Chapter 7

Mitigation Overview: Designing Strategies for Public Health and Near-Term Climate Protection

7.1 Summary of Key Messages

- Existing particle control programs have been effective in reducing BC in many regions, particularly control programs affecting emissions from mobile and stationary sources.
  - While BC is not the *direct* target of existing programs, it has been reduced through controls aimed at reducing ambient $PM_{2.5}$ concentrations and/or direct particle emissions.
  - Past experience suggests that available control technologies and approaches can reduce BC emissions from many key source categories at reasonable cost. However, information is currently limited regarding the effectiveness of control strategies for reducing BC in a targeted fashion and the associated costs of those strategies.
- While global BC emissions are likely to decrease in the future, this trend will be dominated by emissions reductions in developed countries and may be overshadowed by emissions growth in key sectors (transportation, residential) in developing countries, depending on growth patterns.
  - Developed nations have already made significant progress in reducing BC emissions, and further reductions are expected to occur through 2030 with full implementation of existing regulations particularly in the transportation sector.
  - Emissions projections for developing countries are more variable, with studies indicating that emissions are likely to increase in some sectors and regions and decrease in others.
- Available control technologies can provide low-cost reductions in BC emissions from a number of key source categories. BC emissions reductions are generally achieved by applying technologies and strategies to improve combustion and/or control direct $PM_{2.5}$ emissions from sources.
  - Some of the strategies utilized by developed countries have also been undertaken in developing countries or could be adopted on a broader scale internationally. In other cases, developing countries have a different mix of sources and constraints that may require different types of control strategies.
- In selecting BC mitigation measures, policymakers must consider three overlapping goals: climate benefits, health benefits, and environmental benefits. In most cases, policymakers will seek to achieve multiple goals simultaneously; this requires taking into account a suite of impacts and attempting to maximize co-benefits and minimize tradeoffs across all objectives (health, climate, and environment).
- With a defined set of goals, policymakers can evaluate the "mitigation potential" within each country or region. The mitigation potential depends on total BC emissions and key emitting sectors, and also depends on the availability of control technologies or alternative mitigation strategies.
- Selection of ideal emissions reduction strategies will depend on a range of constraining factors, including:
  - Timing
  - Location
  - Atmospheric Transport
  - Co-emitted Pollutants
  - Cost
  - Existing Regulatory Programs
  - Implementation Barriers
  - Uncertainty
- Considering the location and timing of emissions and accounting for co-emissions will improve

the likelihood that mitigation strategies will be beneficial for both climate and public health.

- While all PM mitigation strategies that reduce human exposures will benefit health, strategies that focus on sources known to emit large amounts of BC—especially those with a high ratio of BC to OC, like diesel emissions—will also maximize climate benefits.

- The location and timing of the reductions are also very important. The largest climate benefits of BC-focused control strategies may come from reducing emissions affecting the Arctic, Himalayas and other ice and snow-covered regions. This would include BC emitted directly in those areas as well as BC transported into those areas from other areas.

- Cost is a prime consideration in both developed and developing countries, as is feasibility of implementation. Some physical and political constraints may hinder full implementation of even those strategies for which there is high confidence of large health and climate benefits.

- Optimizing climate, public health and environmental benefits requires a broad, multi-pollutant approach to BC mitigation that includes looking at the entire suite of options and evaluating them carefully to understand the full range of costs and benefits.

7.2 Introduction

As outlined in the previous chapter, reducing BC emissions has tremendous potential for improving global public health while achieving climate benefits. The optimal path forward will vary as decision-makers in each country weigh desired health and environmental outcomes, costs and benefits, and mitigation potential. This is a complex calculus that depends on a large number of considerations. This chapter presents a decision framework to help guide policymakers who want to develop BC mitigation strategies.

First, the chapter examines what is known about the overall impact of existing or planned control programs on emissions of BC and how current BC emissions are projected to change over the next several decades in response to these control programs and/or economic growth and development. Next, the chapter describes a decision framework, which includes both key factors to consider when developing a BC mitigation strategy and how different approaches for reducing BC emissions have potential to provide climate and public health benefits. The chapter concludes with several examples of how the decision framework could help guide mitigation choices. The chapter is followed by more detailed mitigation chapters covering four major emissions sectors—mobile sources; stationary sources (including both power generation and industry); residential heating and cooking; and open biomass burning. Chapters 8-11 describe projected changes in emissions in these sectors in the United States and globally, available control technologies and strategies and their associated costs, and implementation challenges. Chapter 12 provides a summary of how the mitigation options in these various sectors translate into near-term mitigation opportunities for BC to benefit climate and public health.

7.3 Effect of Existing Control Programs

Many existing control programs have been highly effective in reducing BC, however, it is important to note that BC is not the *direct* target of any currently existing emissions control program. Rather, BC has been reduced through control programs focused on reducing ambient $PM_{2.5}$ concentrations or direct particle emissions in general. As discussed throughout this report, BC is always co-emitted with other particles and gases. Therefore, determining the effect of various mitigation strategies on BC emissions requires an understanding of the entire emissions mixture coming from a given source and the extent to which the BC fraction is reduced by specific control technologies or strategies. Currently, there is only limited information about effective control strategies for reducing BC in a targeted fashion and the associated costs of those strategies.

In recent years, the overarching $PM_{2.5}$ control program for stationary sources in the United States and Europe has focused mainly on secondarily formed particles such as sulfates and nitrates, rather than on direct $PM_{2.5}$ emissions. This is because PM controls motivated by public health and environmental goals are focused on reducing total PM mass (a large portion of which is sulfates and nitrates formed in the ambient air from SO_x and NO_x) at least cost. PM controls oriented toward climate would have to consider the light absorbing and scattering properties of the various PM constituents.

Controls on direct $PM_{2.5}$ emissions do affect emissions of BC and other constituents such as OC. This is clear from the limited emissions testing data and the observational record that link declining BC concentrations to $PM_{2.5}$ control programs (see Chapters 4 and 5). However, the extent to which BC has been controlled as a component of an overall $PM_{2.5}$ mixture has depended somewhat arbitrarily on the proportion of BC in the emissions mix from a particular source category and the specific control strategy applied. Some strategies in some sectors (such as mobile source emissions standards for diesels) effectively reduce BC emissions as much or more than other constituents, while in other instances, BC reductions may be proportionally smaller. In addition to uncertainty regarding the composition of PM emissions from many sources, the relative effectiveness of a particular control technology for reducing specific constituents is often unknown, which means that for most sectors, it is not clear whether $PM_{2.5}$ controls will reduce BC preferentially or even proportionally to other constituents. Ongoing research will help to clarify this issue.

