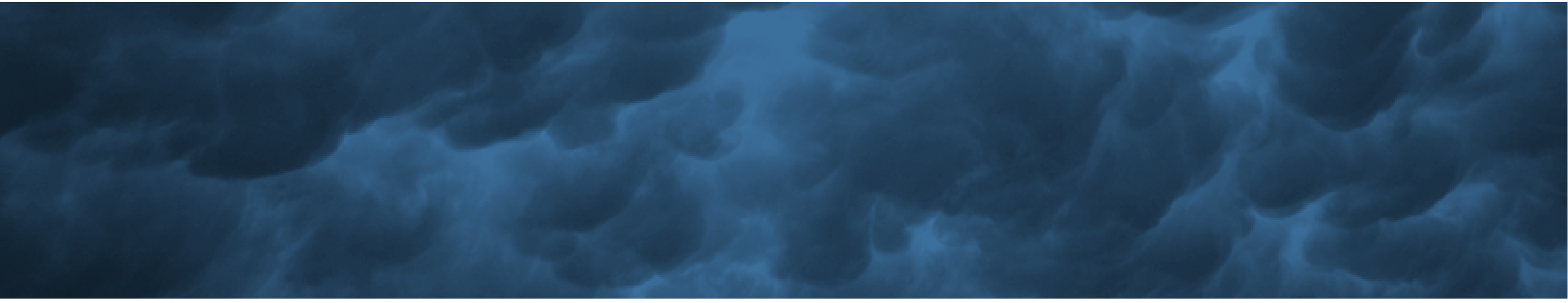


REDUCING GLOBAL HEALTH RISKS

Through mitigation of short-lived climate pollutants

Scoping report for policymakers

CLIMATE & CLEAN AIR COALITION TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

World Health Organization

REDUCING GLOBAL HEALTH RISKS

Through mitigation of short-lived climate pollutants

Scoping report for policymakers

CLIMATE & CLEAN AIR COALITION
TO REDUCE SHORT-LIVED CLIMATE POLLUTANTS

World Health Organization

WHO Library Cataloguing-in-Publication Data

Reducing Global Health Risks Through Mitigation of Short-Lived Climate Pollutants. Scoping Report For Policy-makers.

I.World Health Organization. II.Scovronick, Noah

ISBN 978 92 4 156508 0
Subject headings are available from WHO institutional repository

Printed in Switzerland

Acknowledgments:

This report was developed as a policy-relevant summary of potential benefits to health from reducing emissions of short-lived climate pollutants. The report brings together available knowledge from the health and climate domain into one scoping review. It was developed by the World Health Organization (WHO) in collaboration with the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC). The CCAC, hosted by the United Nations Environment Programme, is a voluntary partnership of governments, intergovernmental organizations, and civil society supporting actions to reduce emissions of short-lived climate pollutants, complementary to the global effort to reduce emissions of long-lived CO_2 and other greenhouse gases covered by the United Nations Framework Convention on Climate Change (UNFCCC).

Content for this report was developed by:

Lead author: Noah Scovronick, Princeton University (Princeton, New Jersey, United States of America)

Significant peer review and additional technical contributions were provided by:

Heather Adair-Rohani, World Health Organization (Geneva, Switzerland)
Alexander Balakanov, World Meteorological Organization (Geneva, Switzerland)
Nathan Borgford-Parnell, Institute for Governance & Sustainable Development (Bogotá, Columbia)
Michael Brauer, University of British Columbia (Vancouver, Canada), and member of CCAC Scientific Advisory Panel
Diarmid Campbell-Lendrum, World Health Organization (Geneva, Switzerland)
Andy Haines, London School of Hygiene and Tropical Medicine (London, United Kingdom of Great Britain and Northern Ireland) and member of CCAC Scientific Advisory Panel
Michal Krzyzanowski, Environmental Research Group of King's College (London, UK), World Health Organization Centre for Environment and Health – retired (Bonn, Germany)
Jonathan Patz, University of Wisconsin (Madison, Wisconsin, United States of America)
Annette Prüss-Ustün, World Health Organization (Geneva, Switzerland)
Veerabhadran Ramanathan, University of California at San Diego (California, United States of America), TERI University (Delhi, India) and member of CCAC Scientific Advisory Panel
Federico San Martini, Montreal Protocol Multilateral Fund (Montreal, Canada) and (formerly) US Department of State (Washington DC, United States of America)
Drew Shindell, Duke University (Durham, North Carolina, United States of America) and Chair of the CCAC Scientific Advisory Panel
Oksana Tarasova, World Meteorological Organization (Geneva, Switzerland)

Project oversight:

Maria Neira, Director, Department of Public Health, Environmental and Social Determinants of Health (PHE), World Health Organization (Geneva, Switzerland)
Carlos Dora, Coordinator, Interventions for Healthy Environments/PHE, World Health Organization (Geneva, Switzerland)
Helena Molin Valdés, Head of the Secretariat, Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants (CCAC), hosted by the United Nations Environment Programme (Paris, France)
Marit Viktoria Pettersen, Section for Climate and Environment, Ministry of Foreign Affairs, Government of Norway (Oslo, Norway)

Editorial management and research support:

Elaine Fletcher, Science Editor, Interventions for Healthy Environments/PHE, World Health Organization (Geneva, Switzerland)
Research support: Sandra Cavalieri, Health Initiative Coordinator, Consultant, Climate and CCAC Secretariat; **Alejandro Costa Perez,** Intern, **Tony Zhang**, Intern and **Ariel Charney,** consultant, Interventions for Healthy Environments/PHE, World Health Organization (Geneva, Switzerland)

Copy editor: Vallaurie Crawford
Graphic design: Mark Wickens

Cover photographs: (Clockwise from top)
- Mammatus clouds in San Antonio, Texas, USA (Credit: Derrich)
- Inside rocinha favela Rio de Janeiro, Brazil (Credit: Chensiyuan)
- Terrace rice fields in Yunnan Province, China. (Credit: Jialiang Gao)
- People hire bikes in Kensington Gardens, London, UK. (Credit: Garry Knight)
- Rotis and Dahl for breakfast. (Credit: Karan Singh Rathore)

Table of Contents

Reducing global health risks

Through mitigation of short lived climate polutants

Executive Summary

OVERARCHING MESSAGES

Reducing emissions of short-lived climate pollutants (SLCPs), which produce strong warming effects but persist in the atmosphere for periods ranging from days to decades (Figure 2), can provide health benefits in three key ways: directly from reduced air pollution and related ill-health; indirectly from reduced ozone and black carbon effects on extreme weather and agricultural production (affecting food security); and from other types of health benefits that are not associated with air pollution but may accrue as a result of certain SLCP mitigation actions, such as improved diets or increased physical activity.

- **Decreased emissions of black carbon and its co-pollutants, as well as emissions of ozone precursors, will reduce the substantial disease burden attributable to air pollution.** Exposure to ambient (outdoor) fine particulate matter ($PM_{2.5}$), of which black carbon is a substantial component, is estimated to cause some 3.7 million premature deaths annually *(6)*.[I] 4.3 million deaths are attributable to exposure to $PM_{2.5}$ (which includes BC) from the household combustion of solid fuel *(7)*. Diseases caused by $PM_{2.5}$ exposure include stroke, ischaemic heart disease, acute lower respiratory disease, chronic obstructive pulmonary disease, and lung cancer (see Figure 1). Exposure to ozone is responsible for roughly 150 000 deaths annually from respiratory conditions *(8)*. A major study by the United Nations Environment Programme and the World Meteorological Organization estimated that implementing a small suite of SLCP mitigation actions could prevent about 2.4 million premature deaths annually, mainly from targeting black carbon *(9)*. Updated analyses indicate even larger potential health benefits that may eventually rise to 3.5-5-million premature deaths averted *(10)*.

- **The indirect effects of reduced SLCP emissions can also yield health benefits through impacts on weather and food production.** Ozone and black carbon decrease agricultural yields, thus threatening food security; ozone is toxic to many plants, whereas black carbon diminishes the amount and quality of sunlight available for photosynthesis *(9)*. SLCPs also affect weather patterns and the melting of snow and ice, which may harm health through extreme weather events such as floods *(9)*.

- **Health benefits directly related to some SLCP mitigation actions can also accrue independently of reduced air pollution.** In affluent populations, for example, healthier diet choices that include increased consumption of nutritious plant-based foods such as fruits, vegetables, nuts and seeds, and whole grains, along with reduced consumption of red/processed meats, can support healthier diets, reduce related health risks, and lessen the demand for livestock products – which is expected to soar in the coming decades – and the associated emissions of methane, a powerful SLCP *(11, 12)*.

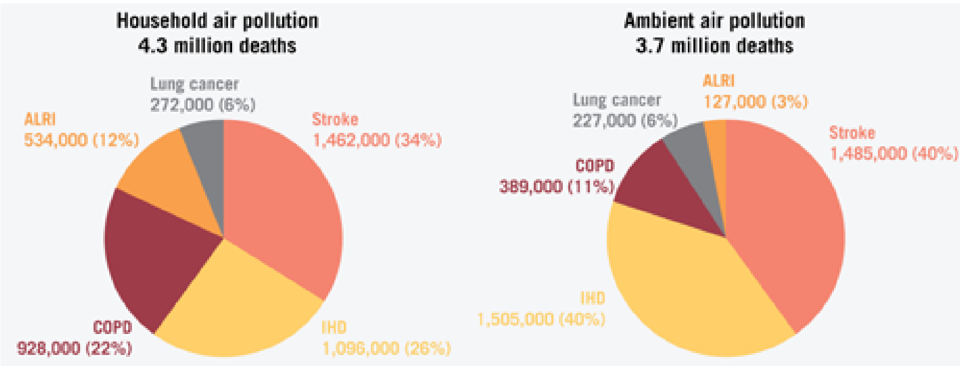


Figure 1. Deaths attributable to household and ambient air pollution, 2012 ALRI = acute lower respiratory infections, IHD = ischemic heart disease, COPD = chronic obstructive pulmonary disease. Source: WHO, 2014 (6,7)

[I] $PM_{2.5}$ refers to "fine" particulate matter defined as particles with an diameter ≤ 2.5 micrometers.

Some mitigation actions provide advantages from all three of the above mechanisms, leading to large benefits for public health. Policies and investments that prioritize dedicated rapid transit and walking and cycling networks can promote safe active travel, reducing health risks from air pollution ($PM_{2.5}$ and ozone) and noise, physical inactivity, and road traffic injuries *(13)*. Clean household energy solutions also offer a range of benefits, including reduced exposure to household and outdoor air pollution, reduced risk of injuries and burns, and time savings from eliminating the need to collect wood or other solid fuels *(14)*. These measures can provide substantial reductions in emissions of SLCPs as well as carbon dioxide (CO_2) (Table 1 and Table 8).

Some of the most health-enhancing strategies for reducing SLCP emissions can also lead to substantial co-reductions in CO_2 emissions, and therefore help mitigate both near- and longer-term climate change. Because longer-term climate change will largely be determined by CO_2, SLCP-related policies should be viewed as complementary to actions that reduce long-lived climate pollutants, particularly CO_2 *(9, 15)*.[II] Health-promoting policies that reduce both SLCPs and CO_2 are thus particularly attractive and are available in multiple sectors (see Table 8). An indicative example of potential co-benefits from reducing air pollution, SLCP emissions, and CO_2 is illustrated in Figure 3, which presents data from the transport sector in Los Angeles, California.

Many of the health benefits produced from SLCP reduction are realized locally and in the near term – two features that make SLCP mitigation measures particularly attractive to local and national policy-makers. Many of the health gains and weather benefits of reducing SLCPs occur near where mitigation action is taken, thus directly benefiting the communities within the decision-making jurisdictions. This is true of some direct health impacts, such as reduced human exposure to black carbon and other particulates, as well as of ancillary benefits such as the creation of healthier urban spaces. The short time frame for realizing benefits is a second feature attractive to policy-makers. While SLCPs are powerful warming agents, generally causing more radiative forcing per unit than CO_2, emissions disappear from the atmosphere relatively quickly due to their short lifespan (Figure 1). Once emissions are reduced, benefits are seen soon thereafter *(18)*.

What are Short-Lived Climate Pollutants?

The SLCPs of greatest health relevance include black carbon, a common component of fine particulate matter ($PM_{2.5}$), which is the air pollutant most associated with premature death and morbidity, as well as ozone, which has significant adverse impacts on respiratory health *(1-5)*. Methane, another SLCP, contributes to ozone formation. Some strategies to reduce hydrofluorocarbons (HFCs) may also have health benefits.

Figure 2. Properties of common short-lived climate pollutants. Note: "Current radiative forcing" refers to atmospheric changes due to emissions of climate forcers, from the pre-industrial era (1750) to the present, as reported by the Intergovernmental Panel on Climate Change. For reference purposes, the corresponding value for CO2 is 1.82. Adapted from UN Environment Programme, by permission of the Climate and Clean Air Coalition.

[II] The Kyoto Protocol, the legally-binding international treaty linked to the United Nations Framework Convention on Climate Change (UNFCCC), does not include emissions reductions targets for either black carbon or ozone. Targets do cover methane and HFCs as well as the long-lived climate pollutants carbon dioxide, nitrous oxide and sulphur hexafluoride as well as perfluorocarbons.

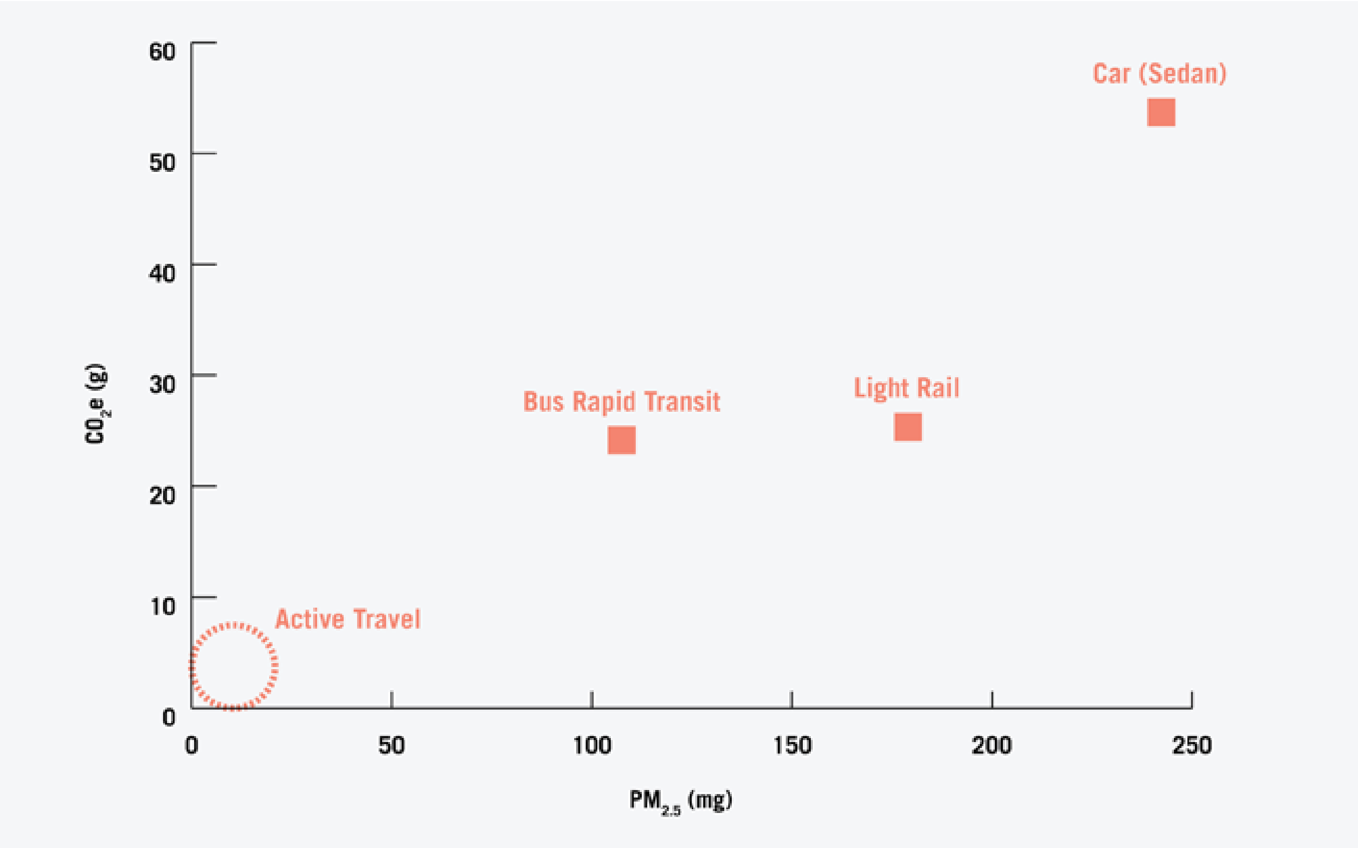


Figure 3. Life-cycle emissions of $PM_{2.5}$ and grams of embodied carbon (CO_2e) per passenger mile for different modes of urban transport. Results for car, bus, and light rail are from Chester et al., 2013 & 2014 (16, 17) and are for average-occupancy vehicles in Los Angeles. Results for active travel are estimated.

PART 1. HEALTH EFFECTS OF SLCPs

Recent studies have reported significant associations between exposure to black carbon (short- and long-term) and all-cause and cardiopulmonary mortality. There is also evidence of associations with increased hospital admissions for certain cardiovascular and respiratory diseases *(19, 20)*. These effects may be due to certain characteristics of black carbon, which include the following:

- Most black carbon emissions are "fine" particles ($PM_{2.5}$) that penetrate deeply into the lungs.
- Black carbon particles are a product of combustion, and evidence suggests that combustion-related particles may be more dangerous than those from non-combustion sources (e.g. dust), although this is still under investigation *(20-22)*.
- Laboratory studies have found that black carbon may be a "universal carrier" of the toxic components of $PM_{2.5}$ *(19)*.
- Black carbon is almost always emitted with other types of particles, some of which may be harmful to health in and of themselves.
- Nonetheless, more research is needed to definitively identify the role of various types of particles in causing the observed health effects and to determine their mechanisms of effect.

In terms of sources, it is estimated that fuel combustion in residential and commercial buildings and transport together account for approximately 80% of anthropogenic black carbon emissions (Figure 4). $PM_{2.5}$ emissions from burning diesel, biomass, and kerosene are among the sources with the heaviest concentrations of black carbon and accordingly, have been identified as among the priority sources for reducing emissions that contribute to near-term climate change; some other sources of black carbon emissions, such as coal-fired power plants, emit a high concentration of cooling co-pollutants and therefore are unlikely to provide an SLCP-related climate benefit *(9, 23)*. (However, if the focus of a policy is exclusively to improve health, other sources of black carbon will also produce benefits, as $PM_{2.5}$ will be reduced. They may also mitigate longer-term climate change through reductions in CO_2).

