve some additional caveats which I will discuss below. Both involve thousands or millions of small sources and operators whose ability to afford the relatively small, low-cost investments is limited.

5.2. Changing household energy use patterns is limited by access and financial resources

Cooking and heating with wood, coal and waste is often done in small stoves with no or limited pollution control. Users who are exposed to the smoke from indoor burning of solid fuels are at risk for acute and life-threatening respiratory infections [44, 45]. The apparent simplicity of the solutions to this challenge is deceptive.

Improved stoves. Improving wood cookstoves is one method of reducing radiative forcing. The lowest costs in Table 2 are associated with small, inexpensive improved stoves. However, the least expensive stoves presently do the least to reduce emissions. Quality cookstoves may cost $50 or more, instead of the $3 used for the lowest cost estimates in the table. Dissemination, uptake and persistence of the improved stoves have also proven difficult. Viable technology is only a prelude to clean combustion; programs must consider the wishes of the affected populations [46].Technical and marketing aspects of improved wood stoves are active areas of exploration. For example, improved cookstove programs in China have been successful [47], and both pilot and full-scale projects have been conducted by the Partnership for Clean Indoor Air and the Shell Foundation.

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[v] Furthermore, the trading community has no experience with 20-year time horizons; it is not clear that accepted prices for short-term reductions would remain identical to the long-term reductions contemplated today.

Cleaner fuels. Transition to cleaner fuels is a second method of reducing radiative forcing, even if these fuels are derived from fossil fuels [see 17]. Distillate fuels such as kerosene and LPG, or compacted solid fuels such as charcoal and densified briquettes often burn cleanly. To the users, they may represent convenience and a modern lifestyle, in addition to cleanliness. However, unprocessed wood is often perceived as "free", and marketed fuels such as LPG, kerosene or charcoal or even electricity are still affordable to only a small fraction of consumers in developing countries. Reducing adoption costs, and supporting the development of supply and service infrastructure may make these sources affordable.

5.3. There is a built-in lag in vehicle fleets

There are two major impediments to altering diesel emissions immediately: the heterogeneity and the longevity of the vehicle fleet. The costs in Table 2 reflect studies in industrialized countries, and simple, inexpensive maintenance procedures or training programs may reduce emissions when vehicle quality or maintenance is lower on average.

Heterogeneity. In the United States and Europe, regulations have a long history, and regulations for off-road vehicles will be implemented in the near future. When emissions are not uniformly high, a few vehicles may contribute a large fraction of the pollution. These high emitting vehicles or "superemitters," which may be difficult to locate, are also the place to target either clean up or replacement. Emission reductions and costs vary widely between vehicles, so that black carbon reductions range from economical to rather costly [48].

Longevity. While black carbon remains in the atmosphere for just a few days, a vehicle in use remains so for several years. Thus, there is a long-lived reservoir in the black carbon system, but it exists in the vehicle fleet, not in the atmosphere. Based on modeling done for ref [49], fleet-average emissions for normal vehicles lag the standard by about five years. Because stringent standards must be eased in, it is critical to implement regulations in developing countries as soon as possible, so that the cleanest possible vehicles are put into action during periods of rapid growth when the fleet is being developed.

6. Conclusions

- History indicates that black carbon emissions can and will be reduced as development occurs. However, this transition can be accelerated.
- Black carbon can make rapid contributions to reducing warming, and some of its major sources exert net warming despite the co-emission of cooling aerosols.
- In developed countries, mitigation options for black carbon are not always cost-effective compared to greenhouse gases. Black carbon is unlikely to detract from the need for greenhouse gas reductions.
- Some black carbon mitigation options can economically reduce warming. These actions also have significant health or air-quality benefits. However, implementing each has challenges.

Thank you for your consideration.

Acknowledgements

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