In general, available estimates of BC emissions reductions are calculated from analyses of $PM_{2.5}$ controls. As discussed in Chapter 4, EPA's trends report (2010i) shows that U.S. emissions of direct $PM_{2.5}$ have declined by 58% since 1990, a reduction of over 1.3 million tons. Over half of this reduction has come from controls on stationary fossil fuel combustion, with substantial reductions also occurring in emissions from industrial processes and mobile sources. Using speciation factors, it is possible to calculate BC reductions in these sectors, but these estimates are generally rough. Information on BC reductions is strongest for the mobile source sector, where the BC fraction of emissions and the impact of specific controls are well understood. As discussed in more detail in Chapter 8, mobile source BC emissions declined by approximately 32% between 1990 and 2005. For other sectors, precise, measured data about the effectiveness of specific controls for reducing BC emissions is often not available. As described in Chapter 5, however, recent ambient BC measurements do appear to indicate a decline in neighborhood/urban and regional scale concentrations of BC in the United States between the mid 1980s and the present (see section 5.4.1).

While control strategy information and cost data for BC mitigation approaches are generally limited, this varies by sector and location. Some of the best information is available for mobile source controls. Analyses conducted for recent regulatory actions in the United States provide a solid foundation for understanding applicable technologies and costs, and related implementation issues. For other sectors where less information is available, for example open biomass burning, better information on BC-specific control strategies, effectiveness and costs is needed. EPA has historically evaluated PM control strategies for specific sectors as part of the regulatory impact analyses for specific rulemakings. These analyses generally include best-available information on control options, effectiveness, and costs. Some of them include information on controls for specific PM constituents, but this rarely includes BC.

Despite what is known from analysis conducted in the United States, many of the strategies that have been applied domestically differ in important ways from control strategies that have been adopted internationally. Some of the strategies utilized by developed countries have also been undertaken in developing countries or could be adopted on a broader scale internationally. In other cases, developing countries have a different mix of sources and other relevant constraints that will require different types of control strategies. These issues are discussed further in the sections that follow, and in the conclusion to this chapter.

7.4 Future Black Carbon Emissions

The influence of BC on climate and public health in the future, and the need to more precisely determine the effectiveness of various mitigation strategies for reducing BC, depends in large part on the magnitude of future emissions. This section describes what is known regarding these future emissions, but available estimates are variable and uncertainty about future emissions trajectories remains high.

Developed nations have already made significant progress in reducing direct PM emissions, and further reductions are expected to occur through 2030 with full implementation of existing regulations. In particular, substantial BC reductions have been achieved through controls in the mobile source sector (particularly diesels), and additional reductions will continue to be realized over the next two decades. In the case of stationary sources, the most substantial BC emissions reductions in the United States and other developed countries were achieved decades ago (often through fuel switching away from coal).

Recent studies (Streets et al., 2004; Cofala et al., 2007; Jacobson and Streets, 2009; Rypdal et al., 2009) provide a snapshot of potential future BC emissions trends. These studies have produced a range of estimates for future BC emissions depending on assumptions about economic growth, population levels, and development pathways. In an analysis of future BC emissions trends based

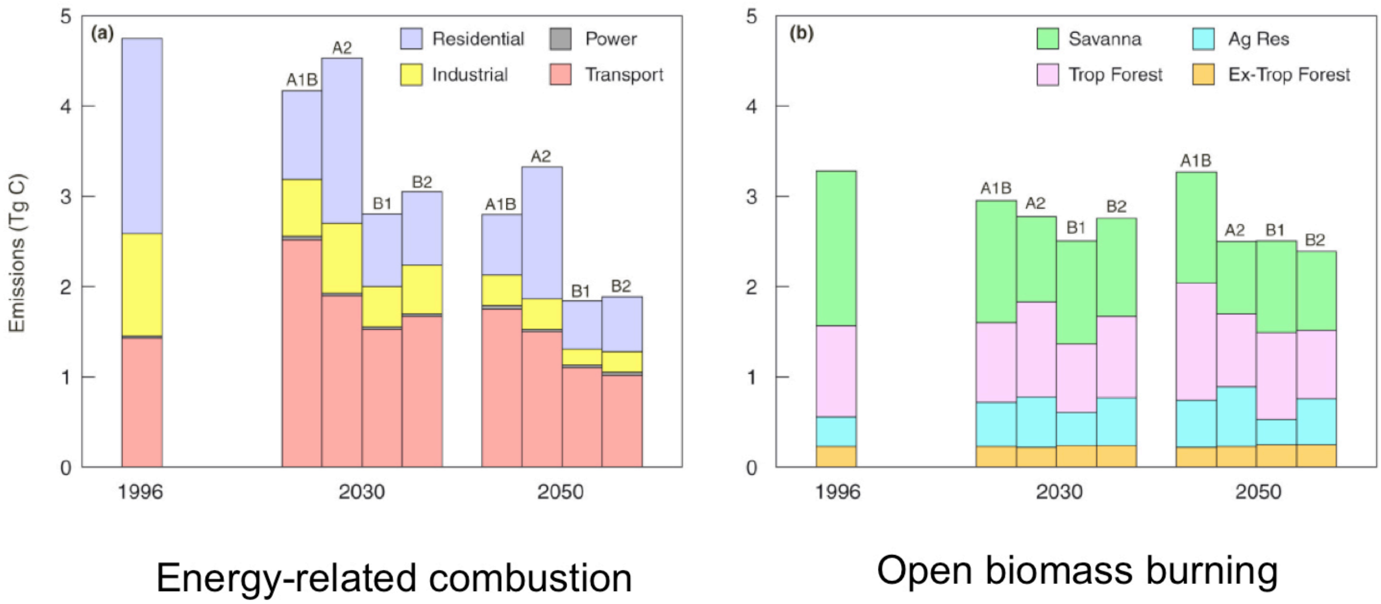

Figure 7-1. Global BC Emissions Forecasts for Various Sectors under Alternative IPCC SRES Scenarios (in teragrams (Tg) of carbon). Scenarios generally show a modest decrease in BC emissions from all sectors as compared to 1996 baseline emissions. (Streets et al., 2004)

on the IPCC SRES scenarios, Streets et al. (2004) projected BC emissions to decrease globally by 9% to 34% by 2030 relative to 1996 levels depending on assumptions about economic growth and development. However, there was considerable variation among projections for the different sectors depending on the SRES scenario examined (Figure 7-1). Thus, while aggregate emissions were generally projected to decline under alternative growth scenarios, emissions growth was projected for certain sectors or regions. The sectors where Streets et al. (2004) indicate a potential for future emissions growth include residential emissions in Africa, open biomass burning emissions in South America, and transportation emissions in the developing world (for example, where fuel sulfur levels are still too high for implementation of DPFs—see Chapter 8 and Appendix 3). In general, industrial emissions and transport emissions were projected to decline in developed countries.

An analysis by Jacobson and Streets (2009) found that under the assumptions embedded in the A1B scenario for IPCC, total global BC emissions may increase substantially. Again however, this analysis indicates that projected emissions growth or decline varies significantly among regions and sectors, as Figure 7-2 illustrates. In general, BC emissions in developed countries are projected to decline, while emissions in developing countries may grow. Transportation (mobile source) emissions in particular are projected to grow in several world regions but decline in others, as illustrated by growth factors greater than or less than one, respectively (Jacobson and Streets, 2009). In developed countries, the majority of the emissions reductions in the transportation sector are projected to result from implementation of 2007 U.S. on-highway diesel engine standards and similar standards, such as Euro V, that lead to the use of diesel particulate filters (DPFs) in the diesel fleet. Also, in the United States, other standards for diesels (nonroad diesels, locomotives, and commercial marine) contribute to these reductions. However, other studies have indicated that emissions from shipping in the Arctic region may increase due to the retreat of Arctic sea ice, opening up new shipping routes and increased economic activity in that region (Corbett et al., 2010).