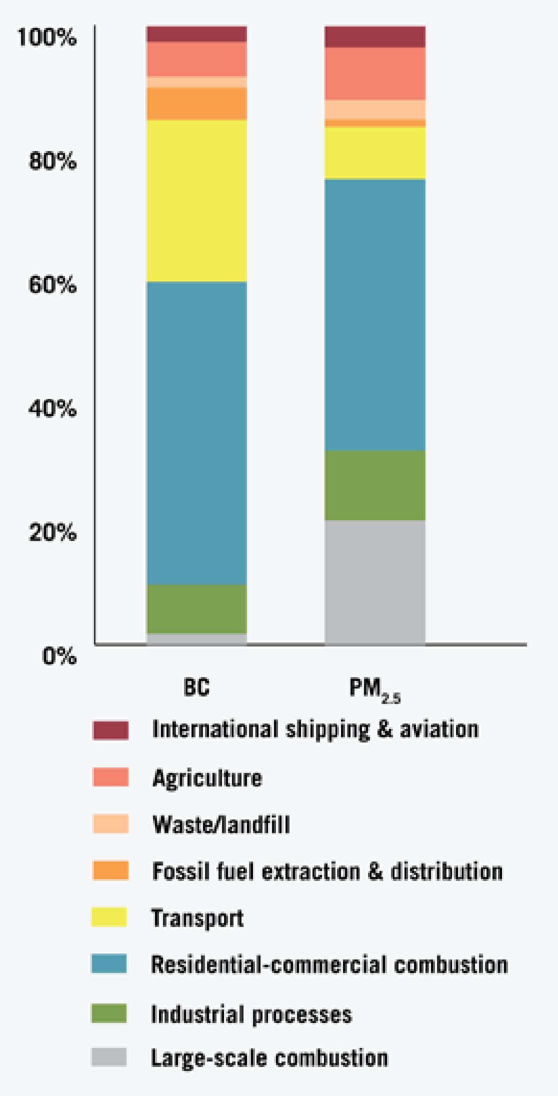


Figure 4. Anthropogenic BC and $PM_{2.5}$ emissions by sector, 2005. Note that open burning (e.g. forest or brush fires) is not considered here as an anthropogenic (human-made) source, although it is the single largest BC emission source overall. Source: UNEP/WMO, 2011 (9)

Ozone is the second SLCP directly associated with air pollution-related health effects. Specifically, there is strong evidence that ozone is causally associated with adverse respiratory effects, with impacts ranging from changes in lung function and increased incidence of asthma to premature mortality *(5, 24)*.

A causal association with cardiovascular effects and total mortality is also likely *(5)*, and there is some evidence of links with central nervous system and reproductive and developmental effects *(4, 5)*. Most countries have air quality standards that set limits for ambient ozone concentrations.

Ozone is not emitted directly, so control measures must focus on precursor emissions. These include oxides of nitrogen (NOx), methane, carbon monoxide, and volatile organic compounds. Two of these deserve special mention: methane for being a powerful SLCP by itself, and nitrogen dioxide (NO_2) both for its role as a contributor to ozone creation and because it may produce adverse respiratory and cardiovascular effects of its own (4, 25-27).

Methane is the second most important contributor to radiative forcing from the pre-industrial era to the present, behind only CO_2 *(28, 29)*. It is produced mainly by the agriculture and waste management sectors. Reducing methane emissions can lead to health benefits by preventing ozone formation as well as by generating ancillary benefits associated with certain mitigation actions such as promotion of healthier diets (see next section). NO_2 is one of the major components of NOx, which contributes to ozone formation.[III] A regulated air pollutant, NO_2 is is a product of combustion processes including vehicle combustion (particularly diesel vehicles) as well as power plants. There is increasing concern about health impacts from NO_2, and it may soon figure prominently alongside $PM_{2.5}$ and ozone in estimates of health burdens from air pollution *(4, 25-27)*.

Along with direct impacts from air pollution, black carbon and ozone pollution also have indirect impacts on health: both can reduce plant productivity, and black carbon deposition increases the pace of snow/ice melt, affecting water supplies. These effects may increase food insecurity among low-income populations in certain regions.

Approximately 800 million people globally are estimated by the Food and Agriculture Organization to be "undernourished" (an indicator of food insecurity) *(30)*. Lack of food is one contributor to under-nutrition as defined in relation to growth and/or nutrient inadequacy, which is responsible for an estimated 45% of child deaths *(31, 32)*. For example, one study of four staple crops (wheat, soybeans, rice and maize) estimated that current ozone levels cause yield losses of 3-16%, depending on crop and modeling assumptions *(33)*. **Targeting black carbon and ozone precursors will also reduce co-emissions of other air pollutants that are health-damaging.**

Black carbon and ozone precursors are almost never emitted alone. Many of the strategies targeting these pollutants will reduce other harmful emissions directly or indirectly, thus magnifying health benefits *(23)*.

[III] NOx is a term commonly referring to the nitrogen oxides NO and NO_2 (nitric oxide and nitrogen dioxide).

PART II. HEALTH CO-BENEFITS OF KEY MITIGATION ACTIONS

The health co-benefits that may be obtained from specific SLCP mitigation actions are explored by sector below.

Cooking on a low-emissions ethanol stove in Ethiopia. (Credit: Ashden Awards)

SLCP mitigation actions were identified and evaluated through literature reviews and expert consultations. In addition to a systematic search of the scientific literature, this report evaluates reports from major governmental and intergovernmental organizations. Where mitigation actions are explicitly rated (as having "high," "medium," or "low" potential to improve public health, for example), these ratings are designed to be qualitative and are subject to uncertainties; often more quantitative modeling is required for confident evaluation. The methods and supporting evidence behind the ratings are described in detail in Appendix I. Table 8 contains the full list of strategies thus evaluated, along with the ratings. In addition to being subject to expert review as part of this report, an initial version was published in a peer-reviewed journal article *(34)*.

Of the more than 20 SLCP mitigation actions screened in detail, four were identified as offering both a high level of potential health benefit as well as a high level of certainty to produce a large SLCP-related climate benefit. The four interventions are:

- Policies and infrastructure to prioritize safe active travel (walking/cycling);
- Encouraging healthier diets rich in diverse, plant-based foods;
- Providing low-emission stove and/or fuel alternatives to the approximately 2.8 billion low-income households worldwide now dependent primarily on wood, dung and other solid fuels;
- Reducing vehicle emissions by implementing stricter emissions and efficiency standards for both particulate matter and ozone precursors including oxides of nitrogen (NOx).

More details on these interventions are available in the following text and in Table 1 and Table 8 in Appendix I. Many of the other mitigation actions considered and described below also have considerable potential to improve health and reduce emissions. In some cases, further research is needed to confidently determine the extent of potential health gains as well as the real-world effectiveness of different interventions.

Table 1. Four SLCP mitigation actions with potential to produce major climate and health benefits.

Sector and mitigation action	Certainty of major SLCP-related climate benefit	Aggregate level of potential health benefit	Potential level of CO_2 reduction co-benefit
Support active travel (aided by rapid mass transit)	High	High	High
Promoting healthy diets low in red meat and processed meats and rich in plant-based foods	High	High	Medium-high
Low-emission stoves and/or fuel switching to reduce solid fuel use	Medium-high	High	Medium
Stricter vehicle emissions/ efficiency standards	High	Medium-high	High

For more details, see Table 8 and Appendix I.

Transport

Shifting to cleaner transport modes and implementing improvements in vehicle technologies both present good opportunities to reduce SLCP emissions in ways that benefit health. Urban transit schemes as well as other policies or investments that prioritize safe active travel on dedicated networks are necessary and complement strategies that reduce tailpipe emissions.

Cyclists in Mexico City. (Credit: karmacamilleeon/Flickr)

Emissions from diesel vehicles (on- and off-road) that account for about 20% of global black carbon emissions present a particularly good mitigation opportunity and are listed as a Group 1 carcinogen by the International Agency for Cancer Research *(23, 35)*. Particle emissions from older diesel vehicles are often around 75% black carbon *(36)*. Emissions from gasoline engines are also rich in black carbon, but are a smaller source *(23)*. Vehicle emissions are major sources of ozone precursors, including NO_2, with diesel vehicles generally emitting more per km traveled than comparable gasoline vehicles *(37)*. By contrast, active travel produces no meaningful emissions while mass transit usually produces substantially less per capita in comparison to private vehicles *(16)*.

Shifting to "clean transport modes" refers to policies and investments prioritizing the use of active transport (walking/cycling) or rapid urban transit over private vehicles, particularly in cities.

Potential benefits include increased physical activity, which can reduce chronic disease and have positive effects on body weight, as well as reduced air and noise pollution and prevention of road traffic injuries given the provision safe walking, cycling and transit infrastructure *(13, 38)*. Active travel in particular is necessary, as there is a limit to the benefits of technological improvement and because some vehicle emissions are not from fuel combustion (e.g. brakes dust).

Two promising technological approaches with potential to substantially reduce black carbon and particulate matter are retro-fitting diesel particle filters and implementing more stringent vehicle emission and efficiency standards.

These approaches are relatively straightforward and have the potential to produce quick (in some cases, immediate) benefits for health through emission reductions from existing vehicle fleets.

Table 2. SLCP mitigation actions in the transport sector

Sector and mitigation action	Certainty of major SLCP-related climate benefit	Aggregate level of potential health benefit	Indicative health benefit(s) *(red = direct benefits of reduced air pollution; blue = indirect benefits of reduced air pollution; green = ancillary health benefits)*	Potential level of CO_2 reduction co-benefit
Support active (and rapid mass) transport	High	High	Improved air quality Less crop damage and extreme weather Increased physical activity, Reduced noise, Fewer road traffic injuries	High
Ultra-low-sulfur diesel with diesel particle filters	Medium-high	Medium	Improved air quality Less crop damage and extreme weather	None
Stricter vehicle emissions/efficiency standards	High	Medium-high	Improved air quality Less crop damage and extreme weather	High

See Table 8 and Appendix I for details

Agriculture

Supply-side and demand-side mitigation measures are complementary strategies that can reduce methane emissions from the agriculture sector in ways that benefit health. Agricultural emissions also make an important contribution to the secondary formation of $PM_{2.5}$ in the atmosphere and their reduction is therefore another means to improve health *(39).*

Agriculture is the biggest source of anthropogenic methane emissions globally, with livestock production the primary contributor (Figure 5) *(40)*.

Supply-side mitigation actions considered here include: a) improved livestock manure management, which can contain interventions for biogas capture, and b) alternating wet and dry irrigation (AWDI) for rice paddies that produce considerable methane gas when left flooded year-round. Potential health benefits include access to clean energy, reductions in infectious diseases, and increased food security. Reductions in the open burning of agricultural residues can also have important benefits on air quality.

Improving manure management can involve the capture of biogas, a relatively clean energy source that can be used for fuel in the household, for example by rolling out anaerobic digesters both for large-scale producers and at the household level. If biogas replaces solid fuel use, health benefits from reduced household air pollution could be substantial. Improved manure management can also reduce exposures to pathogens by reducing improper handling. If these interventions are coupled with improved sanitation, associated health benefits can be large (see Chapter 10).

Because mosquito vectors may use irrigated fields, including rice paddies, for breeding, rice irrigation that alternates between wet and dry periods (AWDI) has been identified as a strategy for controlling vector-borne diseases such as malaria and Japanese encephalitis *(41, 42)*. AWDI also saves water, which can be diverted for other uses. These are policies that can be implemented rapidly if appropriate incentives are provided.

On the demand side, shifting towards diets rich in plant-based foods is a key mitigation strategy, particularly among affluent populations. This approach can help reduce certain diet-related non-communicable disease risks while also slowing the trajectory of rising methane emissions associated with livestock production.

Shifting affluent populations away from diets that are heavy in animal-sourced foods (particularly processed meats and red meat), and towards diverse plant-based alternatives has great potential health and climate benefits, according to modeling studies and systematic review *(11,12)*; (Table 15). This addresses a key source of methane emissions as well as the growing worldwide disease burdens from obesity and related diet-sensitive non-communicable diseases. Insufficient intake of fruits, vegetables and nuts and seeds have been estimated to cause millions of premature deaths every year *(8, 43)*[IV]. Diets high in red and processed meats are associated with certain cancers and diabetes. Reducing food waste is another key strategy in this sector, although it has fewer direct health implications.

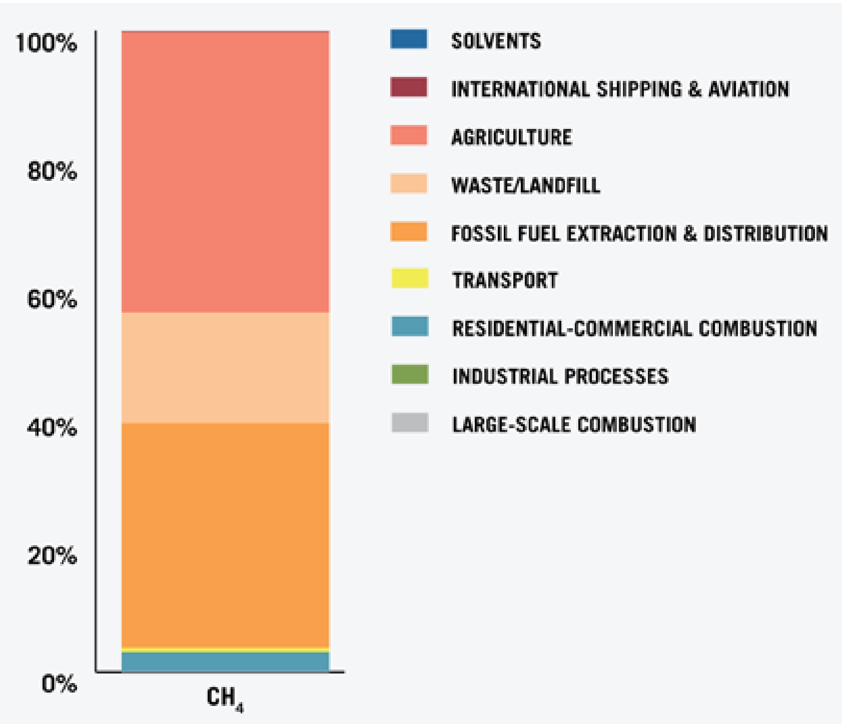


Figure 5. Sources of methane emissions, 2005. Source: IPCC, 2013 (40).

[IV] Diets low in fruits = 4.9 million premature deaths/yr; diets low in vegetables = 1.8 million deaths/yr; diets low in nuts and seeds = 2.5 million deaths/yr; diets low in whole grains = 1.7 m premature deaths/yr. Note: attributable mortality from different risks may overlap *(8)*.

Table 3. SLCP mitigation actions in the agriculture sector				
Sector and mitigation action	**Certainty of major SLCP-related climate benefit**	**Aggregate level of potential health benefit**	**Indicative health benefits (red = direct benefits of reduced air pollution, blue = indirect benefits of reduced air pollution, green = ancillary health benefits)**	**Potential level of CO_2 reduction co-benefit**
Alternating wet/dry rice irrigation	Medium-high	Low-medium	Reduced vector-borne disease Improved food security	Low
Improved manure management, including biogas capture	Low-medium	Low-medium	Improved air quality Reduced zoonotic disease	Low
Reduced open burning of agricultural residues	Medium	Low-medium	Improved air quality Less crop damage and extreme weather	Low
Promoting healthy diets low in red meat and processed meats and rich in plants-based foods	High	High	Reduced obesity and diet-related non-communicable diseases	Medium-high
Reducing food waste	Medium-high	Low-medium	Reduced food insecurity/ undernutrition	Medium-high

See Table 8 and Appendix I for details.

Household Energy Production and the Built Environment

Replacing traditional household solid fuel use with lower-emission cookstoves and /or cleaner fuels has multiple benefits for climate and health.

Exposure to household air pollution, largely from inefficient heatstoves, cookstoves or open fires that burn coal or biomass, is the leading environmental risk factor for ill health (Figure 1) *(44, 45)*. Cleaner fuels and more efficient stoves can substantially reduce air pollution, including black carbon, emissions and improve health while also decreasing demand for fuel, providing economic and other health benefits (e.g. reduced risk of injuries or assault during wood collection). Reduced deforestation pressures helps maintain ecosystem services (including CO_2 uptake by trees) *(14, 46)*.

Kerosene[V] lamps produce high levels of particulate air pollution comprised almost entirely of black carbon.

Discontinuing kerosene use by shifting to other lighting options (preferably powered by renewables) can have benefits for SLCP reductions as well as for health – as per new WHO recommendations for ensuring adequate indoor air quality *(47)*. Along with reduced air pollution, other health benefits include a reduction in deaths and injuries caused by kerosene-related burns and poisonings *(48-50)*.

Improved building design, including through better insulation and natural ventilation, can reduce energy demand while improving indoor air quality and temperature control.

Better building design can reduce demand for energy and air conditioning – a key source of HFCs (another SLCP) – while improving indoor air quality. Poor indoor air quality in buildings can promote mold growth and associated allergies as well as infectious disease transmission (e.g. respiratory illnesses, including tuberculosis) *(51, 52)*. Household exposures to high and low ambient indoor temperatures (e.g. during heat waves or winter storms) is also a major cause of mortality and morbidity *(53-55)*.

[V] Kerosene is also known as paraffin oil

Table 4. SLCP mitigation actions in the household energy and built environment sectors				
Sector and mitigation action	Certainty of major SLCP-related climate benefit	Aggregate level of potential health benefit	Indicative health benefits (red = direct benefits of reduced air pollution, blue = indirect benefits of reduced air pollution, green = ancillary health benefits)	Potential level of CO_2 reduction co-benefit
Low-emission cookstoves and/ or fuel switching to reduce solid fuel use	Medium-high	High	Improved air quality Less crop damage and extreme weather Lower violence and injury risk during fuel collection Fewer burns	Medium
Improved lighting to replace kerosene lamps	Medium	Medium	Improved air quality Less crop damage and extreme weather Fewer burns Fewer poisonings	Low-medium
Passive design principles	Low-medium	Medium	Temperature-related morbidity and mortality Improved indoor air quality	Medium

See Table 8 and Appendix I for details.

Industry

Technologies reducing black carbon emissions from traditional brick kilns and coke ovens can reduce high levels of human exposure to particulate matter from these sources for workers and communities near these industries, providing an important health-enabling opportunity for mitigation through technological improvements.

Technology exists that can dramatically reduce emissions from these small industries, which are important sources of local black carbon and particulate emissions in some locations *(23, 56)*. Occupational exposures may be particularly high. Emissions from coke ovens have been classified as a Group 1 carcinogen by the International Agency for Research on Cancer *(35)*. Due to the high concentration of these industries in Asia, including near the Himalayas and at higher latitudes, the adverse climate impacts of black carbon emissions may be magnified.

An oil platform in Brazil; fugitive methane emissions from oil and gas extraction also contribute to ozone formation. (Credit: Agência Brasil)

Reducing methane losses in the fossil fuel industry is another important strategy that could lead to modest improvements in air quality from reduced ozone.

Fossil fuel extraction and processing are major sources of methane emissions and are regularly identified as presenting major climate change mitigation opportunities *(9, 57)*. Specific actions include the recovery and use of coal mine methane and methane released from oil and natural gas production processes, as well as reducing leakages, including during pipeline distribution *(9, 57)*. Although climate impacts could be large, assessments indicate that mitigation is unlikely to produce major direct public health benefits, though there may be modest gains through reductions in ambient ozone *(9)*.

Table 5. SLCP mitigation actions in the industrial sector				
Sector and mitigation action	**Certainty of major SLCP-related climate benefit**	**Aggregate level of potential health benefit**	**Indicative health benefits (red = direct benefits of reduced air pollution, blue = indirect benefits of reduced air pollution, green = ancillary health benefits)**	**Potential level of CO_2 reduction co-benefit**
Improved brick kilns	Low-medium	Medium	Improved air quality Less crop damage and extreme weather	Low-medium
Improved coke ovens	Low-medium	Medium	Improved air quality Less crop damage and extreme weather	Low-medium
Control of fugitive emissions from the fossil fuel industry	High	Low	Improved air quality Less crop damage and extreme weather	Low-medium

See Table 8 and Appendix I for details.

Energy supply and electricity generation

Replacing or supplementing diesel generators with renewable energy sources is a promising intervention that would reduce local air and noise pollution around homes and health clinics, and also create a more reliable source of electricity for low-income households and communities.