In its most recent work, the IPCC has also developed four "Representative Concentration Pathways" for use as a consistent set of emissions inputs for projecting future climate change. These four pathways (Figure 7-3) are defined by the total radiative forcing resulting from each pathway in 2100, including GHGs and other forcing agents, which ranges from 2.6 to 8.5 W m^{-2}. Global BC emissions in all four pathways peak in 2005 or 2010, are 8 to 20% below 2010 levels by 2030, and continue decreasing for the rest of the century to about half of 2010 levels. Emissions for the

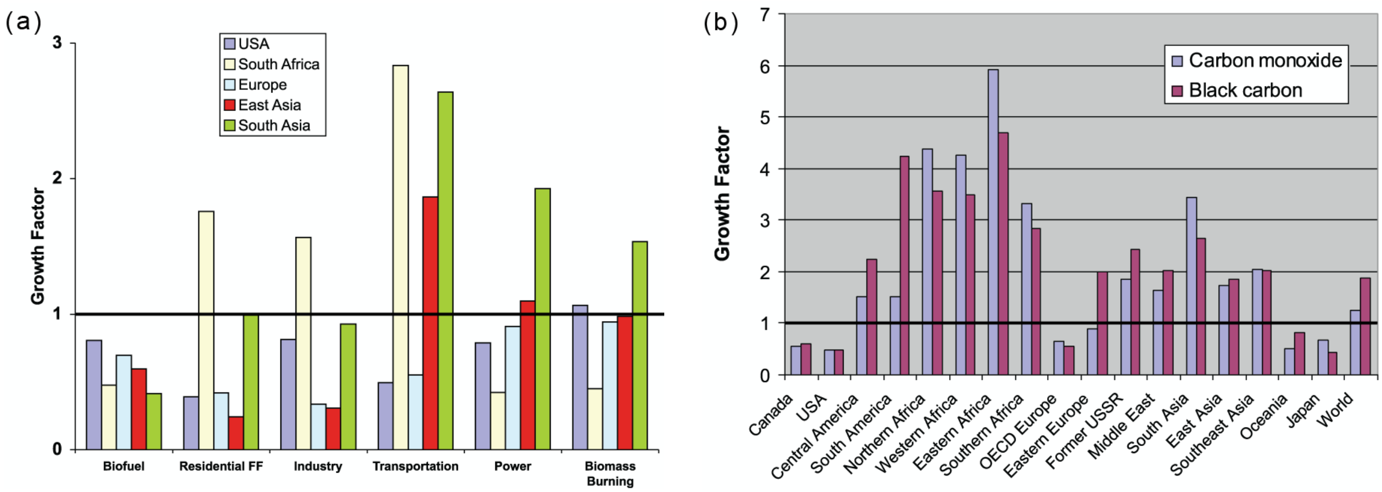

Figure 7-2. Black Carbon Emissions Growth, 2000-2030 under IPCC A1B Scenario. Top: 2000-2030 Black Carbon Emissions Growth Factors by Sector for Selected World Regions (from IPCC A1B scenario). Bottom: 2000-2030 Black Carbon and Carbon Monoxide Emissions Growth Factors for Transportation (Mobile) Sector in Specific Regions. Emissions in sectors with a growth factor less than one (see dark line, added) will decline. (Source: Jacobson and Streets, 2009)

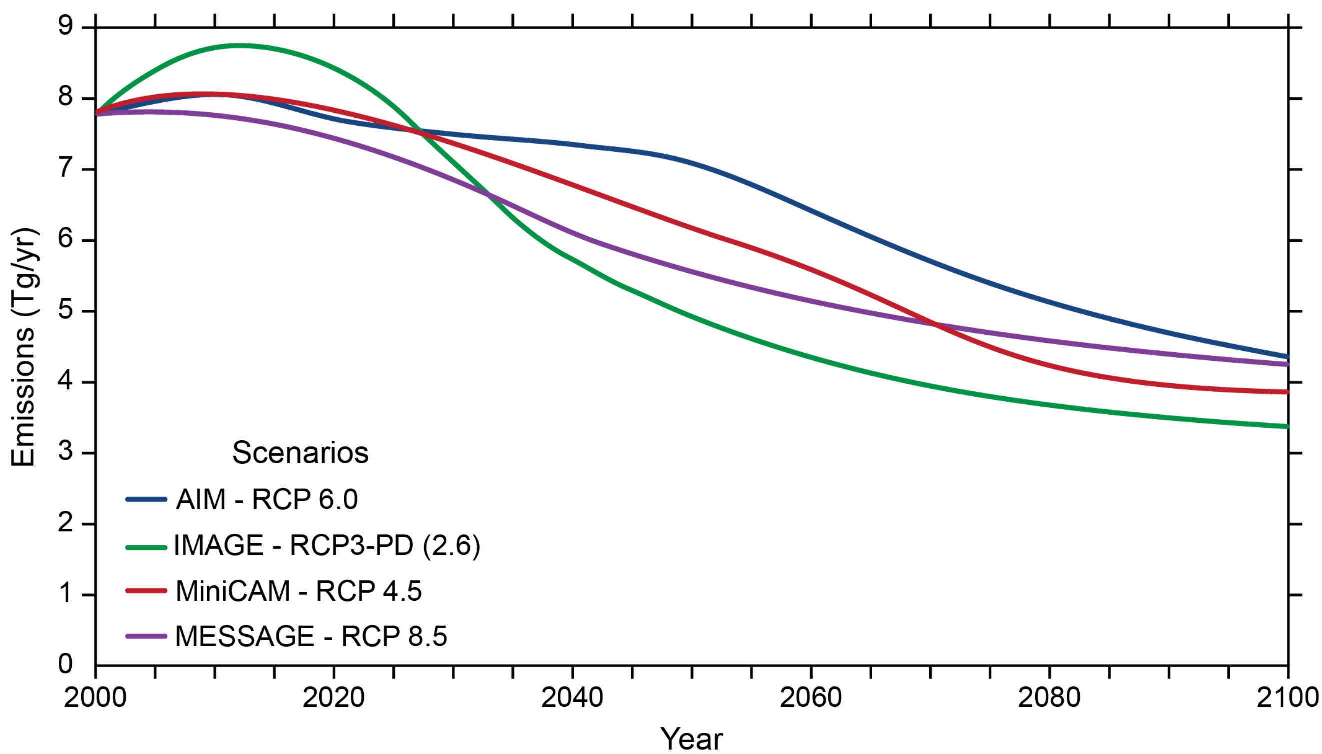

Figure 7-3. Future Emissions of BC under IPCC Representative Concentration Pathways, 2000-2050 (Gg/year).

Notes:

1. RCP2.6 (RCP 3-PD) – van Vuuren et al., (2007)
2. RCP 4.5 – Clarke et al. (2007); Smith and Wigley (2006); and Wise et al. (2009)
3. RCP 6.0 – Fujino et al. (2006); and Hijioka et al. (2008)
4. RCP 8.5 – Riahi et al. (2007)

RCP pathways are reported in combinations of five regions and four sectors on the website[1] (though the underlying, gridded dataset is further disaggregated).

Consistent with the findings of the academic studies, under certain pathways there are a few region and sector combinations whose BC emissions do not peak until 2020 or 2030. Two out of the four RCP pathways show near-term increases in BC emissions from all sectors in Asia, the Middle East, and Africa, and for all regions some of the pathways show increases in open burning emissions (from both deforestation and agricultural burning). Because of the potential for increases in open burning, OC emissions are not projected to decline as quickly as BC emissions.

BC emissions in the United States are projected to decline, driven largely by reductions in mobile diesel emissions, as discussed in detail in Chapter 8. The limited EPA modeling inventories that project emissions into the future (year 2020) indicate that direct $PM_{2.5}$ emissions from industrial sources are not expected to decline significantly in the next decade, and emissions from fossil fuel combustion will only decline about 20% by 2020 (U.S. EPA, 2006c). Because of the small size of anticipated reductions in direct $PM_{2.5}$ emissions from these categories, projected BC emissions changes are also small and unlikely to affect the U.S. BC emissions trend in the future in the absence of additional control requirements. Open biomass burning, the second largest source category in the United States, exhibits significant year-to-year variability in emissions, and it is difficult to predict future year emissions. However, it should be noted that emissions in this category may grow significantly in the future if climate change results in increased wildfires, as predicted in many scenarios (Wiedinmyer and Hurteau, 2010).

Projected future emissions reductions may not occur in the United States or elsewhere in the absence of continued policies to encourage adoption of DPFs in the mobile sector, continued economic development leading to a more rapid shift away from traditional cookstoves than is currently predicted, and other environmental and economic developments. As noted, there are also several sectors and regions, such as transport emissions in developing nations and open biomass burning emissions globally, for which emissions are not projected to peak for another decade or two. Given the array of available control technologies and strategies, as outlined in the next several chapters of this report, it is possible to make larger and more rapid reductions in BC emissions globally than current baseline estimates project.

Some countries have already begun looking at these possibilities. For example, the Arctic Council countries (Canada, Denmark, Finland, Iceland, Norway, Russia, Sweden, and the United States) formed a special Task Force on Short-Lived Climate Forcers in 2009 to consider whether additional or accelerated mitigation strategies may be needed to address warming in the Arctic region. Noting that emissions in the Arctic region from sources other than land-based transport—particularly residential heating, agricultural and forest burning, and marine shipping—will likely remain the same or increase without new measures, the Task Force has recommended that "Arctic Council nations individually and collectively work to implement some early actions to reduce black carbon" (Arctic Council Task Force on Short-Lived Climate Forcers, 2011, p. 5). A new Project Steering Group (PSG) under the Arctic Council's Arctic Contaminants Action Programme (ACAP) is currently investigating which measures would be implemented, and the impact of such measures on total BC emissions from Arctic Council nations. The PSG has identified a number of key sources affecting the Arctic and is developing pilot programs to advance BC emissions reduction efforts, particularly in the Russian far north.

7.5 Key Factors to Consider in Pursuing BC Emissions Reductions

Significant reductions in BC emissions are expected to occur in certain regions in the coming decades; however, these reductions will be gradual, and even after they are fully realized, substantial BC emissions will remain in some sectors and regions. There is a core set of factors that policymakers can consider to improve the likelihood that selected mitigation strategies will achieve substantial public health and environmental benefits and reduce the rate of near-term warming. Policymakers can examine the challenge of BC mitigation from the perspective of three different (but overlapping) goals: climate benefits, health benefits, and environmental benefits. With a defined set of goals, policymakers can evaluate the "mitigation potential" within each country or region. The mitigation potential depends on total BC emissions and key emitting sectors, and also depends on the availability of control technologies or alternative mitigation strategies, such as fuel switching, improvements in energy efficiency, or changes in land-use patterns. The ideal emissions reduction strategies will also depend on a