Per kilowatt hour (kWh) of energy production, portable diesel generators produce large quantities of health-damaging particulate emissions that are rich in black carbon. Diesel generators are often an unreliable source of electricity due to fuel costs and distribution challenges. Shifting to renewables or hybrid power generation approaches can help slow the rapid growth of air pollution emissions in some emerging economies.

Table 6. SLCP mitigation actions in the energy supply/electricity generation sector				
Sector and mitigation action	**Certainty of major SLCP-related climate benefit**	**Aggregate level of potential health benefit**	**Indicative health benefits (red = direct benefits of reduced air pollution, blue = indirect benefits of reduced air pollution, green = ancillary health benefits)**	**Potential level of CO_2 reduction co-benefit**
Replace or supplement diesel generators with renewables	Low-medium	Low-medium	Improved air quality Less crop damage and extreme weather Reduced noise	Low-medium
Switch from fossil fuels to renewables for large-scale power production*	Low	High (coal/oil) Low-medium (gas)	Improved air quality Less crop damage and extreme weather Fewer occupational injuries	High (coal/oil) Medium-high (gas)

** Note: Health and climate gains will be higher when accompanied by efficiency measures along the continuum of power supply and distribution systems.*
See Table 8 and Appendix I for details.

Waste management

The waste management sector is one of the major sources of methane emissions globally. Reducing emissions involves two complementary strategies. The first is to reduce the volume of solid waste generated, as through recycling and composting programs, although this will produce limited direct health impacts. The second is to improve waste management regimes, including:

- **Capturing landfill gas can reduce emissions. Direct health impacts via reductions in air pollution will be modest, but there can also be a benefit if the captured gas replaces fossil or biomass fuels.**
- **If waste interventions include increased provision of sanitation, strong health benefits may be produced through the prevention of infectious diseases.**

The reduction of methane emissions, which is feasible at both landfills and wastewater treatment facilities, has the potential to reduce ozone formation. Lack of improved sanitation is still prevalent in many low-income areas of the world, and providing sanitation can markedly reduce disease, including diarrhea and helminth infections *(58, 59)*. Any intervention that impacts pest populations may also reduce vector-borne disease.

Table 7. SLCP mitigation actions in the waste management sector

Sector and mitigation action	Certainty of major SLCP-related climate benefit	Aggregate level of potential health benefit	Indicative health benefits (red = direct benefits of reduced air pollution, blue = indirect benefits of reduced air pollution, green = ancillary health benefits)	Potential level of CO_2 reduction co-benefit
Landfill gas recovery	Medium	Low	Improved air quality Less crop damage and extreme weather Reduced noise	Low-medium
Improved wastewater treatment (including sanitation provision)	Medium	Medium-high	Improved air quality Less crop damage and extreme weather Reduced infectious disease risk	Low-medium

See Table 8 and Appendix I for details.

Efforts to minimize waste by recyling reduces the need for landfilling and associated emissions. (Credit: antoniothomas)

The Urban Environment

"Smart" planning and development of compact, walkable cities offer opportunities to integrate many SLCP mitigation actions.

If well-planned, cities can take advantage of their population density and resource concentration to implement many of the mitigation actions described above to create climate- and health-friendly environments. Specific actions include "proximity planning," where neighborhoods integrate housing with basic services and businesses to reduce travel distances to daily routines, as well as broader metropolitan planning around mass transit and active transport arteries and routes. Other complementary interventions include the creation of green spaces and the implementation of modern waste management systems. Extra attention should be given to low-income areas including slums, as these communities tend to be vulnerable to climate and health threats, but also have unique opportunities for green development.

Part III. CONCLUSION: IMPLICATIONS FOR POLICY-MAKERS

Interventions to reduce SLCP emissions can provide major health and climate benefits.

High-impact mitigation actions are available in many sectors and include technological approaches as well as policies. Many of the best policies simultaneously reduce harmful air pollution and SLCPs, often acting as well on longer-term climate emissions, and create enabling factors for more healthy lifestyles.

The ancillary benefits of certain SLCP mitigation actions may produce large health gains in addition to those related to air pollution.

Interventions that improve diets and physical activity, for example, have a strong potential to enhance public health. Some potential ancillary benefits of mitigation actions, however, are less understood and require further evaluation, such as AWDI's impacts on vector-borne diseases and impacts on food security from reducing food waste.

Insofar as many health benefits of SLCP reduction are often realized in the near-term and on a local scale, policies adopting such measures are highly compatible with the immediate development priorities of local and national policy-makers.

Many benefits from reducing SLCPs begin quickly, in some cases almost immediately, and occur near where mitigation actions take place.

The impact of SLCP mitigation actions will be greatest if there is cooperation between government agencies.

The co-benefits approach to climate change mitigation is most successful when policy-makers recognize that single interventions can fulfill multiple objectives in parallel. However, taking advantage of these synergies requires cross-sectoral collaboration.

The health and climate benefits of SLCP mitigation can be magnified if multiple mitigation actions are implemented together.

Many of the most attractive urban air pollution and SLCP reduction measures need to be made in an integrated manner to realize their full potential. Implementing multiple mitigation actions at the same time and/or in the same location enables decision-makers to take advantage of economies of scale and complementarities across policies.

Table 8 lists important SLCP-related climate mitigation actions and their main health benefits. The table also qualitatively assesses the potential magnitude of climate and health impacts, including whether or not a given action will result in significant CO_2 co-reductions.

An explanation of the ratings can be found in Appendix I.

Table 8. Potential magnitude of climate and health impacts of selected mitigation actions.

Sector and mitigation action	Certainty of major SLCP-related climate benefit[1]	Aggregate level of potential health benefit[2]	Main health benefits (red = direct benefits of reduced air pollution; blue = indirect benefits of reduced air pollution; green = ancillary health benefits)	Potential level of CO_2 reduction co-benefit
Transport				
Support active (and rapid mass) transport	High	High	Improved air quality Less crop damage and extreme weather Increased physical activity Reduced noise Fewer road traffic injuries[3]	High
Ultra-low-sulfur diesel with diesel particle filters	Medium-high	Medium	Improved air quality Less crop damage and extreme weather	None
Higher vehicle emissions/efficiency standards	High[4]	Medium-high	Improved air quality Less crop damage and extreme weather	High[4]
Agriculture				
Alternate wet/dry rice irrigation	Medium-high[5]	Low-medium	Less crop damage and extreme weather Reduced vector-borne disease	Low[5]
Improved manure management	Low-medium	Low-medium	Reduced zoonotic disease Improved indoor air quality	Low
Reduced open burning of agricultural fields	Medium	Low-medium	Improved air quality Less crop damage and extreme weather	Low
Promoting healthy diets low in red meat and processed meats and rich in plant-based foods[6]	High	High	Less crop damage and extreme weather Reduced obesity and diet-related non-communicable diseases	Medium-high[7]
Reducing food waste	Medium-high	Low-medium	Less crop damage and extreme weather Reduced food insecurity/undernutrition	Medium-high[7]
Household air pollution and building design				
Low-emission stoves and/or fuel switching to reduce solid fuel use	Medium-high	High	Improved air quality Less crop damage and extreme weather Lower violence and injury risk during fuel collection Fewer burns	Medium[7]
Improved lighting to replace kerosene lamps	Medium	Medium	Improved air quality Less crop damage and extreme weather Fewer burns Fewer poisonings	Low-medium
Passive design principles	Low-medium	Medium	Thermal regulation Improved indoor air quality	Medium

Table 8 (continued)

Energy supply/electricity				
Switch from fossil fuels to renewables for large-scale power production[7]	Low	High (coal/oil) Low-medium (gas)	Improved air quality Less crop damage and extreme weather Fewer occupational injuries	High (coal/oil) Medium-high (gas)
Replacement or supplementation of small-scale diesel generators with renewables	Low-medium	Low-medium	Improved air quality Less crop damage and extreme weather Reduced noise	Low-medium
Control of fugitive emissions from the fossil fuel industry	High	Low	Improved air quality Less crop damage and extreme weather	Low-medium[8]
Industry				
Improved brick kilns	Low-medium	Medium	Improved air quality Less crop damage and extreme weather	Low-medium[7]
Improved coke ovens	Low-medium	Medium	Improved air quality Less crop damage and extreme weather	Low-medium[7]
Control of fugitive emissions from the fossil fuel industry	High	Low	Improved air quality Less crop damage and extreme weather	Low-medium
Waste Management				
Landfill gas recovery	Medium	Low	Improved air quality Less crop damage and extreme weather	Low-medium[9]
Improved wastewater treatment (including sanitation provision)	Medium	Medium-high	Improved air quality Less crop damage and extreme weather Reduced infectious disease risk	Low-medium[9]

See Appendix I for details.
[1] Incorporates both the potential for major emissions reductions as well as the certainty that those reductions will have the desired climate effect. For example, reducing BC emissioans from BC-rich sources (e.g. diesel) will have less uncertainty than reducing BC from sources higher in co-emitted cooling agents (e.g. open burning). Near-term refers to anytime over the next few decades, though some climate benefits may occur almost immediately. [2] Assessed at the population level. [3] Assumes provision of safe infrastructure. [4] Increased efficiency may induce increased travel (a 'rebound') so should be combined with the complementary interventions (e.g. fuel taxes). [5] Note that potential climate benefit could potentially be offset by increases in nitrous oxide emissions, a long-lived greenhouse gas. [6] Avoid where there is a high risk of nutrient inadequacy. [7] Includes potential of CO_2 uptake by reforested land or use for bioenergy crops. [8] Does not include fugitive emissions, which are considered separately. [9] Includes potential displacement of fossil fuels by utilizing captured gas.

Panoramic view of pollution over Colombian capital, Bogotá. (Credit: Mariusz Kluzniak)

GLOSSARY[VI]

Black carbon: A product of incomplete combustion and an important component of particulate air pollution, black carbon is defined as an ideally light-absorbing substance composed of carbon. Black carbon is associated with adverse health outcomes (mortality and morbidity) and is a short-lived climate pollutant.

Carbon dioxide equivalent: A measure that incorporates the effect on global warming over a given time horizon of different greenhouse gases, using carbon dioxide as a reference. It allows for a single metric to be presented (and compared) when an intervention affects emissions from multiple climate forcing agents.

Climate forcer: Any gas or particle that alters the earth's energy balance, thus affecting the climate. Many climate forcers are greenhouse gases, but some, such as black carbon particles, are not.

Embodied emissions: The sum of the emissions produced during the whole life-cycle of a good (or service), from production through to end-use and disposal.

Exposure-response function: The estimated change in a health outcome associated with a given level of exposure to a stressor after a certain amount of exposure time. In air pollution epidemiology, the term "concentration-response function" is also common, as ambient concentrations are often used as a proxy for personal exposure.

Global warming potential: The potential contribution to radiative forcing over a specified time period resulting from the emission of one unit of a gas (or particle) relative to one unit of carbon dioxide, which has a designated value of one.

Greenhouse gas: Gaseous constituents of the atmosphere that absorb and emit infrared radiation, thus causing the greenhouse effect (which produces warming). Carbon dioxide, methane and ozone are examples.

Ozone: A short-lived climate pollutant, ozone is a highly reactive gas formed through chemical reactions of ozone precursors (mainly CH_4, CO, VOCs, and NOx) in the presence of sunlight. In the stratosphere, ozone has the beneficial effect of filtering out dangerous ultraviolet radiation, but tropospheric (ground-level) ozone is a harmful air pollutant.

Particulate matter (PM): A heterogeneous mixture of tiny solid or liquid particles suspended in the air. "Particulate matter" is sometimes used interchangeably with the term "aerosols," although the latter technically includes the suspending gas (usually air). Indicators of particulate matter usually refer to the mass of particles in a given size range, such as those with an aerodynamic diameter less than 10 μm (PM_{10}) or 2.5 μm ($PM_{2.5}$).

Primary pollutant: A pollutant that is emitted directly into the air.

Radiative forcing: A measure of the difference in energy from the sun received by the earth/atmosphere and the energy radiated back to space.

Secondary pollutants: Pollutants that are not emitted directly, but instead form in the atmosphere through chemical reactions.

Short-lived climate pollutant (SLCP): A gas or particle that has a climate warming effect and with an atmospheric lifetime shorter than carbon dioxide, often persisting for only days or weeks (longer for methane). Important examples include black carbon, methane, ozone, and hydrofluorocarbons. Some SLCPs are also harmful air pollutants.

Troposphere: The lower portion of the Earth's atmosphere. Ozone in the troposphere is a harmful air pollutant (stratospheric ozone produces beneficial effects by filtering out dangerous ultraviolet radiation).

[VI] More technical definitions for many of these (and other) terms are available from the IPCC and/or UNEP/WMO *(9, 60)*. These sources are the basis for many of these more simplified definitions.

LIST OF ACRONYMS			
AWDI	alternating wet and dry irrigation	GWP	global warming potential
BC	black carbon	HFC	hydrofluorocarbon
BCP	black carbon particles	IPCC	Intergovernmental Panel on Climate Change
CCAC	Climate and Clean Air Coalition	nmVOC	non-methane volatile organic compound
CH_4	methane	NO_2	nitrogen dioxide
CO	carbon monoxide	NOx	oxides of nitrogen
CO_2	carbon dioxide	O_3	ozone
CO_2e	carbon dioxide equivalent	PM	particulate matter
DALY	disability-adjusted life-year	SLCP	short-lived climate pollutant
EC	elemental carbon	UNEP	United Nations Environment Programme
EPA	Environmental Protection Agency	VOC	volatile organic compound
FAO	Food and Agriculture Organization	WMO	World Meteorological Organization
GHG	greenhouse gas		

Photo: Bus-rapid transit in Rio de Janeiro.
(Credit: Mariana Gil/EMBARQ Brasil)

Introduction

It is now well-established that human activity has interfered with the global climate system *(61)*. The resulting climate changes are expected to cause an array of adverse consequences, including disrupted livelihoods, ecosystem degradation, and an overall negative impact on human health *(62)*.

Anthropogenic emissions of greenhouses gases (GHG) and other climate forcers are the primary drivers of climate change. As a result, limiting emissions is a key mitigation strategy. Much of the policy attention has thus far focused on carbon dioxide (CO_2) emissions, which have increased dramatically since pre-industrial times and have not abated. However, emissions of other gases and particles also have important effects on climate, including short-lived climate pollutants (SLCPs).

SLCPs include methane, black carbon (BC), ozone and hydrofluorocarbons (HFCs). As the name implies, SLCPs persist in the atmosphere for anywhere from days to about a decade, while CO_2 remains for centuries (Figure 6). However, the radiative forcing of SLCPs is often higher per unit mass than CO_2 and therefore can strongly affect (near-term) climate.

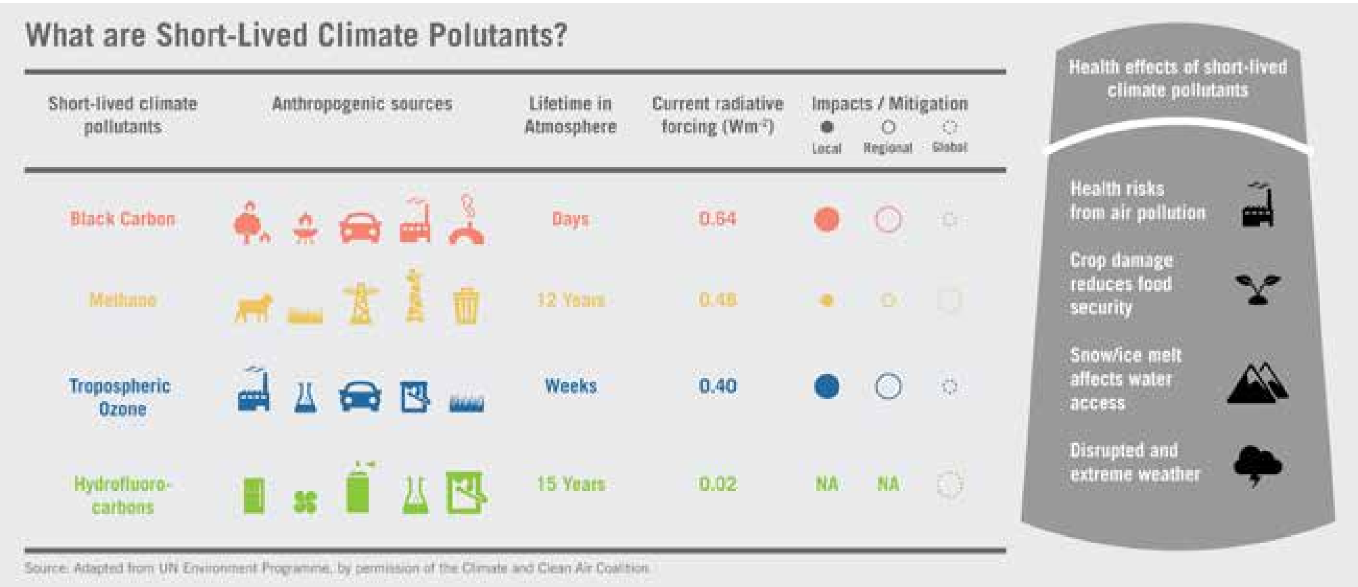


Figure 6. Properties of common short-lived climate pollutants. Note: "Current radiative forcing" refers to atmospheric changes due to emissions of climate forcers, from the pre-industrial era (1750) to the present, as reported by the Intergovernmental Panel on Climate Change. For reference purposes, the corresponding value for CO_2 is 1.82. Adapted from UN Environment Programme, by permission of the Climate and Clean Air Coalition.

Direct exposure to certain SLCPs is associated with ill-health. BC and ozone are the primary examples, as both have been linked to premature mortality and morbidity from a variety of adverse health outcomes *(1, 3-5, 19, 20)*. Methane is not a major health risk itself, but is an important ozone precursor. As a result, there is considerable scope to simultaneously improve public health while mitigating climate change by reducing emissions of SLCPs. Climate-health "co-benefits" are also well recognized in measures aimed at limiting CO_2, but as this report will demonstrate, addressing SLCPs has some distinct advantages when compared to some other potential climate change mitigation policies. Specifically:

- Many of the health benefits will accrue locally, near where mitigation actions take place. The same is true of (some) climate and weather effects.
- Health and climate benefits will occur soon after emissions reductions.

Another important feature of SLCP mitigation is that even though many of the health co-benefits will result from reduced emissions, large additional benefits may also occur for reasons independent of the reduced emissions. For example, promoting active travel (walking/cycling) will not only reduce particle emissions (including black carbon), but can increase physical activity and reduce noise pollution as well.

For these reasons, reducing SLCP emissions provides a unique opportunity for implementing "win-win" policies that improve health and mitigate near-term climate change, with many of the potential benefits realized on a temporal and spatial scale that is appealing for local and national policy-making. However, long-term climate change will largely be determined by CO_2 emissions; therefore, SLCP-related policies should be viewed as complementary to CO_2 policies, not as a replacement *(9)*.

In order to design the most effective policies, it is important to have a good understanding of how SLCPs (and their co-pollutants) influence public health, and to tailor policy messages to the needs of policy-makers. Accordingly, this document synthesizes a now-considerable literature on SLCPs to summarize the state of evidence linking them to human health, and outlines priority areas for mitigation action.

Chapters 1 and 2 review the health effects of black carbon and ozone, relying heavily on existing systematic reviews and meta-analyses. Each chapter incorporates background information about the pollutant, including its radiative forcing mechanisms, main emission sources, and common co-pollutants. The focus, however, is on describing the relevant health effects research and outlining key areas of uncertainty. Meth-

Old diesel vehicles are a key source of black carbon emissions, which have major effects on both human health and the climate. (Credit: Ben Welle)

Solar power in off-grid communities can reduce reliance upon diesel powered generators which are a source of black carbon emissions as well as of air pollution. (Credit: Abbie Trayler-Smith/Panos Pictures/UK Department for International Development - DFID)

ane and other ozone precursors are discussed in Chapter 2. HFCs are not given their own chapter because at current concentrations they are not a direct source of health problems at the population level. However, because they are strong warming agents and their use can be reduced through mitigation actions that also benefit health, such as through improved building design, HFCs are discussed accordingly.

It is important to note that there are also short-lived climate forcers that, unlike the SLCPs mentioned thus far, generally have a net cooling effect. Some, such as organic carbon and sulfates, have also been associated with ill health (note however, that a fraction of organic carbon known as brown carbon absorbs sunlight and has a warming effect) *(4, 63, 64)*. We do not discuss these in the same detail as BC and ozone, as their reduction will not be the focus of policies intended to mitigate climate change. Still, they are hugely important to consider when designing SLCP mitigation actions (see Chapter 1 in particular for more details).

Chapter 3 focuses on potential indirect health impacts associated with emissions of SLCPs. These include impacts on food security from changes to crop productivity and effects on climate and weather. This report does not review expected health impacts from global climate change itself, which are likely to be adverse overall, as these have recently been assessed in depth by the Intergovernmental Panel on Climate Change (IPCC) and the WHO *(62, 65)*.

Chapters 4–11 describe policies capable of reducing SLCPs and mitigating their health impacts. Chapter 4 summarizes two multi-sector studies that help set a foundation for Chapters 5–11, which are sector-by-sector analyses that identify priority sectors and policies where mitigation action can maximize climate-health co-benefits.

The final chapter (Chapter 12) presents the conclusions with subsequent appendices providing some additional technical detail, including information on how different interventions were rated in terms of their health and climate impacts and how the relevant scientific literature was identified. There are also links to some ongoing climate change mitigation projects aimed at SLCPs.

PART I

Scavenging in Jakarta, Indonesia. Landfills are a major source of methane emisisons. Improved landfill management can capture this methane as a clean fuel source as well as reducing other health risks, e.g. from landfill scavenging and leachage into water sources. (Credit: Jonathan Mcintosh)

PART I: HEALTH EFFECTS OF SLCPs

Part I describes the links between SLCPs and human health. Although it draws heavily on the epidemiological literature, it is a summary that does not assume a high level of technical expertise; like the rest of the document, these chapters are aimed at policymakers and are written accordingly.

The first two chapters focus on black carbon and ozone respectively. Both are air pollutants that have been associated with a range of health problems, and these are described in detail. The third chapter discusses more indirect routes through which SLCPs can affect health, for example through changes in agricultural productivity and weather patterns.

The information found in these chapters will also help the reader to understand how the SLCP mitigation actions presented in Part II are likely to affect population health.

1

A woman wears a mask to protect herself from air pollution.
(Credit: Nicolò Lazzati)

Chapter 1: Health effects of black carbon and links with particulate matter

Chapter highlights:

• Black carbon (BC) is a component of combustion-derived particulate matter, a type of particulate matter that may be particularly harmful to health.

• BC may be a universal carrier of toxic components of combustion-derived particulate matter (PM)

• BC has been associated with an increased risk of mortality and morbidity in meta-analyses of epidemiological studies.

• BC is often co-emitted with other types of particles associated with ill health.

• Health impact assessments of mitigation actions aimed specifically at combustion-related particles (e.g. from traffic abatement policies) could underestimate potential health benefits if using effect (relative risk) estimates for undifferentiated particulate matter.

• Despite the growing evidence, more research is needed to conclusively differentiate the health effects of the constituents of particulate matter.

This chapter describes the state of evidence linking black carbon and human health. The first two sections focus on exposure to ambient (outdoor) pollution, as most of the health research on black carbon has been conducted accordingly. However, many aspects of this discussion also apply to the household environment, which is the topic of the third section *(66)*.

Health effects of particulate matter: a brief summary

Epidemiological studies exploring the association of air pollution and health have generally focused on exposure to particulate matter (PM), which refers to a heterogeneous mix of tiny solid or liquid particles suspended in the air. Indicators describing PM usually denote its mass concentration and most commonly refer to particles with an aerodynamic diameter less than 10 µm (PM_{10}) or 2.5 µm ($PM_{2.5}$). PM is a complex mixture composed of dozens of biological and chemical constituents of both anthropogenic and natural origin *(67)* (Figure 7). Some particles are emitted directly, while others are formed through reactions in the atmosphere. BC is a type of particle that is emitted directly and often comprises around 5-15% of fine PM (see Box 1 for a general description of BC, its sources and climate effects) *(9, 36, 68)*. The composition of PM varies by location (and time) and depends on local sources as well as PM transported from elsewhere *(69)*.

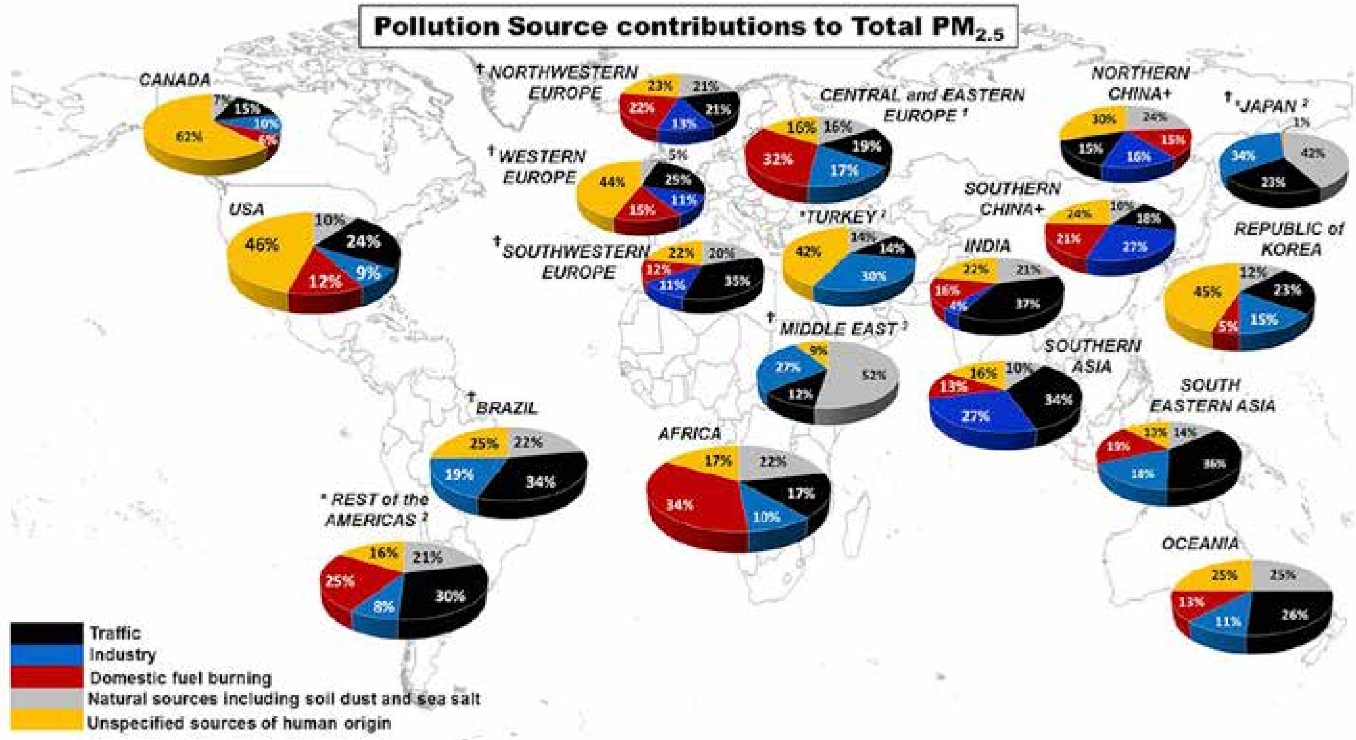


*Figure 7. Population-weighted averages for relative source contributions to total $PM_{2.5}$ in urban sites. *,† regions in which (*) unspecified sources of human origin and (†) domestic fuel burning sources have not been assessed.[1] Based only on one study including domestic fuel burning, and therefore only provides indicative results.[2] Based only on two studies, and therefore only provides indicative results. (See the source reference for details on interpreting this figure, which is constrained by limitations including heterogeneity in reporting of source sectors, an inconsistent distinction of household fuel combustion, a lack of allocation of secondary aerosols and a relatively large unspecified category). Source: Karagulian et al., 2015 (67).*

There is strong evidence for a causal association between both short-term (hours/days) and long-term (months/years) exposure to ambient PM and a range of adverse health outcomes (mortality and morbidity), though studies have mainly focused on cardiorespiratory disease, lung cancer, and all-cause mortality (Figure 8) *(1-4, 29, 70)*. Health risks from long-term exposure to $PM_{2.5}$ are much larger than those from short-term exposure, and represent more than the cumulative impacts of repeated short-term exposures *(3, 4, 70)*. Toxicological studies support the epidemiological evidence showing a number of possible biological mechanisms for the observed outcomes, such as systemic inflammation and vascular dysfunction *(1)*. The epidemiological literature indicates that there is no safe level of PM exposure below which no population health effects are evident, but that risks may vary: the change in risk per unit increase in exposure is generally larger at lower levels *(1, 4, 66)*. To summarize, it appears that all-cause mortality increases by about 7% for a 10 $\mu g/m^3$ increase in long-term exposure, at least in areas with low-to-moderate levels of pollution *(27)*.

In terms of total health impact, the burden of disease from ambient outdoor $PM_{2.5}$ was estimated at 3.7 million deaths globally in 2012 (Figure 8), 88% of which occurred in low- and middle-income countries *(6)*. If exposure is reduced, the elevated health risks appear to be at least partially reversible in the first few years after the reduction *(71)*. To help diminish the sizeable health burdens from PM, the WHO provides air quality guidelines (Table 9), while many countries and regions also have their own standards.

Table 9. World Health Organization guidelines for particulate matter (PM) *(29, 47)*.

WHO air quality guidelines for particulate matter	
PM_{10} annual	20 $\mu g/m^3$
PM_{10} 24-hr mean	50 $\mu g/m^3$
$PM_{2.5}$ annual	10 $\mu g/m^3$
$PM_{2.5}$ 24-hr mean	25 $\mu g/m^3$

Black carbon and ambient air pollution

Reviews and meta-analyses of the PM-health relationship often find that the magnitude of effect differs across studies *(1, 3, 72, 73)*. This is likely attributable to a number of factors, but differences in the composition of PM have emerged as one potentially important reason *(1, 3, 4, 73, 74)*. The composition of PM in a given location depends in part on local emissions sources, and particles from certain sources such as combustion-related PM may be particularly harmful, although this is not yet definitive *(3, 20-22).*

As an important component (and marker) of combustion-related PM, there has been growing interest in the potential health effects of BC. As mentioned, BC often comprises 5-15% of ambient $PM_{2.5}$ concentrations. BC particles are generally small (≤ 2.5 µm), including those falling into the ultrafine category (<100 nm), and penetrate deeply into the lungs *(9, 19)*.

A 2011 systematic review and meta-analyses by Janssen et al. (and the 2012 update) investigated the relative effect sizes of BC versus PM using epidemiological studies that quantified exposures to both *(19, 20)*. The individual studies reviewed used different but related exposure metrics (BC, black smoke, absorbance or elemental carbon). Therefore the following paragraphs adopt the terminology of Janssen et al. (2011), referring to the specific metric where possible or using the term black carbon particles (BCP) as an inclusive term where these were analyzed jointly.

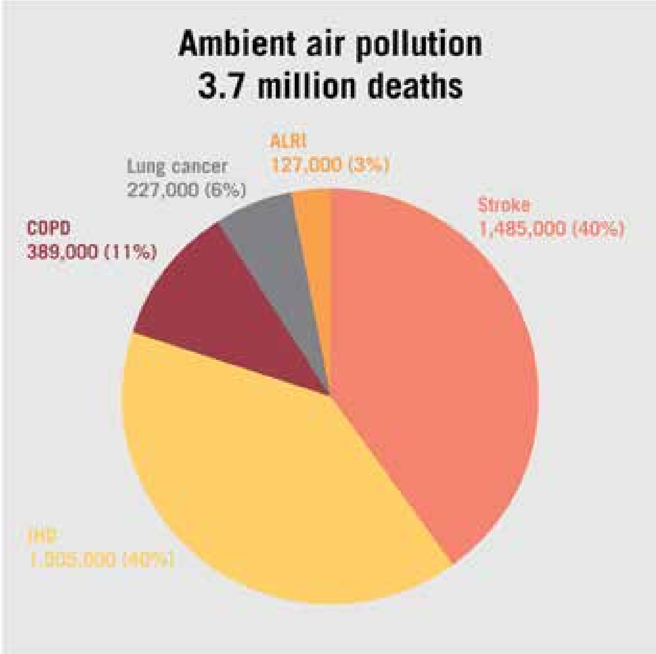


Figure 8. Deaths attributable to ambient air pollution, 2012. ALRI = acute lower respiratory infections; IHD = ischemic heart disease; COPD = chronic obstructive pulmonary disease. Source: WHO, 2014 (6).

The results of their meta-analysis of short-term exposure, based on time-series studies, shows strong evidence for an association between black smoke and all-cause and cardiovascular mortality (Table 10). Black smoke was also associated with all-age hospital admissions for cardiovascular disease, as well as admissions for specific cardiorespiratory diseases in certain age groups (not shown). Effect sizes for the same unit increase in mass were generally larger for black smoke compared to PM_{10}, though these were comparable when expressed per interquartile range (IQR) of exposure.[VII] A comparison of the effects of BCP and $PM_{2.5}$ showed similar results: a higher effect per µg/m³ increase, but similar effects when expressed as a change in the IQR. (In other words, on an absolute basis, BC may have stronger effects, but in terms of the relative impact of PM or the component of PM that is BC, the effects are likely to be similar.)

The small number of available studies that compared effect sizes using two-pollutant models suggested that the effects of BCP are more robust than the effect of PM. In studies that compared the effect sizes of many individual components of PM, elemental carbon (EC) tended to have some of the strongest associations. This is supported by some newer analyses but not others *(21, 73, 74)*; therefore, more work is needed in this area.

[VII] In statistics, the interquartile range refers to the difference between the upper and lower quartiles, also known as the 75th and 25th percentiles. It is therefore a relative measure (rather than an absolute measure) that depends on the specific dataset being described. In terms of ambient air pollution, concentrations of undifferentiated $PM_{2.5}$ are virtually always higher than concentrations of black carbon (black carbon is a component of $PM_{2.5}$). Therefore, a reduction of one µg/m³ of black carbon would indicate a greater relative impact on exposure to that pollutant than a one µg/m³ reduction in $PM_{2.5}$. However, the relative impact on exposure of a reduction by one interquartile range is, by definition, the same for both. In this context, it is important to note that an intervention that reduces emissions from a specific source of $PM_{2.5}$ may have a similar (relative) impact on exposure to black carbon, or it may have a disproportionate impact. For instance, if the intervention was aimed at an emission source that is particularly rich in black carbon, exposure to black carbon would be more reduced in relative terms than would exposure to undifferentiated $PM_{2.5}$.

Table 10. Selected effect estimates from meta-analyses of exposure to black carbon particles			
Study	Exposure	Mortality outcome	Percent increase (95% CI)
Short-term exposure			
Janssen et al. (2011) *(20)*	10 μg/m³ BS	All-cause	0.68 (0.31, 1.06)
	10 μg/m³ BS	Cardiovascular	0.90 (0.40, 1.41)
	1 μg/m³ EC	All-cause	1.45 (1.32, 1.57)
	1 μg/m³ EC	Cardiovascular	1.77 (1.08, 3.08)
Long-term exposure			
Janssen et al. (2011)	1 μg/m³ EC	All-cause	6 (4, 9)
Hoek et al. (2013)	1 μg/m³ EC	All-cause	6.1 (4.9, 7.3)
BS = black smoke, EC = elemental carbon			

Fewer studies have quantified the association between long-term exposure to BC and health. In the meta-analysis by Jansen et al. that included cohort studies that examined both EC and $PM_{2.5}$, the former showed a relative risk 7-16 times higher than the latter when expressed per unit mass; but again, effect estimates would be similar for an IQR increase in exposure *(20)*. In a more recent meta-analysis, Hoek et al. (2013) found a similar pooled effect size to that of Jansen et al. (Table 1). Additionally, unlike their analysis for $PM_{2.5}$, Hoek et al. noted that the magnitude of the EC estimates were very consistent across studies *(3)*.

Despite the evidence of an association between BC and mortality/morbidity, epidemiological studies alone are not sufficient to establish causation. Toxicological evidence, though limited, has not demonstrated that BC or EC is a directly toxic component of PM *(19)*. Instead, the associations of BC may be attributable to other co-varying constituents of combustion-derived particles, and/or BC may act as a "universal carrier" of toxic components of PM that bind to BC particles after emission *(3, 4, 19, 20)*.

The finding that effect estimates for BC tend to be higher than for PM_{10} or $PM_{2.5}$ per unit increase in mass but are similar for a given change in the IQR of exposure has important implications when quantifying the potential health benefits of pollution abatement policies. When policies target PM generally – and PM components are therefore expected to decrease in more or less equal proportion – it will make little difference whether the potential health benefits are estimated based on effect sizes of PM or BC. However, for policies targeting combustion emissions in particular, assessments based on PM may underestimate health benefits and therefore effect estimates for BC may be more appropriate *(19)*. For example, Janssen et al. (2011) conducted a simple calculation for a hypothetical policy that would reduce traffic-related $PM_{2.5}$ by 1 μg/m³, finding that the associated increase in life expectancy for people living near roadways would be five times higher when using a BC effect estimate compared to one for PM *(19)*. This is of notable relevance with regard to policies aimed at reducing SLCP emissions, as they will specifically target BC and therefore combustion-derived particles.

Black carbon and household air pollution

For the purpose of this report, household air pollution refers to air pollution inside or near the household, whether from fuel used for cooking, lighting, or space heating. In practice, the vast majority of evidence relates to household air pollution resulting from cooking with solid fuels.

Nearly 2.8 billion people worldwide cook primarily with solid fuels *(79)*. The latest WHO estimates (2012) attributed about 4.3 million premature deaths to household air pollution exposures (Figure 10). Burden of disease estimates (a measure that includes both morbidity and mortality), regularly updated, have shown that household air pollution has long been, and continues to be, the most significant environmental health risk in terms of the total loss of healthy life. *(7, 8, 44)*. Furthermore, the contribution of household air pollution to ambient air pollution is often considerable; it is estimated to be responsible for about 12% of outdoor combustion-derived $PM_{2.5}$ globally *(44)*.

Air pollution from cooking with solid fuel. (Credit: Romana Manpreet/Global Alliance for Clean Cookstoves)

Although everyone is exposed to ambient air pollution, the higher disease burden attributable to household air pollution is mainly a result of very high exposures experienced by members of solid fuel-using households. Average personal exposures in solid cooking fuel-using households have recently been estimated at 204 µg/m³ for men and higher for women (337 µg/m³) and children (285 µg/m³), which are all over 20 times WHO guideline levels (Table 9) *(44)*.