[1] *http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=welcome#*

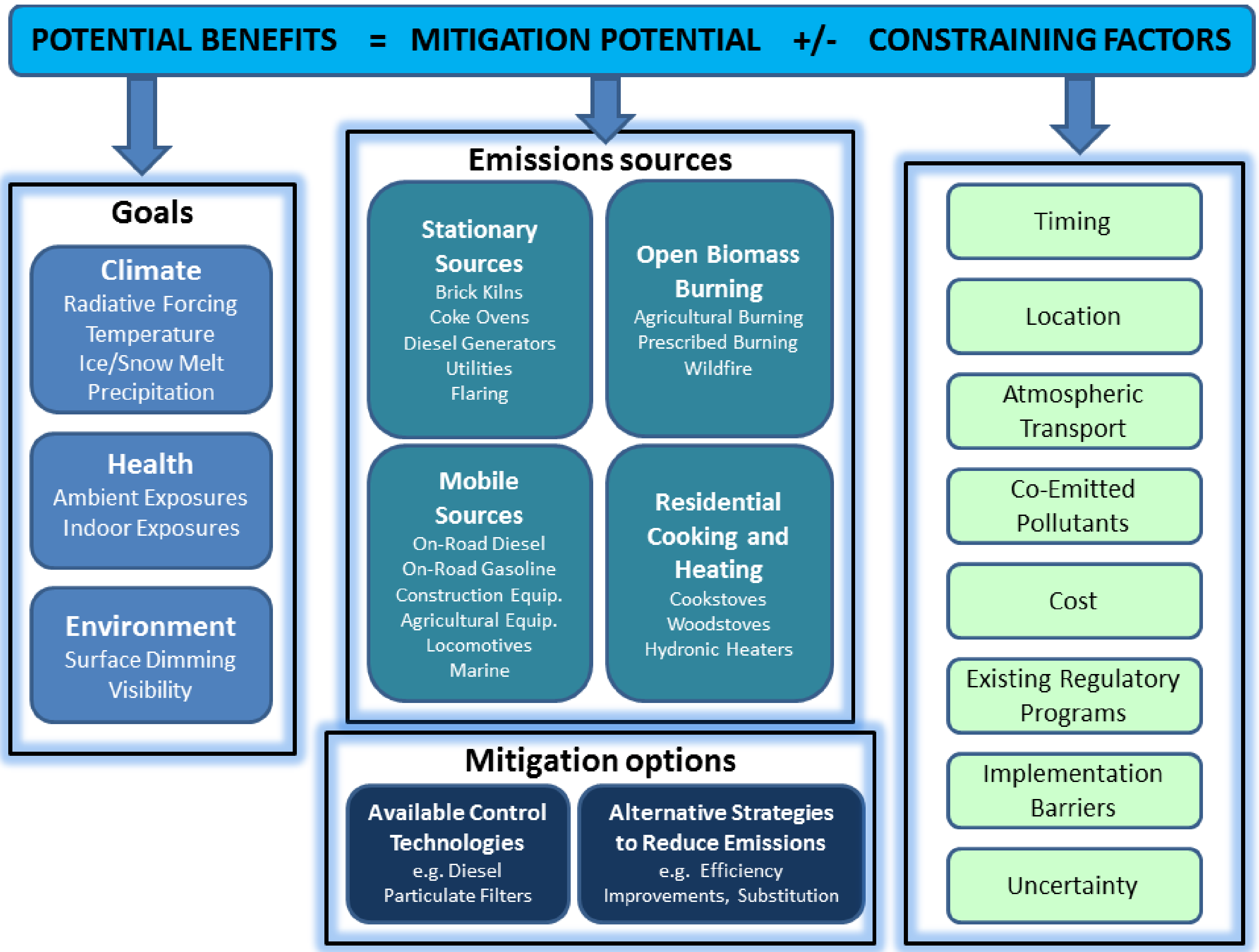

Figure 7-4. Policy Framework for Black Carbon Mitigation Decisions. (Source: U.S. EPA)

range of constraining factors, such as cost, location, and co-emitted pollutants. This decision-making framework is illustrated in Figure 7-4. Each of the key factors policymakers must consider is discussed further below.

7.5.1 Defining Goals: Climate, Health and Environmental Outcomes

Reducing BC emissions offers a win-win opportunity with the potential to achieve benefits for climate, public health and the environment simultaneously. The preferred mitigation strategies could differ depending on the main policy goal. Policymakers focused primarily on climate objectives might choose different mitigation approaches than policymakers who are interested in maximizing public health benefits or protecting visibility. BC plays an important role in all of these effects, but achieving different goals might require different mitigation strategies oriented toward different sources in different locations. In most cases, policymakers will be seeking to achieve multiple goals at the same time; thus, preferred strategies will likely take into account a suite of impacts and decision-makers will attempt to maximize climate, health and environmental benefits and minimize tradeoffs across all objectives. However, it is important for policymakers to be clear about what the goals are, and to prioritize among them when tradeoffs are involved.

Often, policymakers will be considering BC reductions as merely one part of a broader PM mitigation agenda, and decisions will be driven first by health considerations. This is consistent with the mitigation pathway in developed countries, where the primary goal has been improving public health, and the secondary goal has been reducing non-climate environmental effects of PM (such as acid deposition and visibility impairment). PM mitigation programs in most countries have not given direct consideration to climate benefits. Policies have generally focused on reducing emissions of secondary PM precursors (SO_2 and NO_x) as the most cost-effective strategy for those health benefits. While enormously successful for public health, strategies that reduce SO_2 and NO_x emissions to control secondarily formed PM are not expected to result in substantial decreases in BC emissions. Moving forward, as climate becomes an additional consideration, SO_2 and NO_x reductions should be accompanied by corresponding reductions in BC. The practical result would be additional policies that more actively target sources of direct PM emissions. This would ensure that ongoing reductions in SO_2 and NO_x emissions, which are critical to achieving public health and non-climate environmental goals, are complemented and enhanced by BC emissions reductions for climate.

Even within a specific category (climate, health, environment), there are multiple sub-goals to be considered. While related, these different objectives may require different strategies and approaches. For example, BC reductions could provide climate benefits in the form of reduced radiative forcing and temperature, but could also be aimed at reducing precipitation impacts and the melting of ice and snow. The optimal control strategy will depend on the impact(s) of concern. Scientific evidence discussed in Chapter 2 suggests that direct radiative forcing and temperature increase are driven largely by BC emissions, offset by emissions of other aerosols. Reducing these impacts, therefore, may require strategies that preferentially reduce BC relative to cooling species. On the other hand, a broader variety of aerosols (including nitrates, sulfates, OC) are contributing to snow/ice albedo effects, ABCs, and precipitation effects, so to reduce these impacts, a wider variety of $PM_{2.5}$ reduction strategies may be beneficial. For health, policymakers are interested in both indoor and outdoor exposures and risks. However, reducing indoor exposures to $PM_{2.5}$ (including BC) often requires different strategies than reducing ambient $PM_{2.5}$ concentrations. Identifying clearly which set of impacts the mitigation action is designed to reduce is critical for selecting appropriate measures.

Because of the nested nature of the climate, public health and environmental goals driving policy decisions about BC mitigation, cost-benefit analysis conducted to support mitigation decisions should incorporate public health and welfare benefits as well as climate benefits. Such analysis can fully inform decision makers regarding available choices, but can also be complicated by uncertainties in valuing the climate impacts. This is particularly true for other environmental outcomes, such as for visibility and impacts on agriculture. The impact of BC on these outcomes is less well understood, and therefore there is less known quantitatively about expected benefits of BC reductions. Nevertheless, as discussed in Chapter 6, public health benefits of many BC reduction strategies may be large enough to justify the costs, regardless of the climate impacts.

7.5.2 Identifying Opportunities for Emissions Reductions

Designing BC mitigation programs requires policymakers to carefully evaluate both the total BC emissions inventory in a specific region or country, and the contribution of specific sectors to that total. As discussed in detail in Chapter 4 and mentioned earlier in this chapter, BC emissions—and therefore BC mitigation potential—vary widely by region. In some countries, aggressive programs to reduce PM emissions mean that the remaining emissions are limited, making further reductions more difficult and expensive to achieve. Nevertheless, virtually every country, including the United States, still has substantial BC emissions remaining across a number of source categories, meaning that further BC reductions are possible. For example, while U.S. BC emissions are expected to drop considerably by 2030 due to controls on new mobile diesel engines (see Chapter 8), significant emissions remain from the existing fleet of diesel vehicles. Achieving additional reductions from mobile diesel engines is currently possible through EPA's National Clean Diesel Campaign and SmartWay Transport Partnership Program. However, funding would be required in order to address a majority of the legacy fleet of existing vehicles. Furthermore, as discussed in Section 7.4, several recent studies identify regions and emissions source categories in which BC emissions are likely to increase over time. These sectors represent important potential mitigation opportunities, even though total emissions from some of them may not be large at present.

Careful investments in emissions inventories and emissions measurements can greatly improve policymakers' ability to identify key emitting sectors and sources. This includes evaluating current emissions and anticipated future BC emissions in terms of both specific facilities (how many? where?) and control technologies already in place. Having a clear understanding of exactly where potential emissions reductions could be achieved based on current sources and technologies opens the door for practical conversations about specific avenues and means for achieving those reductions. This includes considering both:

- **Availability of control technologies:** As individual countries examine the options for reducing BC to improve air quality and benefit the climate, they must consider the availability of control technologies that are effective for BC mitigation. Technologies to reduce PM and co-pollutant BC emissions are in widespread use globally, as are technologies that reduce PM and co-pollutants more broadly.

- **Alternative mitigation strategies:** Even when conventional control technologies are ineffective or costly, other strategies may be available to reduce BC emissions. In some cases, BC reductions may be achieved not through end-of-pipe controls (such as particle filters) but through substitution of new, cleaner technologies (such as improved cookstoves and brick kilns) or more efficient combustion practices that substantially alter the emissions stream. Changes in land-use patterns or greater reliance on alternative forms of energy can also result in BC reductions.