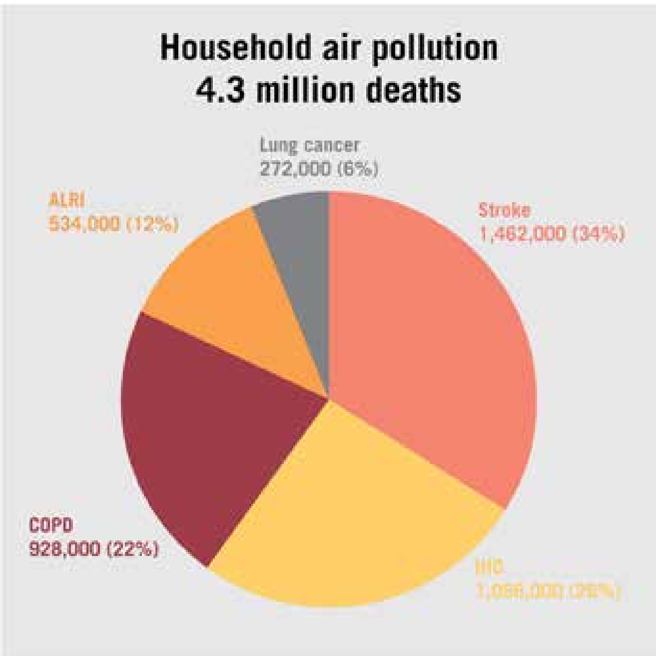


Figure 10. Deaths attributable to household air pollution, 2012. ALRI = acute lower respiratory infections; IHD = ischemic heart disease; COPD = chronic obstructive pulmonary disease. Source: WHO, 2014 (7).

BC, as a product of (incomplete) fuel combustion, is a major component of biomass-burning emissions and therefore of household particulate air pollution. The quantity of BC emitted per kg of fuel can be high, and residential biofuel combustion has been estimated as the single largest anthropogenic source of BC globally *(9, 23)*. However, there has not been much research into the specific health effects of BC in household environments; exposure to $PM_{2.5}$ is generally used in epidemiological studies *(44)*.

Due to the high disease burdens, the relatively BC-rich emissions (see side panel) and the many options for reducing household emissions, there is substantial scope for climate-health co-benefits from addressing the traditional use of solid fuels (see Chapter 7 for a more detailed discussion). However, it is important to note that because exposure-response functions for $PM_{2.5}$ are non-linear and, generally speaking, tend to weaken (though remain significant) at higher exposure levels, substantial reductions in exposure may be required to produce large health benefits *(44, 66)*.

Box 1. What is black carbon?

Put simply, BC refers to the dark carbonaceous component of particulate air pollution and is commonly referred to as soot. More formally, BC is defined as an ideally light-absorbing substance composed of carbon *(75).* It is a product of incomplete fuel combustion, mainly of fossil fuels (diesel, kerosene, and coal) and biomass, with the latter referring primarily to solid biomass burned for household use, as agricultural waste or during wildfires *(9, 23, 76).* Specifically, data from 2005 show that residential and commercial combustion and transport together account for approximately 80% of anthropogenic BC emissions (Figure 9). These estimates, however, do not include open burning (e.g. forest fires or agricultural fields), which is the single greatest BC source overall *(9, 23)*. These are also important sources of particulate air pollution generally, of which BC is only one component.

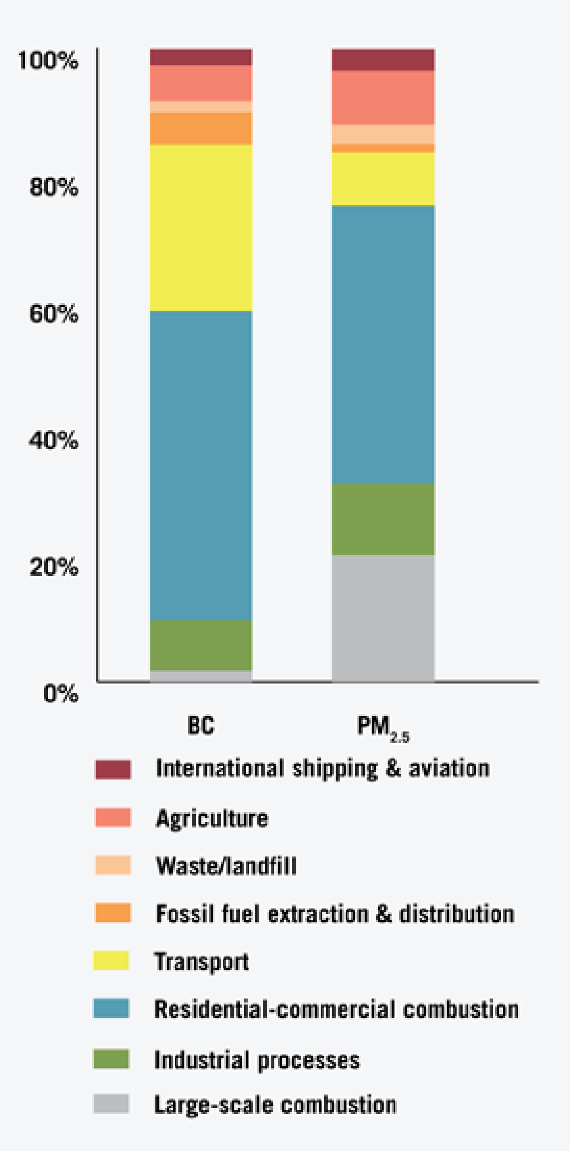


Figure 9. Anthropogenic BC and $PM_{2.5}$ emissions by sector, 2005. Note that open burning (e.g. forest or brush fires) is not considered here as an anthropogenic (human-made) source, although it is the single largest BC emission source overall. Source: UNEP/WMO, 2011 (9).

BC persists in the atmosphere for only a matter of days. Deposition is the main removal process. Consequently, concentrations of BC can vary over short distances and tend to be highest in areas close to emission sources, such as near roadways with heavy traffic and inside households cooking with sold fuels *(19)*. It is however possible for BC to travel long distances, including in transcontinental "brown clouds" *(76)*. Without additional mitigation measures, BC emissions are expected to remain fairly constant to 2030, as increased emissions from economic growth will be offset by technological advances *(9)*.

BC impacts on climate and weather

BC affects climate and weather through several mechanisms *(9, 23, 76)*. In the atmosphere, BC particles absorb incoming solar radiation and re-emit the energy as heat. Due to its dark color, BC absorbs roughly a million times more energy per unit mass than CO_2 *(9)*. BC deposition also darkens surfaces, reducing reflectivity (albedo) and increasing heat absorption. This is particularly problematic when BC is deposited on snow and ice, which are light in color, as it facilitates increased melting and diminishes their otherwise substantial reflective capacity. As a result, the Arctic and glaciated areas are especially vulnerable to BC, compounded by the fact that some of these areas are also near major BC emission sources. In the Himalayas, for example, BC may be as important a contributor to the melting of glaciers and snowpacks as CO_2 *(76)*. Effects on cloud formation and rainfall are other pathways by which BC can affect climate, though the net impact of these effects is still somewhat uncertain.

Despite its short persistence, the global warming potential (GWP) of BC is estimated at ~3,200 over a 20-year period, or in other words causes around 3,200 times more radiative forcing than CO_2 on a per-unit basis (Table 11). (Note, however, that the GWP metric should be interpreted with caution, as it does not account for all BC climate impacts and because it produces effects on a time scale that is radically different from that of CO_2). Accordingly, BC has been one of the top contributors to the radiative forcing that has occurred over the last ~250 years (behind only CO_2 and probably methane) *(23, 28)*. Approximately 60% of BC radiative forcing thus far is attributable to fuel combustion (fossil or biofuel), about 30% to other biomass burning, and the rest to deposition on snow and ice *(28)*.

Evidence that BC is an important climate forcer is well established. However, during combustion BC is not emitted in isolation, but nearly always with a number of co-pollutants *(4)*. Unlike BC, some of these co-pollutants, such as organic carbon, can act to cool the climate. Therefore, mitigation actions aimed at limiting future warming need to consider not only the capacity for absolute reductions in BC, but also the ratio of the reductions relative to these co-varying cooling agents (see side panel for more detail on this important issue) *(9, 23)*.

Table 11. Summary of black carbon characteristics

Name	Primary or secondary	Main emission sources(s)	Atmospheric lifetime	Removal mechanism(s)	$GWP_{20†}$	Radiative forcing (W m^{-2}) ‡
BC	Primary	Combustion: mainly transport and residential/commercial	Days	Deposition	3200 (270, 6200)*	0.64 (0.25, 1.09)

† GWP = Global Warming Potential, and the estimate provided is for a 20-year time horizon, as calculated in reference (23).
‡ From reference (28) for a chance in emission over the period 1750 to 2010.
** Note that GWP does not fully represent black carbon's impact on climate, and should therefore be interpreted with caution (also see main text).*

Accounting for heating and cooling aerosols in black carbon mitigation

As mentioned, BC emissions have a strong warming effect, particularly when deposited on snow and ice. However, because BC is almost never emitted alone, the net climate effect of any targeted mitigation action depends on both BC and its co-pollutants, the latter including reflective cooling agents, such as many types of organic carbon *(23)*.

This is an emerging research area whose importance should not be understated. The most recent IPCC assessment (AR5) explicitly warns that reducing particle emissions for air quality purposes without considering the cooling properties of some components could lead to rapid near-term warning *(28)*.

The implication therefore is that policies aimed at reducing BC for climate purposes need to focus on those actions that reduce emissions with a high heating-to-cooling ratio. In a recent major scientific assessment of BC, the authors emphasize this point and differentiate emission sources based on their likelihood of producing net warming *(23)*. They pinpoint diesel engine emissions as the best mitigation opportunity from this perspective, with residential solid fuel use and certain industrial activities (e.g. the use of traditional brick kilns) also likely to be suitable. New studies that have accounted for the warming effects of brown carbon, a fraction of organic carbon that absorbs sunlight, further suggest that addressing the burning of biomass fuels (including some types of open burning) is likely to be a good target for climate mitigation *(77, 78)*. Location also plays a role, with BC mitigation actions likely to have a more beneficial effect if occurring near snow and ice.

Despite these issues, if the potential health benefits are large enough or if the reduction in cooling aerosols is part of a wider strategy leading to deep cuts in GHGs, policies that may cause near-term warming should not necessarily be disregarded outright. Policy-makers will need to balance the costs and benefits of different strategies to determine which policies are most in line with their goals, and competing interests can be considered in multi-criteria decision-making approaches.

2

Smog over Delhi, India. Tropospheric ozone is a major constituent of urban smog and is an SLCP. (Credit: Jean-Etienne Minh-Duy Poirrier)

Chapter 2:
Health effects of ozone

Chapter highlights:

• Ozone is a SLCP and highly reactive gas that is formed when precursors react in the atmosphere in the presence of sunlight.

• As ozone is not emitted directly, control measures must focus on the precursor emissions.

• There is strong evidence from epidemiological and toxicological studies that ozone is causally associated with adverse respiratory effects ranging from changes in lung function and asthma to mortality. A causal association with cardiovascular effects and total mortality is also likely.

• An estimated 150,000 people died prematurely from respiratory disease in 2010 as a result of exposure to ambient tropospheric (ground-level) ozone.

Ozone is a highly reactive (oxidizing) compound present in both urban and rural areas. It is not emitted directly, but is formed when precursors react in the atmosphere in the presence of sunlight (see Box 3 for a general description of ozone, its sources and climate effects). A major review by the US Environment Protection Agency (EPA) recently determined that there is good evidence supporting a causal relationship between exposure to tropospheric (ground-level) ozone and respiratory effects, and a likely causal relationship with cardiovascular effects and total mortality *(5)*. Reviews by the WHO have reached similar conclusions *(4, 24)*. Although the two are sometimes correlated, health effects of ozone appear to be largely independent of the effects attributable to PM *(5, 80, 81)*. The WHO guideline value is 100 μg/m^3 (or below) measured as an average over an eight-hour period *(29)*.

In terms of respiratory disease, toxicological and clinical (controlled human exposure) studies have consistently reported outcomes including decreased lung function, inflammatory responses, and increased airway reactivity *(4, 5)*. Epidemiological studies of short-term (hours/days) exposure regularly find positive and statistically significant associations with respiratory hospital admissions and/or emergency department visits, including for asthma *(5, 80)*. The strength of effect varies according to location and season, but the increase in hospital admissions is normally about 1-6% for every 80 μg/m^3 increase in the 1-hour maximum ozone concentration (or equivalent change in the 8-hr maximum or 24-hr average) *(5)*. There is also good evidence that short-term ozone exposure is associated with respiratory mortality *(5, 80)*.

Cardiovascular effects have not been studied as extensively, but there is also evidence supporting a causal association between short-term exposure and cardiovascular system effects *(5)*. Toxicological and clinical studies report an effect of short-term exposure on heart rate variability, systemic inflammation,

Vehicle traffic contributes significantly to ozone formation through emissions of NOx, VOCs and CO. (Credit: Gemma Longman)

and oxidative stress *(4, 5)*. Epidemiologic studies find fairly consistent associations with cardiovascular mortality, but the interpretation is complicated by inconclusive evidence for an association with cardiovascular morbidity *(5, 82)*.

There is also strong evidence of a causal relationship with short-term ozone exposure and total (non-accidental) mortality *(5, 82)*. The effect sizes from different studies normally report a small but significant increase in mortality of up to about 4% for a 80 μg/m^3 increase in the 1-hour maximum (or equivalent change in the 8-hour maximum or 24-hour average) *(5)*. Because the lung contains antioxidant defenses, researchers have proposed that there may be a dose threshold below which ozone exposure does not have an adverse effect, although evidence is limited and inconsistent *(83)*. However, even if a threshold were discovered, it would likely be surpassed at relatively low ambient concentrations *(4, 84)*.

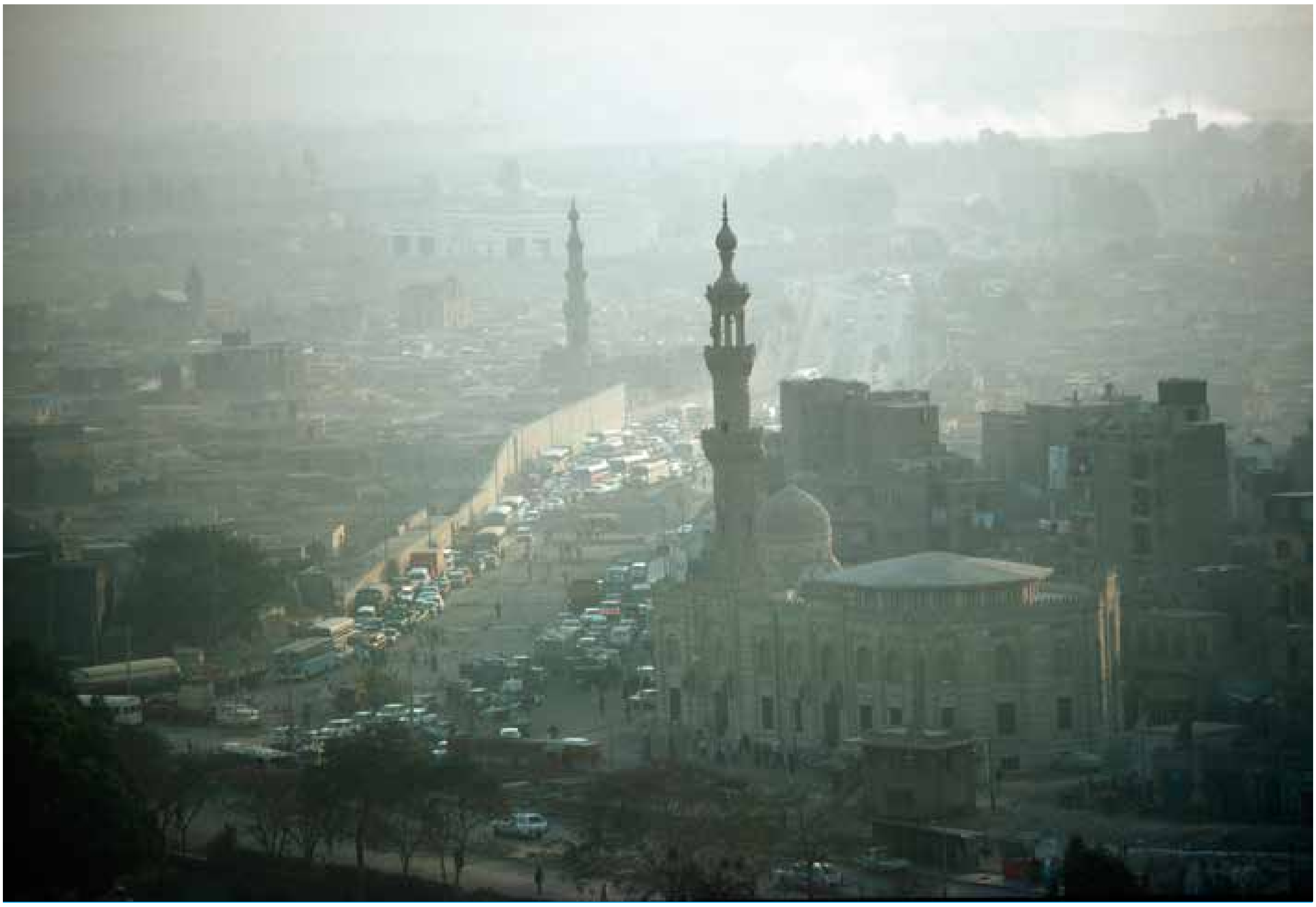
Fewer epidemiological studies have explored the association of long-term ozone exposure and health. A study using data on adults from the American Cancer Society cohort reported significant unadjusted associations with death from both cardiovascular and respiratory causes. However, only respiratory causes remained significant after $PM_{2.5}$ was included in the model, showing a 4% (1.3, 6.7) increase in respiratory mortality for an increase of 20 μg/m^{3}of ozone *(85)*. This estimate forms the basis for recent modeling of the global burden of disease attributable to ambient ozone exposure (Box 2). Other cohort analyses have also reported associations between long-term exposure to ozone and respiratory mortality *(4)*. In addition to respiratory effects, which have the strongest evidence base, recent reviews have noted credible evidence for a causal relationship between long-term exposure to ozone with cardiovascular, reproductive/developmental and central nervous system effects as well as total mortality *(4, 5, 70)*. There is no apparent threshold concentration below which health effects do not occur *(4)*.

Ozone is present worldwide, but exposure levels vary for a number of reasons. Among other factors, concentrations are affected by local precursor emissions, geography, and weather variables. Weather has multiple effects, as sun and temperature influence the ozone-producing reactions, while wind can move ozone over large distances ("transboundary" ozone), and rainfall affects ozone deposition. As a result, ozone concentrations normally consist of both a local component and a background component that has migrated from elsewhere and cannot easily be affected by local mitigation policies *(5)*. Ozone concentrations are often higher in suburban and rural areas compared to urban cores, in part because freshly emitted NOx in vehicle exhaust destroys ozone nearby, but helps produce it downwind *(5, 83)*. Specific episodes of ozone intrusion from the upper atmosphere to the boundary layer can also be a source of surface ozone.

Furthermore, although it may correlate moderately with outdoor ozone, indoor concentrations are generally much lower, meaning that people spending lots of time outside will have higher exposures *(5, 83)*. Children are considered particularly vulnerable to ozone-related health impacts, as they spend more time outdoors, do more physical activity (which causes faster and deeper breathing), and have higher metabolic rates compared to the general population *(5, 83)*. Athletes and people working outdoors are also considered susceptible for this reason *(5)*. Other populations at increased risk include people with pre-existing respiratory disease, older adults, people with certain genetic polymorphisms, and people with reduced intake of certain nutrients *(5)*.

Box 2. The global burden of disease attributable to ozone

Analyses conducted by the Institute for Health Metrics and Evaluation recently provided estimates of health impacts specifically attributable to ambient ozone exposure (8). Using the concentration-response functions for respiratory mortality from the American Cancer Society study (see main text), the researchers calculated the global disease burden resulting from long-term exposure to ambient ozone above a theoretical minimum level. Global exposures were estimated using atmospheric chemistry transport models. The researchers estimated that approximately 150 000 deaths were attributable to ambient ozone exposure in 2010, an increase of about 6% over 1990 (8).



Smog over Cairo, Egypt. (Credit: UN Photo/B Wolff)

Box 3. What is ozone?

Ozone is a secondary pollutant, meaning that it is not directly emitted. Instead, it is produced when CO, methane, or other VOCs are oxidized in the presence of NOx and sunlight. Together these compounds (CO, methane, non-methane VOCs, and NOx) are termed "ozone precursors." In addition to their role as ozone precursors, emissions of CO, VOCs and NOx are dangerous air pollutants themselves, thus providing additional impetus for their reduction. NO_2 in particular appears to be responsible for large disease burdens, with exposure linked to premature mortality and morbidity from cardiovascular and respiratory diseases *(4, 25-27).*

In the stratosphere, where ~90% of ozone is located, ozone plays a beneficial role, filtering out dangerous ultraviolet radiation. At ground-level (in the troposphere), however, it is harmful to humans and plants *(5, 86)*. After formation, ozone has a lifetime of days to weeks, which is shorter than some of its precursors, but longer than others (Table 12). Days with high ozone concentrations tend to be sunny and warm, which facilitates ozone formation, and also windless, which keeps the ozone from dispersing. Ozone is removed from the atmosphere through reactions that break its chemical bonds and also through deposition. Tropospheric ozone is a powerful greenhouse gas (warming agent).

Table 12. Characteristics of ozone and its four main precursors

Name	Effect	Primary or secondary	Main anthropogenic emission source(s)	Atmospheric lifetime	Removal mechanisms	GWP_{20}[1]	Radiative forcing[2] ($W\ m^{-2}$)
Ozone	Warming	Secondary	N/A	Weeks	Chemical, deposition	N/A[3]	0.40 (0.20, 0.60)[4]
Methane	Warming	Primary	Agriculture, fossil fuel industry, waste	~12 years	Chemical, soil uptake, migration to stratosphere	84	0.48 (0.43, 0.53)
CO	Warming	Primary	Transport, residential / commercial combustion	Months	Chemical	18.6 ± 8.3	0.23 (0.18, 0.29)
NOx	Uncertain (cooling likely)	Both	Transport, large-scale combustion	Hours to days	Chemical, solar radiation	-560 ± 279	-0.15 (-0.34, 0.02)
nmVOCs	Warming	Primary	Various	Variable (hours – years)	Chemical	14	0.10 (0.06, 0.14)

GWP = Global Warming Potential. [1] Based on a 20-year time horizon. Reflects estimates from the literature reported by the IPCC (18). [2] Estimates for precursors include impacts from ozone as well as other pathways and is from reference (28) and refers to the change in emission between 1750 and 2010. [3] GWP is not estimated for ozone, as it is a secondary pollutant. [4] Tropospheric only (does not include stratospheric).

Due to increased precursor emissions, ozone concentrations are estimated to have increased 2.5 times since pre-industrial times (1750), and may have increased up to five-fold in some regions *(5, 28)*. The different precursors have different sources (see Figure 11 and Table 12) and therefore mitigation policies can target a variety of sectors. However, from a climate mitigation perspective, methane deserves special attention, as it is itself a major SLCP and GHG. In terms of radiative forcing from GHGs, methane is currently second only to CO_2, and is also a primary contributor to the radiative forcing attributable to ozone *(28)*. Although other precursors are also radiative forcing agents (positive or negative: see Table 12), many studies have noted the most straightforward route to climate change mitigation is through methane reduction *(5, 9)*. Anthropogenic methane emissions are concentrated in the fossil fuel, agricultural, and waste management sectors (Figure 11). Controlling methane emissions, however, is not necessarily the most effective means for reducing ozone-related health (or climate) impacts *(87)*.

Box 3 (continued)

Tropospheric ozone is one of the most important greenhouse gases, affecting the climate by reducing the amount of infrared radiation that exits the earth's atmosphere *(28)*. It also inhibits photosynthesis and plant growth, thereby diminishing the ability of vegetation to absorb carbon dioxide from the atmosphere *(9, 28)*.

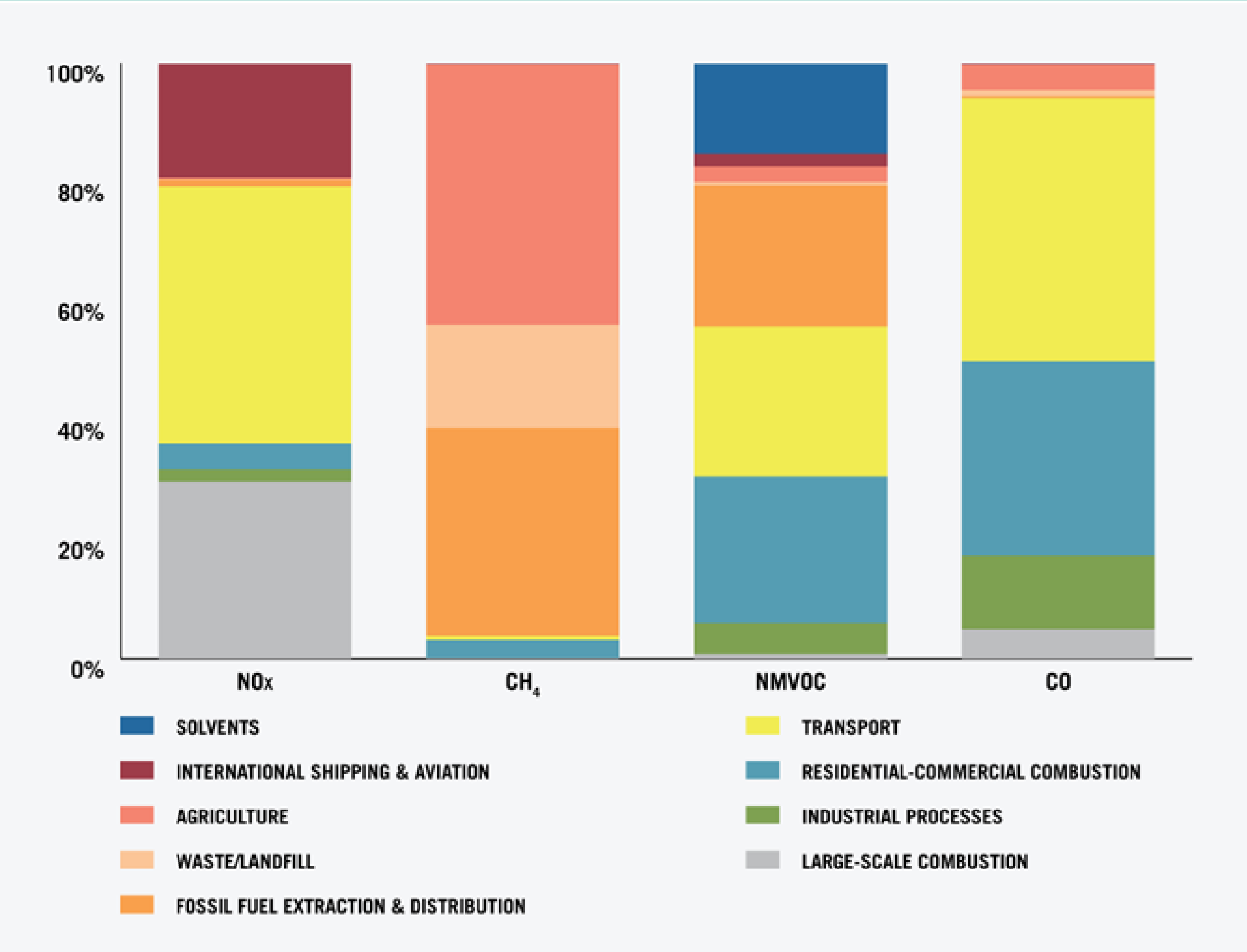


Figure 11. Sectoral shares of global anthropogenic emissions of ozone precursors, 2005.
Source: UNEP/WMO, 2011 (9).

3

Short-lived climate pollutants can reduce crop yields, thereby threatening food security in some regions. (Credit: Nicholas Boos)

Chapter 3: Indirect health impacts of SLCPs

Chapter highlights:

• Reducing emissions of SLCPs can indirectly improve health in many ways.

• Black carbon and ozone in the atmosphere reduce agricultural productivity, thereby threatening food security and nutrition.

• SLCP emissions can influence local and regional climates, which can affect air temperature and exposure to natural hazards. They also contribute to global climate change, which entails numerous additional health risks.

The previous two chapters focused on the evidence of health effects resulting from direct exposure to SLCPs, namely BC and ozone. However, SLCPs also exert indirect health effects through their impacts on plant growth as well as on near-term regional climate and weather processes. The following sub-sections outline the indirect pathways to health related to SLCPs that are capable of having a potentially important impact on population health.

Food security and nutrition

Ozone and BC in the atmosphere can both negatively influence plant growth and agricultural productivity. Ozone is toxic to a large number of agriculturally important species, affecting crop yields and nutrient composition, while BC can reduce the amount and quality of solar radiation available for photosynthesis *(9, 86, 88)*. Both SLCPs can affect agriculture (and ecosystems) through changes in weather and climate, including short-term effects on temperature, cloudiness, and rainfall. Modeling has suggested that implementing a suite of 16 mitigation actions to reduce BC and methane could prevent the loss of 52 million tonnes of maize, rice, soybean, and wheat annually, with possible implications for food security *(9)*. A study looking specifically at India recently estimated that the combined effects of climate and air pollution reduced the country's wheat yield by as much as 36% in 2010, with the majority of the reductions attributable to the direct effects of SLCPs *(88)*.

The relationships between food production, food security, and nutrition are complex. Globally, enough food energy is produced for everybody given equitable distribution *(89)*. Nevertheless, hundreds of millions of people are food insecure – they do not have stable access to a sufficient amount of high-quality food *(30)*.

Undernutrition (as opposed to food security) is generally defined in relation to growth and/or nutrient adequacy and is estimated to account for 45% of child deaths *(31)*. However, food security alone does not ensure adequate nutrition. Modeling studies indicate that non-food variables (environmental and/

or socioeconomic) have a strong influence on the prevalence of undernutrition *(32, 90, 91)*. Nutrient-depleting diseases (e.g. diarrhea, worms) can increase nutritional deficits *(92, 93)*.

It is therefore not easy to predict how reduced crop production due to ozone or BC will affect nutrition. Reduced yields for subsistence farmers will have a direct adverse impact, but the impact of diminished food production may also manifest through economic processes such as higher food prices. Food prices affect what people eat, in both high- and low-income countries, and studies have linked higher food prices to reduced food and nutrient intake and, in some cases, to growth faltering *(94-100)*.

A vegetable farmer waters her crops in Boung Phao Village, Laos. (Credit: Asian Development Bank)

Temperature

SLCPs affect near-term local and regional weather, in addition to their impacts on global climate change *(9, 101)*. This section is primarily concerned with the former, as temperature-related impacts from long-term global climate change (discussed below) may be modified by adaptation.

There is now a substantial literature investigating the association of temperature with mortality and morbidity. Studies from many parts of the world have demonstrated that health risks increase at high and low temperatures *(53, 54, 102-104)*. Higher risks are observed not only during temperature extremes, but also from short-term changes in ambient temperatures that are commonly experienced.

The relationships differ somewhat by location – this is likely due in part to adaptation, which may be physiological, behavioral, or related to infrastructure – but in most cities it is roughly U-shaped. In other words, there is a minimum mortality (or morbidity) temperature range with increasing health risks experienced as temperatures get colder and/or warmer beyond this range *(53, 104)*. Other factors likely affecting the temperature-mortality relationship include population characteristics, health service provision, and the prevailing climate *(102)*.

Studies on temperature and health often report associations with all-cause and cardiorespiratory outcomes (mortality and morbidity), but elevated risks have been reported across a wide range of causes *(54, 105)*.

Icefjord, Greenland is suffering first-hand the effects of climate change as the melting of ice sheets accelerates. Black carbon particles increase the warming impact of sunlight upon snow and ice, accelerating melt, and changing water resource patterns. (Credit: UN Photo/Mark Garten)

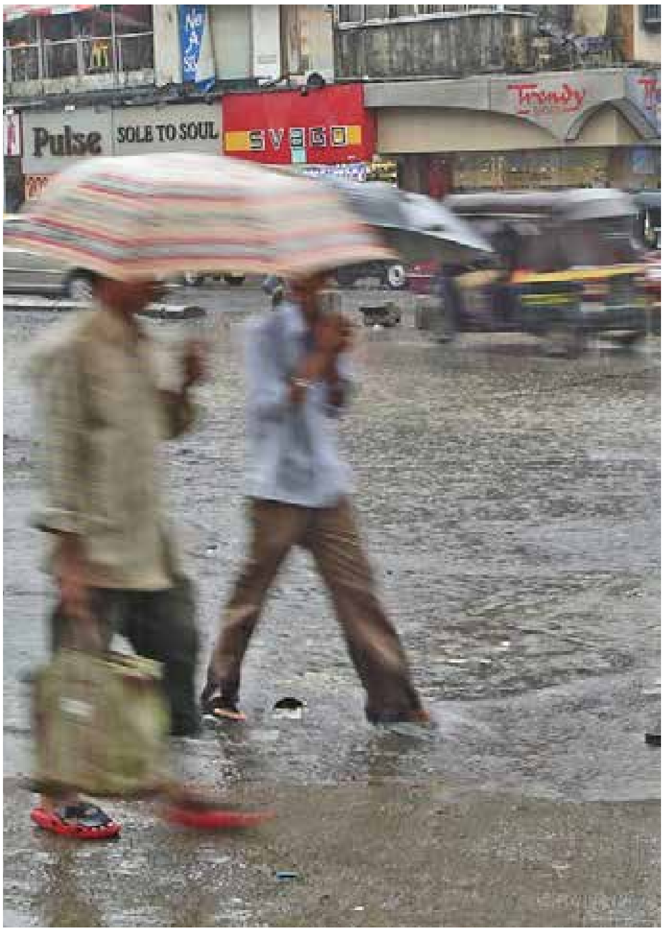
Natural hazards and disasters

A flash flood in Northern India that destroyed several hydropower projects. There is evidence that black carbon emissions can also change local weather patterns, leading to more extreme local weather conditions, e.g. flooding. (Credit: International Rivers/Matu Jansangthan)

In addition to contributing to global climate change (see below), SLCPs can more directly increase the risk of natural disasters, particularly flooding, by accelerating glacial and snow melt and by changing rainfall patterns, including of the Asian monsoon *(9)*. These changes may also compromise water supplies.

Disasters affect health and well-being in a variety of ways. Direct impacts include injuries and drowning during the actual event, but these are sometimes outweighed by indirect impacts such as loss of infrastructure (e.g. affecting water provision and sanitation), disrupted livelihoods, displacement, and mental health effects *(106-108)*. However, it is important to note that a natural hazard only becomes a disaster if exposure affects vulnerable populations. Potential vulnerabilities include a lack of warning systems, weak infrastructure, certain land-use practices and geographical features, inadequate emergency preparedness and response, and a variety of social/community factors *(107)*.

According to the UN Office for Disaster Risk Reduction, disasters affected 2.9 million people between 2000 and 2012, killed 1.2 million and caused nearly 2 trillion dollars in damages *(109)*. Floods were the most common disaster type, but earthquakes/tsunamis were responsible for most of the mortality impacts in absolute terms, largely attributable to a small number of highly impactful events *(110)*.



Monsoon showers cause waterlogging in Mumbai, India. (Credit: w:user:PlaneMad)

Global climate change

Many policies directed at SLCPs will have mitigation of global climate change as a primary objective. Reviewing the health impacts of global climate change is beyond the scope of this report, and has recently been addressed in depth by the IPCC, WHO and other international organizations *(62, 65, 111)*. In brief however, climate change is expected to increase health burdens from extreme weather events and increase risks from undernutrition and certain vector-, food-, and water-borne diseases. Despite some potential positive impacts (e.g. reduced cold-related mortality), impacts over the 21st century are projected to be strongly adverse overall, particularly if we continue on a high-emission trajectory *(62, 65, 111)*.

PART II

A popular pedestrian path in Beihai Park, Beijing.
(Credit: Michael Coghlan)

PART II: SLCP MITIGATION OPTIONS

Part II provides a sector-by-sector analysis of potential "win-win" policies capable of simultaneously reducing SLCP emissions and improving population health. The analysis draws on a review of the recent literature (see Appendix II) to identify the mitigation actions that will have the greatest health benefit. It is important to note that SLCP policies aimed solely at climate change mitigation are concerned primarily with the reduction of emissions, whereas those aimed at public health are concerned with the reduction of exposure. However, as the following sections will demonstrate, there is often substantial overlap of the two and many mitigation actions can provide benefits in both realms.

Part II has two components. The first (Chapter 4) is a summary of two major studies that have investigated potential climate benefits of SLCP mitigation actions. These studies provide a good starting point for the remainder of the report as they are systematic analyses across multiple sectors. Exploring potential public health impacts was not the primary objective of this research, though it was included in one of the studies.

The remaining chapters (Chapters 5-11) explore the key sectors where known interventions have the ability to both reduce SLCP emissions and improve public health. The mitigation actions discussed are not an exhaustive list, but focus on those actions likely to have the greatest potential for co-benefits and which also have a reasonably robust evidence base. The focus of the mitigation actions are generally either BC or methane, the latter being a SLCP and an ozone precursor (as a secondary pollutant formed in the atmosphere, mitigation actions cannot target ozone directly).

4

Bus-rapid transit in Taiwan. (Credit: xhowardlee/Flickr)

Chapter 4: Summary of two major multi-sector studies

Chapter highlights:

• A study from UNEP/WMO identified 16 SLCP mitigation actions, across a range of sectors, that could substantially reduce near-term warming while also preventing millions of deaths annually *(9)*.

• A 2010 study by Unger et al. (2010) found that the sectors producing emissions that most strongly influence near-term climate change are not necessarily the same as those responsible for longer-term climate change, with the possible exception of road transport which has important effects on both *(112)*.

UNEP/WMO study

A 2011 study by the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO) used a global modeling framework to evaluate the potential impact on climate change of ~2,000 existing SLCP mitigation actions *(9)*. The researchers determined that full implementation of only 16 of those actions – seven aimed at methane and nine at BC (Table 13) – could provide 90% of the potential maximum climate benefit that would occur if all 2000 measures were implemented. Together, the 16 measures could reduce future global warming by 0.5 °C (0.2, 0.7) (Figure 12) with disproportionate (positive) benefits in the Arctic, the Himalayas, and other glaciated and snow-covered regions. About 60% of the reduction in future warming was from the methane measures and the remainder was from BC mitigation.

The researchers also quantified the health benefits associated with the 16 measures, finding that they would prevent approximately 2.4 million (0.7 – 4.6) premature deaths annually (results were reported in aggregate but not for specific measures). About 60% of the avoided deaths were from biofuel combustion measures, and more than 80% of the benefits would occur in Asia. The vast majority of the health benefits resulted from the BC measures, mostly as a result of their contribution to $PM_{2.5}$ reductions but also through beneficial impacts on ozone-related mortality (the BC measures also reduce emissions of ozone precursors). The health benefits from the methane measures were much smaller, partly a function of ozone's relatively small effect on health when compared to $PM_{2.5}$ (methane measures have little impact on $PM_{2.5}$). In total, using country-specific values of a statistical life, the avoided deaths were valued at US$ 5 trillion. Other pathways to health (such as through reduced food production, temperature changes, and natural hazards) were not assessed, though the modeling did indicate potentially important impacts. Health impacts from household air pollution were also not fully quantified and morbidity was not assessed in any of the analyses.