Previous chapters have covered in detail what is known regarding emissions sources from the United States and across the globe. The following chapters will go into greater detail regarding specific technologies and strategies available to control BC emissions from the main contributing sectors. Appropriate mitigation choices for individual countries will vary based on scientific variables and policy drivers.

7.5.3 Key Considerations

Even with clearly defined goals and carefully constructed emissions inventories, there are a number of other factors for policymakers to consider that are critically important for mitigation decisions. These include:

- **Timing:** Seasonal timing of emissions reductions is important. As discussed in Chapter 2, the effects of BC in snow- and ice-covered regions are accentuated during times of increased sun exposure. Policies designed to reduce BC impacts on the Arctic, therefore, might need to consider the seasonality of emissions. For example, impacts of open biomass burning on the Arctic spring melt could be influenced by adjusting the timing of agricultural burning. Similarly, the benefits of emissions controls for the Indian Monsoon will depend on the timing of controls relatively to seasonal weather patterns.

- **Location:** Considering the location of emissions is also important when seeking mitigation strategies that will be beneficial for both climate and public health. Because BC is a regional rather than global pollutant, it is important to evaluate the benefits of emissions reductions in terms of specific regional impacts, factoring in source region, emissions transport, and receptor region conditions. For climate, impacts on snow- and ice-covered regions such as the Arctic are of particular concern, as are impacts in regions where the precipitation patterns are heavily impacted by all aerosol emissions, such as India. Location matters for human health benefits too, with proximity of emissions reductions to areas of large population being a prime consideration. In general, the largest human health benefits from BC-focused control strategies occur near emissions sources, where exposure affects a large population. Despite the historical focus on secondary PM for public health, many of the BC sources ripe for mitigation are in large urban areas. These sources of direct PM, from the transportation, residential and industrial sectors, are tied to everyday human activities. This means that the benefit of reducing BC emissions for the health of the people living nearby is expected to be very high.

- **Emissions Transport:** The net impacts of emissions from any specific source will depend partly on atmospheric fate and transport. Meteorological conditions, plume height and other factors will affect the extent to which emissions from particular sources in particular locations affect climate, health and environmental endpoints of interest. Identifying how reductions in emissions from specific sources translate into climate, health and environmental responses in receptor regions requires sophisticated models that can account for myriad chemical and physical processes, as well as climate responses.

- **Co-emitted pollutants:** Maximizing benefits across different goals requires explicitly accounting for co-emitted pollutants. Depending on the goal, reductions in some species may be more valuable than reductions in others. The largest benefits in terms of direct forcing would come from two types of strategies: first, strategies that reduce BC more than emissions of other (cooling) PM constituents like SO_2, NO_x and/or OC; and second, strategies that reduce BC in conjunction with reductions in other GHGs like CO_2 and CH_4. The first approach would include strategies such as controls on mobile diesel engines (see Chapter 8), while the second approach would include strategies

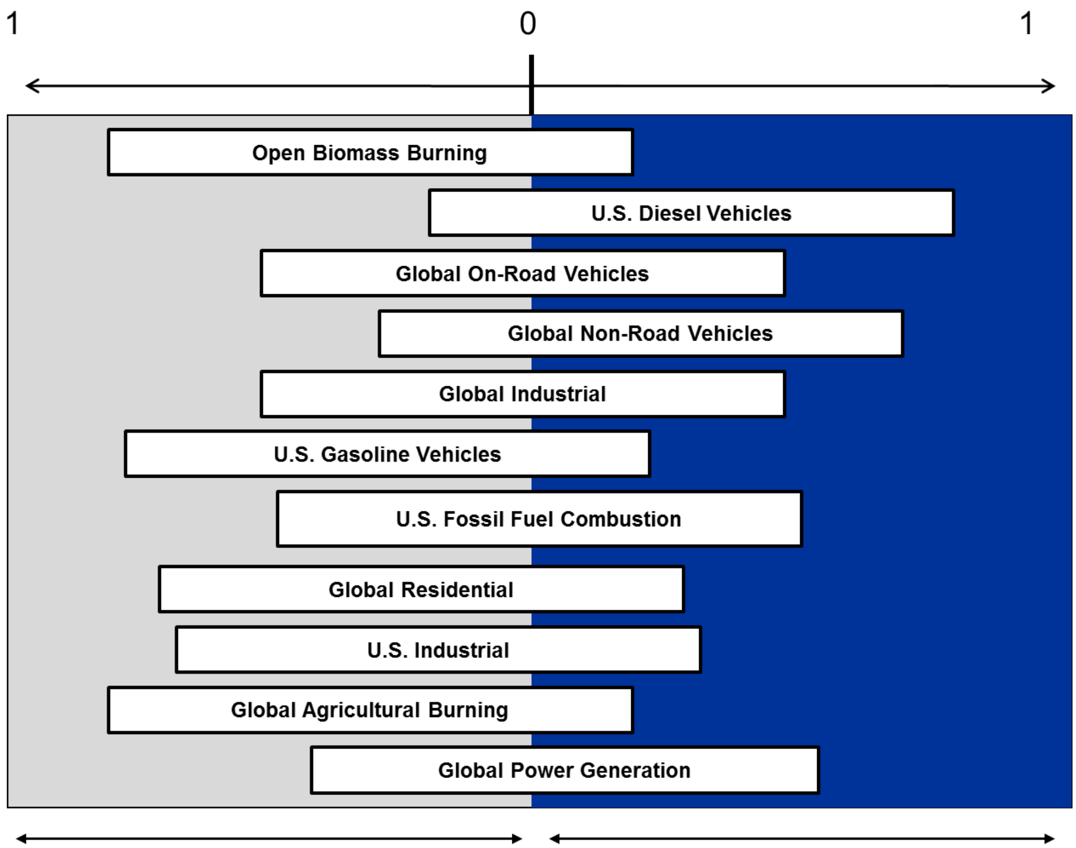

Figure 7-5. OC (left) and BC (right) Emissions from Key U.S. and Global Emissions Source Categories, Expressed as a Fraction of Total Carbon (OC + BC) Emissions from that Category. (Source: U.S. EPA)

such as improvements in combustion and fuel efficiency in residential cookstoves, use of prepared fuels (briquettes or pellets), or a shift to clean cooking fuels (see Chapter 10). For both types of strategies, optimizing control opportunities requires careful analysis of the full emissions stream. When all climate effects (i.e., effects beyond direct forcing) are considered, and particularly when health and environmental benefits are added to the equation, the relative importance of various co-pollutants changes. For reducing direct forcing, mitigation strategies might focus on reducing BC preferentially. If the focus shifts to health impacts or precipitation effects, other aerosol species become equally important and total $PM_{2.5}$ reductions are likely to be preferred over BC-focused strategies.