Table 13. SLCP measures selected in the UNEP/WMO study to improve climate change and air quality *(9)*.	
Methane (CH_4) measures	
Extended pre-mine degasification and recovery and oxidation of CH_4 from ventilation air from coal mines	Extraction and transport of fossil fuel
Extended recovery and utilization, rather than venting, of associated gas and improved control of unintended fugitive emissions from the production of oil and natural gas	
Reduced gas leakage from long-distance transmission pipelines	
Separation and treatment of biodegradable municipal waste through recycling, composting, and anaerobic digestion as well as landfill gas collection with combustion/utilization	Waste management
Upgrading primary wastewater treatment to secondary/tertiary treatment with gas recovery and overflow control	
Control of CH_4 emissions from livestock, mainly through farm-scale anaerobic digestion of manure from cattle and pigs	Agriculture
Intermittent aeration of continuously flooded rice paddies	
BC measures (affecting BC and other co-emitted compounds)	
Diesel particle filters for road and off-road vehicles	Transport
Elimination of high-emitting vehicles in road and off-road transport	
Replacing coal with coal briquettes in cooking and heating stoves	Residential
Replacing current wood burning technologies in the residential sector in industrialized countries with pellet stoves and boilers, using fuel made from recycled wood waste or sawdust.	
Introduction of clean-burning biomass stoves for cooking and heating in developing countries	
Substituting clean-burning cookstoves using modern fuels to replace traditional biomass cookstoves in developing countries	
Replacing traditional brick kilns with vertical shaft kilns vand Hoffman kilns	Industry
Replacing traditional coke ovens with modern recovery ovens, including the improvement of end-of-pipe abatement measures in developing countries	
Ban of open burning of agricultural waste	Agriculture

Slash-and-burning woodlands for plantation agriculture in Thailand; open burning is the largest single source of global black carbon emissions. (Credit: mattmangum/Flickr)

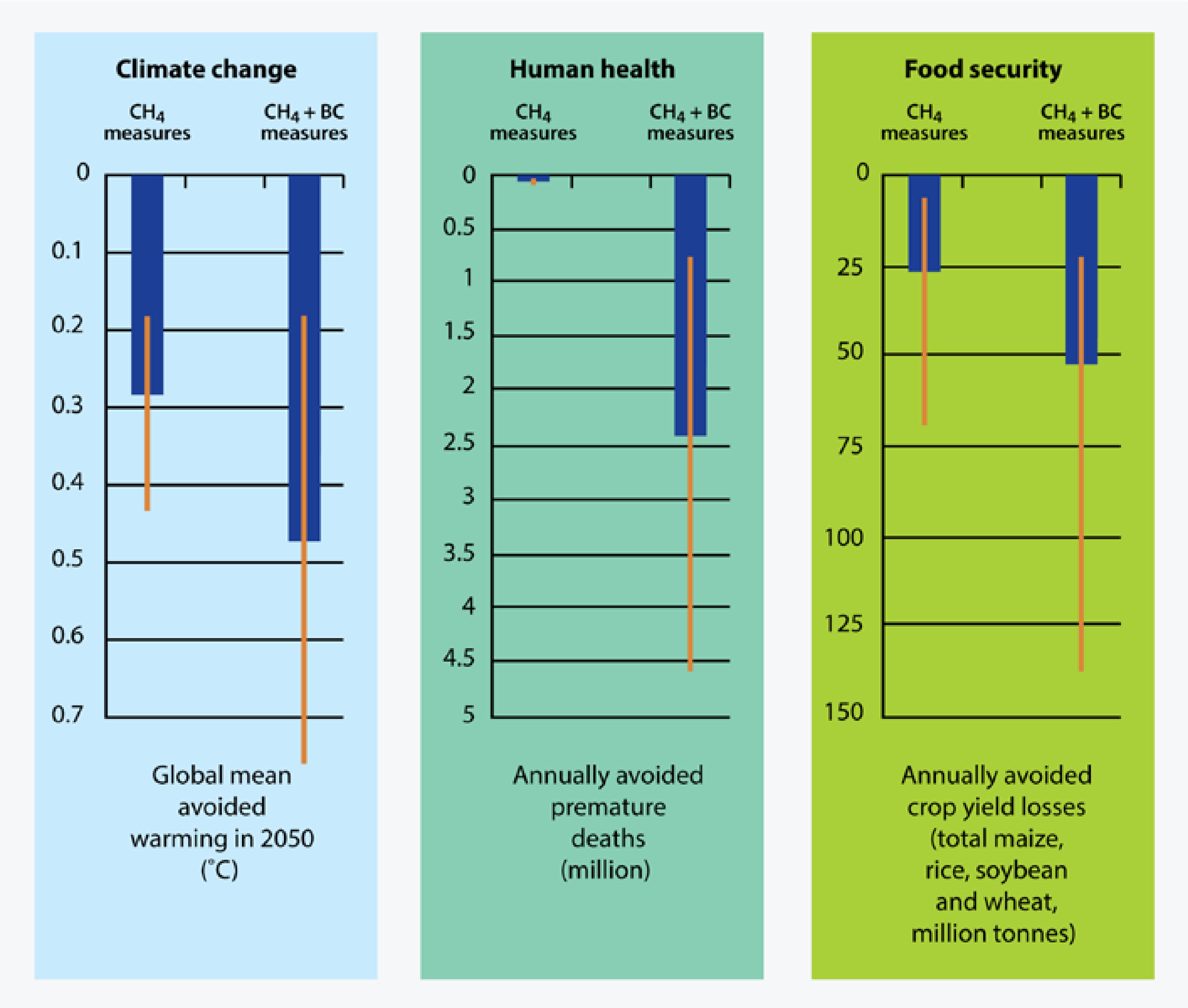


Figure 12. Estimated benefits in a given year (2050) from fully implementing by 2030 the 16 SLCP mitigation actions selected in the UNEP/WMO study. Source: UNEP/WMO, 2011 (9).

This study demonstrates the potential for large health co-benefits associated with SLCP mitigation, particularly when considering that the 16 measures were selected based solely on climate-related criteria. Another important finding from the study is that the SLCP measures would have substantial health benefits independent of the major anticipated CO_2 reduction measures, as the two types of policies largely target different sectors and sources. CO_2 measures will also not strongly influence near-term warming, although it is vital to address CO_2 emissions if dangerous climate change is to be prevented. The study affirms the need to complement CO_2 reduction policies with SLCP mitigation policies.

Updated estimates suggest even larger health benefits

The authors of this study recently conducted new analyses indicating that the health benefits of reducing SLCP emissions may be larger than previously estimated. Under an aggressive SLCP reduction scenario – which includes the original mitigation actions plus three additional measures (focusing on improved methane capture during fossil fuel extraction and hydraulic fracturing and shifting from the use of kerosene lamps to electric lighting) - roughly 2.5-3.5 million premature deaths may be prevented globally each year by 2030, rising to approximately 3.5-5 million per year by 2050 *(10)*. The higher estimates in comparison to the original study largely result from new emissions estimates and the three additional mitigation measures. A recent study looking at Southwest China has also reinforced the conclusion that aerosol emissions, including black carbon, can lead to increased risk of rainfall extremes and catastrophic flooding *(113)*.

Unger et al.

Unger et al. (2010) was one of the first studies to systematically model and compare the climate impacts of short- and long-lived climate forcer emissions from key economic sectors *(112)*. The analysis covered 13 different sectors and included both positive and negative climate forcers (ones that lead to warming as well as cooling. The authors performed their experiment by "resetting the anthropogenic clock to zero at year 2000" and allowing emissions to evolve for the next 100 years. In other words, they assumed no emissions occurred prior to 2000 and that emissions every year thereafter remained constant at 2000 levels.

Smoke from household biomass stoves, a key source of black carbon emissions and health risks, drifts outdoors in Oaxaca, Mexico. (Credit: Bryon Howes)

This approach allowed for a number of important insights. First, the sectors that contributed most to radiative forcing (warming) in the near-term (2020) were not always the same as those contributing most to long-term forcing (2100) (Figure 13). This results in part from the relative emissions of short-lived (both warming and cooling) compared to long-lived climate forcers: long-lived forcers become increasingly important as time passes. Second, the aggregate radiative forcing of the short-lived species from certain sources is sometimes negative (cooling) overall – despite

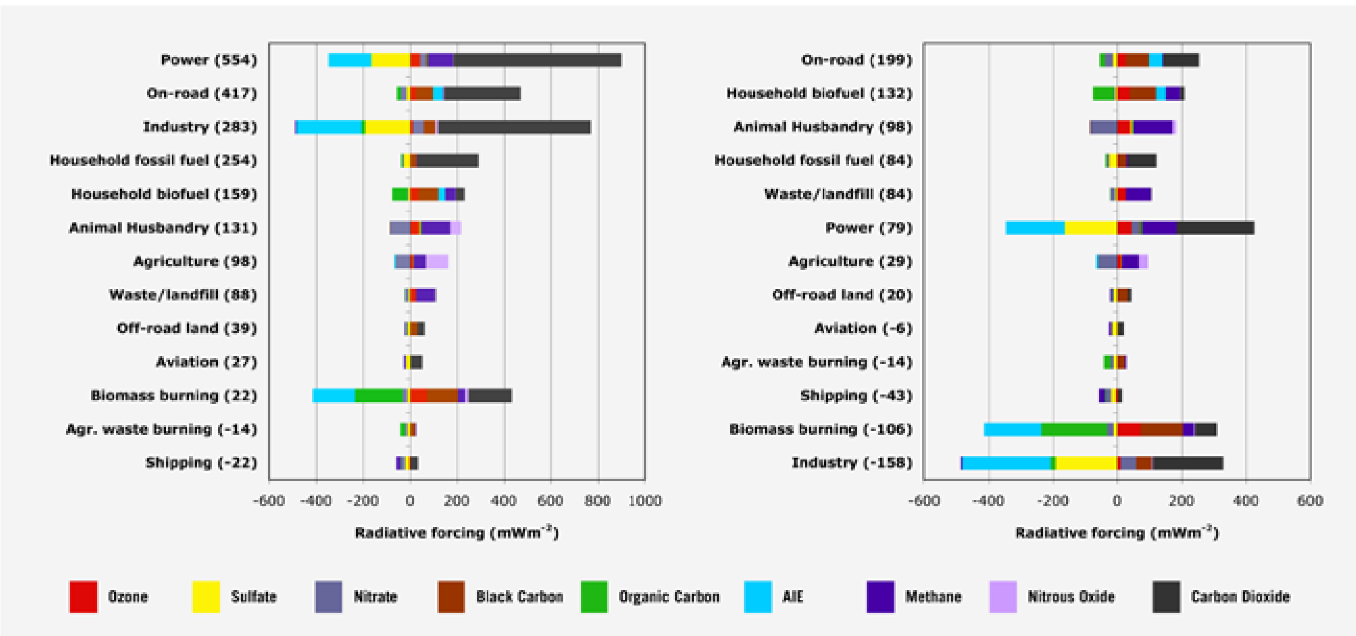


Figure 13. Radiative forcing due to perpetual year 2000 emissions grouped by sector in 2020 (left) and 2100 (right) and showing the contribution of each species. The net sum radiative forcing is indicated by the title of each bar. A positive radiative forcing means that removal will result in climate cooling. AIE = aerosol indirect effect. Source: Unger et al., 2010 (112).

the positive effects of BC – and can offset a considerable amount of positive forcing from the long-lived species, at least initially. Third, the sectors show substantial differences in the geographic distribution of their future radiative forcing. In sectors with a larger contribution from short-lived species, there is more spatial variability, as long-lived species become well-mixed in the atmosphere and therefore have more uniform global effects. And finally, the study underscores the importance of addressing both short- and long-lived climate pollutants.

In terms of prioritizing sectors, the authors note that road transport, animal husbandry, and household biofuel use present good opportunities to achieve immediate climate benefits through the reduction of SLCPs. Power and industry were identified as sectors to concentrate on for longer-term climate benefits. Road transport also provides a good option for long-term mitigation, singling it out as a priority on both temporal scales and also because of its association with health-damaging pollutants. The study did not quantify health impacts.

Traffic congestion in Ho Chi Minh City, Vietnam. (Credit: Ngô Trung)

5

Mexico city's recent mobility law, enacted in 2014, guarantees the right to mobility and prioritizes sustainable active transport. (Credit: karmacamilleeon/Flickr)

Chapter 5: Transport

Chapter highlights:

• The transport sector is a major source of black carbon and certain ozone precursors (e.g. NOx).

• Key mitigation actions to reduce SLCP emissions include improving vehicle technologies (e.g. using diesel particle filters), shifting to low-emission modes of travel (e.g. walking/cycling), and avoiding journeys (e.g. optimizing delivery routes).

• Health benefits from the available mitigation actions are potentially large and can occur through reduced exposure to air pollution, road traffic injuries, and noise as well as from increases in physical activity.

• Many SLCP mitigation actions in the transport sector have the potential for large CO_2 co-reductions.

Global GHG emissions in the transport sector increased 2.5 times between 1970 and 2010 (Figure 14) and were responsible for about 23% of total energy-related CO_2 emissions *(114)*. While most emissions currently originate from high-income nations, transport demand per capita in the future is expected to increase at a much faster rate in developing and emerging economies as a result of rising incomes and infrastructure investments *(114)*. Over the next few decades, emissions in the transport sector could increase more rapidly than in any other energy end-use sector *(114)*. In terms of SLCPs, over half of combustion-related BC emissions in Europe and the Americas result from fuel combustion in vehicle engines *(23)*. Transport is also a major source of NOx, which leads to the production of tropospheric ozone.

Compared to many other sectors, transport emissions (which are high in BC and some ozone precursors) are often concentrated near densely populated areas, in urban centers and near roadways – so human exposures can be high. As discussed in Chapter 1, there is some evidence that transport-derived particles may be more harmful than particles from other sources. The combination leads to high health burdens from road transport emissions, but also demonstrates that the sector has important opportunities for intervention. A recent study of Organization for Economic and Co-operation and Development (OECD) countries estimated that about 50% of the economic costs of outdoor air pollution resulted from road transport, albeit using broad-scale modeling assumptions that require further analysis *(115)*.

Policies to reduce emissions from road transport can be classified into three broad categories: AVOID, SHIFT and IMPROVE *(116)*. The AVOID category relates to journey avoidance and optimization. The SHIFT category calls for encouragement of modal shifts towards low-emission forms of transport, such as dedicated public and mass transport as well as walking and cycling. In the case of low-income and emerging economies, where most travel may already be via walking and cycling, this means prioritizing low-emissions motorized modes as demand for mobility grows. The IMPROVE category refers to technological improvements in motor vehicles and fuels. Aggressive pursuit of all strategies is essential to slow the rapid growth in transport emissions *(114)*, and each is described further below.

Note that this chapter focuses exclusively on land transport, as only a small proportion of SLCPs globally are emitted from marine and air transport *(9, 23, 114)*. Emissions from these sources may, however, be important in specific locations.

IMPROVE: Technological improvements

Technological approaches aim to reduce vehicle emissions without affecting the mode of transport. These include changes in engine characteristics, reducing aerodynamic drag, and retrofitting diesel particle filters (see Case Study 1 below), the latter capable of significantly reducing PM and BC (or EC) up to 90% or more *(117-119)*. Diesel particle filters require low-sulfur (< 50 ppm) to ultra-low-sulfur diesel (<15 ppm), which necessitates fuel refining technology, but this is available in most countries. It is important to note that diesel particle filters may not reduce other health-relevant emissions (e.g. NO_2) and could contribute to increases in some cases, so that other technologies are required to reduce this important ozone precursor *(120, 121)*.

Addressing emissions from diesel fuel is of particular note, as diesel emissions have strong associations with a variety of adverse health outcomes, are the largest source of BC emissions in many high-income countries, and are rapidly increasing in lower-income countries *(2, 4, 9)*. Diesel emissions also have a high proportion of BC relative to co-emitted cooling agents, making their reduction a favorable mitigation opportunity from a climate perspective *(9, 23)*. Additionally, diesel vehicles are a substantial contributor to NOx emissions – including the harmful air pollutant NO_2 – which is a major factor in ozone formation *(5, 24, 122, 123)*. NOx emissions have not been as carefully regulated as some other pollutants and evidence indicates that on-road emissions from diesel vehicles may be much higher than previously assumed *(124-126)*.

In addition to particle filters, setting stringent emission standards is another well-established strategy. For example, recent empirical work from California has linked substantial (up to 90%) reductions in ambient BC concentrations over the past few decades to diesel engine emission mitigation *(127)*. Health impact modeling has demonstrated the very substantial potential health benefits associated with realistic future implementation of tighter emission standards (Box 4).

Fuel-type innovations are another example of a technological approach. Vehicles using compressed or liquefied natural gas are already common in many regions, and experimental studies have reported reductions in PM and GHG emissions, though the latter is somewhat less clear *(132-135)*. The production of liquid biofuels has also increased dramatically in the last decade, due in large part from expectations of improved health and GHG characteristics *(136)*. However, the accumulating evidence is not clear on whether liquid biofuels reduce health-relevant emissions *(136-139)*, and there are additional concerns about competition for land and other agricultural inputs, which may lead to deforestation (negating any potential GHG savings) and upward pressure on food prices *(136, 140, 141)*. More advanced liquid biofuels may alleviate some of these concerns, but commercial production has only commenced recently *(142-146)*. Electric vehicles, which reduce tailpipe emissions to zero, are also gradually being introduced, but if the electricity is provided by fossil fuel combustion, emissions will occur at the source.

Ultimately, while technological approaches are an important element in SLCP mitigation, reducing reliance on private vehicles and motorized transport is at least as important, and can have additional benefits to health beyond improvements in air quality. This is discussed in the following sections.