It is very difficult to establish short-hand approaches for estimating the impacts of specific sources based on their chemical emissions profile. In a number of studies, the OC/BC ratio[2] has been used to rank the net warming potential of individual source categories, based on an assumption that OC will primarily reflect light and thereby induce a negative radiative forcing (cooling) effect in the atmosphere, and that BC will primarily absorb light and induce a positive forcing (warming) effect. Figure 7-5 illustrates the variation in emissions profiles among sources by comparing relative OC/BC ratios. Emission sources with low OC/BC ratios are generally thought to have the largest potential to warm the climate, though there is no agreement within the scientific literature about how to interpret specific ratios. Bond et al. (2011) found that for direct forcing only, a ratio of about 15:1 for OC to BC is close to climate neutral; however, this does not include cloud indirect effects or co-emissions of substances other than OC. Bond et al. also find that the neutral ratio varies substantially depending on where the emissions occur.

[2] The most commonly used ratio is OC:BC or OC/BC, but other ratios include OC/EC, and OM/BC, where OM represents the total mass of organic matter. Chapter 4 of this report provides OC/BC and $BC/PM_{2.5}$ ratios for a number of source categories.

Several factors limit the value of the OC/BC ratio as a short-hand for estimating the climate forcing impact of a combustion source. Assuming that all particle OC (including BrC) is scattering, regardless of location, may underestimate the positive forcing (warming) impact of a given source. Also, the OC/BC ratio ignores other climate-relevant pollutants. Sulfates, nitrates and secondary organic aerosols (SOA) or their precursors, sulfur dioxide (SO_2), NO_x, and VOCs, form additional light-scattering material within the plume. Ramana et al. (2010) note that the extent of BC-induced warming depends on the concentration of both sulfate and OC. Further, the aging process described in Chapter 2 induces optical changes in an emitted particle mixture, including coating of BC particles, leading to enhanced light absorption (Lack and Cappa, 2010). These effects are not captured by an OC/BC ratio. Finally, many analyses that employ OC/BC thresholds for "net warming effects" do not take into account other effects, such as effects on precipitation and all the indirect effects related to particle-induced changes in clouds.

Despite the many limitations of OC/BC ratios, they provide a simple way to evaluate potential climate benefits and therefore continue to be used to prioritize mitigation options. For the reasons stated above, these ratios should serve only as a approximate indicator of potential radiative effects of categories of emissions sources. The specific circumstances or policy goals should override generic OC/BC rankings in cases where, for example, emissions are affecting the Arctic, since even mixtures that contain more reflective aerosols can lead to warming over such light-colored surfaces. In addition, OC/BC ratios are irrelevant to effects that are shared among BC and other aerosols. This includes precipitation or dimming effects, and impacts on public health. For these types of effects, mitigation strategies that reduce direct $PM_{2.5}$ emissions or overall ambient $PM_{2.5}$ concentrations will provide the largest benefits, and the ratio of BC to other constituents is far less important.

- **Cost:** Cost is a prime consideration in both developed and developing countries. Regardless of whether control technologies or alternative strategies to reduce pollution are available, policymakers are only likely to pursue such approaches if the costs are limited and/or clearly outweighed by the benefits of mitigation. For some sectors and locations, BC control costs are low in comparison to the public health benefits that can be achieved (the most easily quantified stream of benefits). However, control costs can vary significantly depending on the technologies being considered, and in many cases, particularly in developing countries, there is a lack of information about costs of BC control.

- **Existing Regulatory Programs:** Countries with existing regulatory programs and statutory mandates may face legal constraints in terms of the types of emissions reductions they can pursue. There may also be technological barriers and phase-in schedules that need to be considered. For example, regulations that require application of specific control technologies or approaches may dictate the extent of emissions reductions achieved. Many regulations are phased in or become effective over an extended time period. Controls on new mobile diesel engines, for example, only reduce BC emissions as new vehicles and engines are purchased and deployed to replace older models. Policymakers must work within existing regulatory constraints in selecting mitigation initiatives.

- **Implementation Barriers:** As policymakers look across the range of available emissions reductions, the other key factor to consider is feasibility of implementation. This is perhaps the most important consideration, because there are some constraints that simply cannot be overcome. Many examples exist for how physical and political constraints hinder full implementation of even those strategies for which there is high confidence of large benefits. Replacement of the 500-800 million traditional solid-fuel burning cookstoves in developing countries has been the subject of numerous public and private campaigns, with one notable large-scale success (China) and many cases of limited success (Sinton et al., 2004). Only recently has progress begun to accelerate, as illustrated by the rapid growth in stove sales tracked by the Partnership for Clean Indoor Air (see Chapter 10) and the emergence of the Global Alliance for Clean Cookstoves. The historically slow progress on this issue is attributable, in part, to the scale of the problem and the difficulty of implementing replacement programs in diverse local environments.

  Some studies have suggested altering the timing of agricultural burning in the United States to avoid transport to the Arctic during the spring melt season (CATF, 2009a). However, the seasonally dependent cycles of planting, harvesting and pest-control (among other considerations) make this a difficult strategy to implement. Also, for stringent PM standards for new vehicles, nonroad diesels, locomotives, and commercial marine (other than ocean going vessels), ultra low sulfur diesel fuel is required to enable use of diesel particulate filters. Many countries already have regulations requiring such fuels. As another example, there is near universal agreement that retrofitting the existing diesel fleet across the globe would reap tremendous public health and climate benefits; however, this kind of program would be very expensive. Cultural practices also come into play. Residential heating in the Arctic region has recently been identified as a key contributor to BC impacts in the Arctic. Nevertheless, both the rising cost of fossil fuel in relation to wood and the cultural connection to in-home wood heating makes a widespread transition to pellet stoves (a recommendation from the UNEP/WMO report) problematic.

- **Uncertainty:** In cases where there is a high degree of uncertainty, policymakers may hesitate to take mitigation actions. For example, if the emissions mixture from particular sources is not well characterized, or if the effectiveness of control strategies is not well understood, the benefits of pursuing reductions may be questioned by decision-makers. This is particularly true if the health and environmental co-benefits of a strategy are limited, or if costs are high. Under these circumstances, policymakers may choose to postpone BC mitigation actions, or limit those actions to a narrower set of controls with more clearly defined costs and benefits.

All of these factors affect which mitigation options are most desirable under different circumstances. Clearly, the complexity of the decision-making calculus requires the balancing of multiple considerations simultaneously. In some cases, these considerations may involve tradeoffs, and policymakers will have to evaluate which options are best given competing goals and considerations. The following section illustrates how the different factors in the decision-making framework can affect which options are preferable under different circumstances.

7.6 Applying the Mitigation Framework

To craft policy that addresses remaining BC emissions, as well as anticipated increases in BC emissions in some sectors and regions, policymakers are faced with a complex set of considerations and potentially competing goals. Optimizing climate and public health benefits requires a broad, multi-pollutant approach to BC mitigation that includes looking at the entire suite of options and evaluating them carefully to understand the full range of possible benefits. Currently, most countries implement a pollutant-by-pollutant approach to air quality management, looking at each pollutant in isolation and developing strategies targeting each one. Though successful in many respects, this approach may not result in the most effective or efficient strategies for achieving multiple objectives. As a result, many countries are moving toward a multi-pollutant approach, where strategies incorporate many pollutants by sector or by region. However, most have yet to incorporate climate pollutants and benefits into those strategies.

A recent case study of Detroit, Michigan conducted by EPA explored how costs and benefits would change if such a multi-pollutant framework was designed (Wesson et al., 2010). This case study compared a traditional pollutant-by-pollutant strategy (status quo) with one that sought to maximize emissions reductions and risk reduction for ozone, PM and selected air toxics (multi-pollutant, risk-based). The study found that the multi-pollutant, risk-based strategy produced over twice the monetized benefits of the status quo. Though the multi-pollutant, risk-based strategy cost slightly more, it resulted in a much more favorable benefit/cost ratio. This result was due, in part, to a shift from reductions in secondary PM to a strategy that achieved greater reductions in primary PM, particularly in emissions from sources affecting vulnerable and susceptible populations. This is exactly the kind of shift in strategy that could achieve BC benefits. This suggests that multi-pollutant assessment can produce more cost-effective strategies, and that targeting primary PM emissions (with BC benefits) can have large health benefits, especially in urban areas.

Policymakers facing choices among different BC mitigation options can apply the 3-step framework described above (defining goals, identifying emissions reduction potential, and weighing key factors) to evaluate the pros and cons of different options and to identify the options that best maximize co-benefits. In many cases, the most desirable mitigation approaches will be determined by the primary goal (or goals) combined with constraints on resources, technologies, or anticipated impacts. Several examples can help illustrate how the factors in the framework affect the attractiveness of different mitigation options.

In the United States, BC is managed as part of the larger PM mitigation program designed to achieve a suite of health and environmental goals. While this generally means focusing on reducing total PM mass, a greater emphasis on climate protection as a goal in the PM program might require more focus on reducing BC emissions within the overall PM mixture. The largest domestic categories of BC emissions are mobile diesel engines and wildfires; emissions from both sectors are large, so both present some mitigation potential. However, there are substantially different mitigation challenges for each sector. Mobile diesel emissions are well characterized and dominated by BC (as opposed to other co-pollutants such as NO_x, SO_x, or OC); they come from a defined set of controllable sources; they can be controlled with known technologies with clearly identified costs; they tend to be concentrated in urban areas where they affect large populations; and they can be regulated through centralized federal programs. On the other hand, mobile diesel emissions from U.S. sources are spread out geographically and while they contribute to overall atmospheric warming and have a large health impact in urban areas, they are not as readily transported to the Arctic. Controls on mobile diesel engines can be expected to provide widespread health and environmental benefits, and climate benefits in the form of overall reductions in radiative forcing. These global climate benefits will accrue in part to the Arctic, helping to alleviate impacts (such as rapid temperature increase) in that region. However, since emissions within or near the Arctic appear to be most closely linked to Arctic impacts (Quinn et al., 2011), diesel reductions in the United States may not be the most effective emissions reductions for reducing impacts in the Arctic. They will have even less impact on the Himalayas.

Wildfire emissions in the United States are less well characterized in terms of volume and radiative forcing potential, in part because they are dominated by OC rather than BC. They are unpredictable and extremely variable across time and space. They are difficult to control with known technologies or approaches, and often occur in locations far removed from people. Implementation barriers are much higher, and anticipated impacts of emissions reduction strategies are much more uncertain. On the other hand, wildfire emissions have been shown to be one of the prime contributors to BC deposition and atmospheric loading in the Arctic, and even lighter-colored OC has been linked to warming in the region (Quinn et al., 2011). Because the volume of emissions from a single event is large and emissions plume height enables long-range transport, wildfire emissions can travel long distances and have impacts far from the location of the fire. In the United States in 2002, nearly 50% of wildfire emissions occurred in Alaska, making them extremely important for impacts on the Arctic.[3] Therefore, if policymakers are seeking mitigation options that provide climate benefits to the Arctic specifically, they might be interested in attempting to control wildfire emissions.

Outside of the United States, similar tradeoffs and challenges exist. Agricultural burning in Africa is one of the world's largest sources of BC. Despite high OC co-emissions, this agricultural burning may have substantial climate impacts because emissions are lofted above deserts, which, like snow and ice, are light-colored surfaces. However, because much of the burning takes place in rural areas, controlling these emissions would provide fewer benefits for health than reducing emissions from the transportation sector in larger African urban areas, or reducing emissions from solid-fuel cookstoves. Again, policymakers must consider a whole range of factors in determining which options are preferable.

Some of the largest climate benefits of BC-focused control strategies may come from reducing emissions that affect the Hindu Kush-Himalayan-Tibetan Plateau (HKHT), as well as other ice- and snow-covered regions. The HKHT and Indian subcontinent is also experiencing some of the most dramatic impacts on precipitation from particle pollution; these multiple climate effects mean there is a tremendous opportunity in that region to maximize climate benefits (including reduced interference with natural precipitation patterns in the region). An aggressive mitigation strategy could reap substantial benefits directly to that region's population, one of the world's largest. Here, many of the variables in the framework align: a variety of sources (cookstoves, diesel trucks, brick kilns) are affecting both climate and health, and low-cost technological solutions are available to help mitigate these emissions. These technologies are discussed further in the next several chapters, and some of the key options for the region are highlighted in Chapter 12.

7.7 Conclusions

Mitigating BC emissions depends on a clear prioritization of goals and emissions reduction opportunities. The challenge for policymakers is clear: identifying feasible and cost-effective mitigation strategies requires carefully weighing a large number of factors, in many cases with incomplete information. The challenge is rarely a purely technological one. As the following chapters will illustrate, many effective control technologies are available to reduce BC emissions. These control technologies can provide cost-effective BC emissions reductions from key source categories,

[3] Alaskan wildfire emissions exhibit significant interannual variability. Emissions in 2002 were particularly high. Factors such as the timing, extent, and location of the fire, the total volume (and type) of fuel consumed, and the burning conditions all affect the fire emissions and the net impact on climate.

and current studies (discussed in Chapter 6) suggest that applying available technologies and strategies will produce near-term climate benefits, especially at the regional level. Available control technologies can also provide substantial health and environmental benefits. The challenge is identifying the strategies that maximize benefits across all these categories. Despite what is known and achievable, the path forward is neither straightforward nor easy, and will vary greatly by country and region of the world. Nevertheless, as demonstrated in the previous chapter, the potential benefits of action are large.

The next four chapters provide an overview of BC mitigation options, including costs where that information is available, in each of four major source categories: mobile sources, stationary sources, residential cooking and heating, and open biomass burning. Policymakers can view these options through the lenses discussed above and determine which, if any, strategies are appropriate to reduce BC emissions in their specific context. In Chapter 12, some of the clearest mitigation opportunities based on current emissions, control technologies, and expected benefits are discussed. These are options that satisfy many of the key criteria that decision-makers care about, as presented in the mitigation framework above. They are options that are most clearly linked to beneficial outcomes, because of their high BC emissions reductions potential, their importance for particular regions, or the lack of constraints on implementation. However, policymakers will need to adapt even these important mitigation options to their particular local and national circumstances.