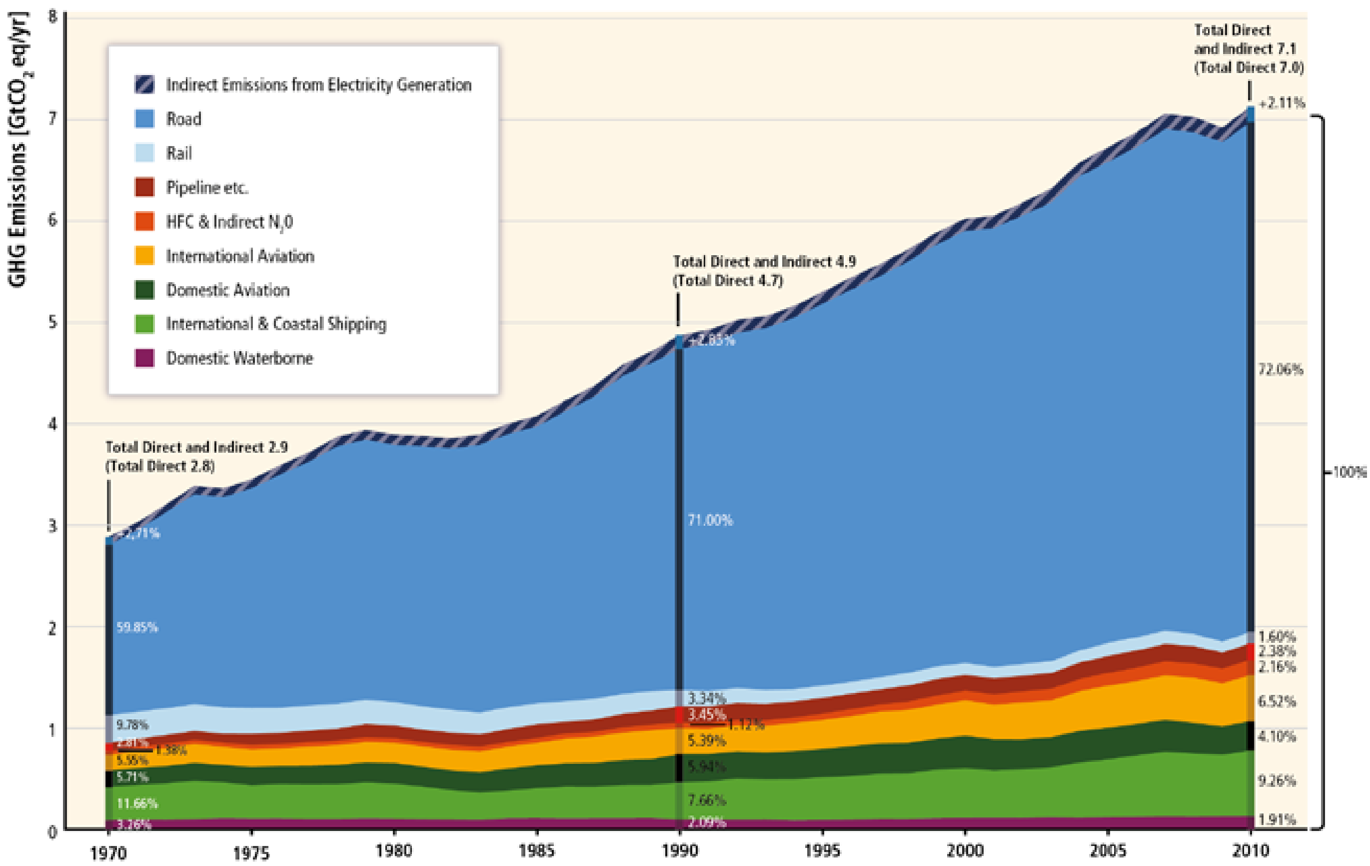


Figure 14. Direct GHG emissions (shown here by transport mode) rose 250% from 2.8 Gt CO_2eq worldwide in 1970 to 7.0 Gt CO_2eq in 2010. Source: IPCC, 2014 (114) - see Appendix IV for details.

Box 4. Vehicle emissions standards, climate and health

In a 2011 study, Shindell and colleagues modeled the impacts on climate and health (from exposure to $PM_{2.5}$ and ozone) of two different future scenarios of vehicle emission standards *(131)*. The first (baseline) scenario reflected only the standards that had already been adopted or proposed at the time of the study. The second scenario was one of much tighter emission standards, which varied regionally based on feasibility (financial, technical, and institutional capacity). The emissions standards primarily affected short-lived climate forcers: CO_2 emissions were not reduced.

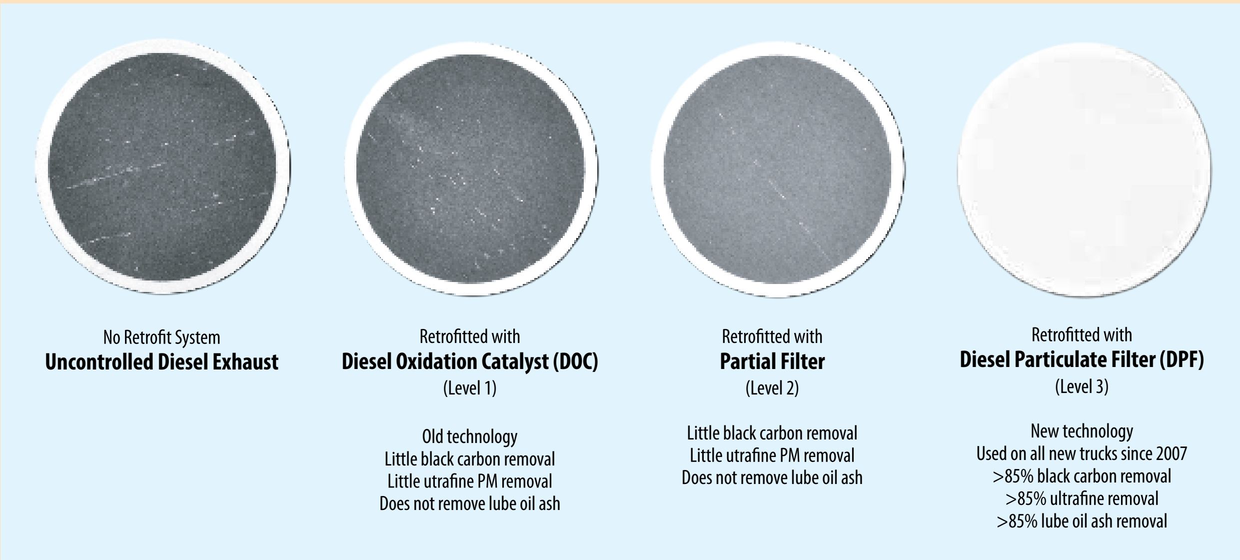
Compared to the baseline scenario, the analysis showed that in 2030, the tighter standards led to reduced radiative forcing in all regions of the world and mitigated extra-tropical Northern Hemisphere warming by about 0.2 °C. In most regions, forcing in 2030 was also lower relative to the year 2000. In terms of health, the tighter standards reversed the baseline increase in deaths between 2000 and 2030, and benefits were even evident in countries without local tightening of emissions controls, primarily due to reduced long-range transport of ozone. In total, the tighter standards scenario was estimated to reduce the number of premature deaths by approximately 190 000 relative to 2000 levels and by around 200 000 deaths relative to the (2030) baseline scenario, resulting in up to $2.4 trillion saved in avoided health damage per year. The tighter standards also avoided billions of metric tons of ozone-related crop yield losses.

Case Study 1. Diesel engines and particle filters: An example from Mexico

In December 2014, Mexico became the first middle-income country in the world to adopt and implement world-class, filter-based standards for heavy-duty vehicles (128). It is hoped that this new regulation will virtually eliminate fine particle and black carbon emissions from diesel trucks; it will also align Mexico's heavy-duty vehicle fleet with the current standards of the United States and European Union. The new standards should significantly improve air quality and reduce health risks and climate impacts from diesel particle emissions. Expected direct health impacts of the measures were estimated as part of the initiative, and included future avoidance of some 6800 premature deaths annually from reduced $PM_{2.5}$ exposures in urban areas (129). Significant NOx reductions are anticipated, and the regulations also establish maximum permissible emission limits of total hydrocarbons, non-methane hydrocarbons and carbon monoxide (129).

Only about half of the world's heavy-duty vehicles are subject to world-class emission standards for diesel particle filters. Outside of the USA, European Union, and Japan, heavy-duty vehicles typically operate with few controls. Since 2013, the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutant's (CCAC) Reducing Black Carbon Emissions from Heavy Duty Diesel Vehicles and Engines Initiative (see Appendix III for details) has been working with countries and governments in low-, middle-income, and emerging economies to support uptake of improved vehicle emissions standards and retrofitting of older vehicles with particle filters (see below image). The initiative also promotes the wider manufacture and use of low- and ultra-low-sulfur diesel fuels, which are required for particle filters to operate effectively.

Other priorities of the initiative include fostering the development of vehicle inspection and maintenance programs and clean public bus fleets. A new Green Freight Action plan announced at the UN Climate Summit in September 2014 will work with governments and industry on a voluntary basis to share knowledge about sustainable freight programs (130).



Overview: The exhibits above are actual PM collection samples from an engine testing laboratory used to collect and measure diesel particulate matter (PM) emissions. Test conditions are:

- Test Cycle: UDDS (Urban Dynamometer Driving Schedule)
- Test Distance: 5.5 miles over 17 minutes
- Fuel Consumed During Test: 1.1 gallons
- Test Vehicle: Heavy-duty truck with a 370 hp Cummins engine (1999 model year)
- PM material on collection samples is 1/1,800th of actual

Samples from an engine testing laboratory illustrate emissions reductions achieved with advanced particle filters. Source: ESW Group, USA.

SHIFT: Prioritizing low-emission modes of transport

This section discusses the benefits of public policies and investments that facilitate low-emission modes of travel. This means shifting transport investments and development policies from the support of private cars to those that prioritize urban rapid transit as well as active travel (walking/cycling) for shorter trips. In low-income cities and regions, where walking and cycling is prevalent, focus should be on ensuring that active travel is a recognized part of the transport system, and that routes are formally designated and protected for users.

By clustering many passengers together on one vehicle, public transport modes tend to reduce total traffic emissions (Figure 15), which are high in BC and some ozone precursors. Strong public transport systems also have the advantage of reducing traffic intensity, which is associated with road traffic injuries and noise-related health impacts (Table 14). Finally, evidence from high-income countries suggests that with suitable regulation of drivers and vehicles, public transport tends to be safer than private vehicle modes, decreasing the risk of road traffic injury, which is responsible for over a million deaths annually worldwide *(147-149)*. Well-planned rapid transit systems also tend to foster investments in more compact urban development because major public transport nodes are attractive for real estate developers. This, in turn, makes walking and cycling for short trips or to get to a transit station more attractive and feasible *(150)*.

Vancouver, Canada offers separated bike lanes which encourage cycling and prioritize riders' safety. (Credit: Paul Krueger)

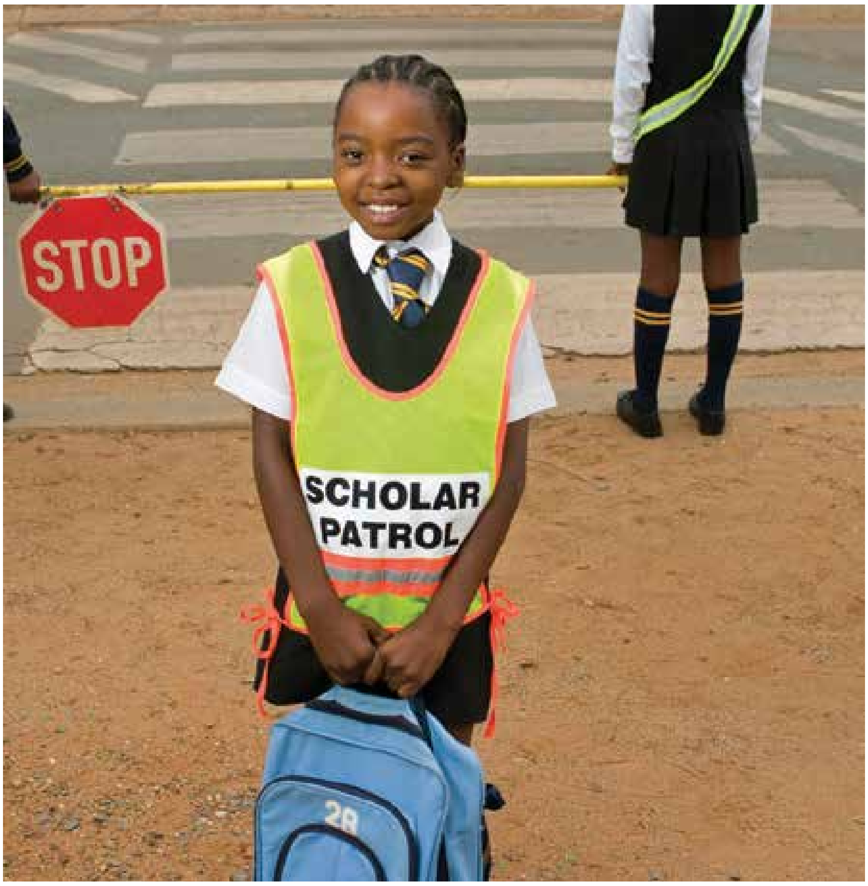
Expanding the use of public transit systems requires that they be competitive with private vehicles in terms of speed, reliability and affordability. Dedicated urban tram or bus rapid transit arteries are commonly used to prioritize public transit vehicles and riders. Other options include subsidizing public transport (e.g. accounting for pollution and health cost savings), or conversely, congestion charging (charging private vehicles for entry into certain urban areas, or making city parking more expensive). Street design and connectivity as well as density of desired destinations can also help reduce car dependence and promote active travel *(114, 151, 152)*.

Similar to public transport, active travel (walking and cycling) reduces emissions and noise pollution (Figure 15) and increases physical activity (Table 14). The latter is particularly important and can help counteract the approximately 3 million premature deaths per year attributable to physical inactivity *(8)*. A WHO review concluded that environmental interventions that make walking and cycling more attractive are one of the more effective ways to increase physical activity *(153)*.

In terms of direct evidence, large epidemiological studies (from Shanghai and Denmark) have recently reported that cycle commuters had significantly reduced risks of premature death, even after controlling for other risk factors *(154-156)*. Health impact assessments of active transport show that both improved air quality and physical activity can provide large health benefits, particularly from the latter *(157, 158)*. For example, Woodcock et al. modeled the health benefits in Delhi, India, of two transport scenarios – one that reduced vehicle emissions and one that emphasized active travel – finding that both were an improvement over a business-as-usual scenario. However, the active travel scenario had far larger health benefits (12 516 DALYs gained in the first year after implementation, compared to 1696 with lower vehicle emissions) *(38)*. Both scenarios resulted in substantially lower CO_2 emissions (the authors did not report SLCPs specifically).

Prioritizing active transport requires investment in safe infrastructure, as pedestrians and cyclists are vulnerable to road traffic injuries *(149, 159)*. Results from a recent analysis in Auckland, New Zealand, emphasize the need for dedicated cycle paths separated from vehicular traffic as well as speed-reduction measures on local streets *(157)*. Studies have similarly found the need for well-planned pedestrian routes to encourage walking while ensuring safety *(151, 152)*. The importance of a cycle- and pedestrian-friendly environment is highlighted by statistics from the Netherlands and Germany, where cycle fatality rates per kilometer are only a quarter as high as those in the United States of America, and pedestrian fatality rates only a tenth as high *(159)*.

Well-planned policies to facilitate safe active travel are likely to be some of the most beneficial SLCP-related mitigation actions in terms of both climate and health.



Locating schools close to residential neighborhoods reduces travel time and traffic emissions, as well as supporting physical activity. Portrayed here is the "Scholar Patrol" on duty at the Banareng Primary School, Atteridgeville, Pretoria, South Africa. (Credit: Brett Eloff)

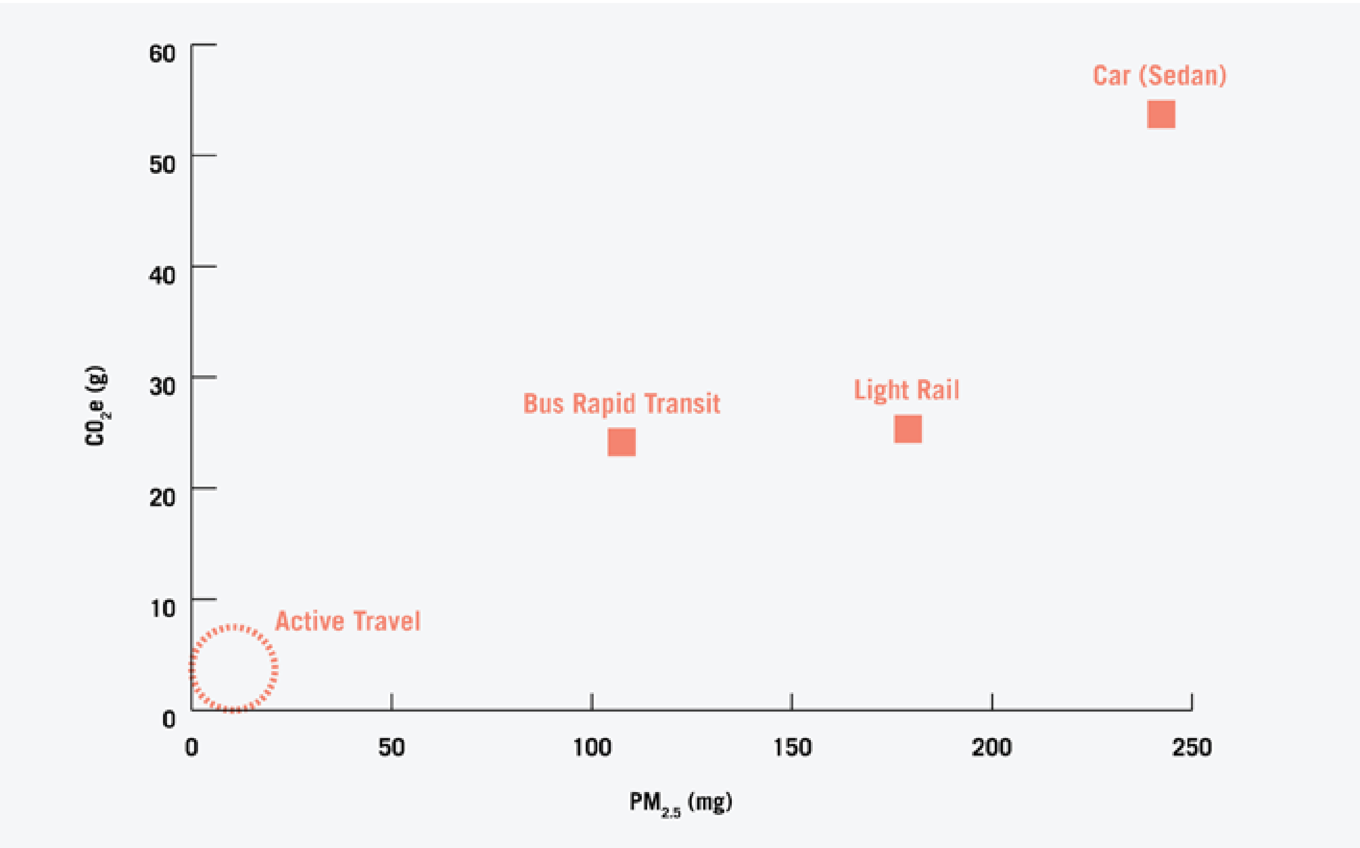


Figure 15. Life-cycle emissions of $PM_{2.5}$ and CO_2e per passenger mile for different modes of urban transport. Note: Results for the car, bus and light rail are from Chester et al., 2013 & 2014 (16, 17) and are for average-occupancy vehicles in Los Angeles. Results for active travel are estimated.

AVOID: Journey avoidance and optimization

Avoiding journeys and/or reducing travel distances can be achieved in many ways. Proximity planning, for instance, aims to minimize travel distances through smart urban planning in which cities are designed to be compact, with complementary goods and services located near each other. Proximity planning is illustrated by a study from Santiago, Chile, where researchers estimated that relocating schools closer to residential areas could reduce transport emissions in the study area by 12% *(160)*.

Electronic information technology can also reduce the need to travel. The use of email and internet shopping (under specific conditions) are two examples *(161, 162)*, but more sophisticated applications are on the rise. In the health-care sector, "e-health" technologies can be used for virtual visits (e.g. video consultations), thus reducing transport demand while also reaching individuals without good access to health services *(163)*.

As compared to journey avoidance and proximity planning, operational optimization is concerned with planning and scheduling transport routes in order to create efficient travel (spatially and temporally), or to ensure that the lowest-emission vehicles are assigned to a given route. In a study analyzing twelve potential bus route scenarios for the British Columbia transport system, Gouge et al. (2013) recently found that a worst-case scenario (in terms of health) would result in more than double the intake of $PM_{2.5}$ compared to a best-case scenario *(164)*. Climate benefits (which included effects of BC and methane) were also evident.

Table 14. Likely direction of health impact from selected broad road transport interventions having potential to reduce SLCPs

	Air pollution	Road traffic injuries (RTI)	Physical activity	Noise	Comments
Improved vehicle technology	-- to ++	0	0	0	Potential for improved air quality, but also possible perverse effects such as incentivizing more transport through lower travel costs.
Increased mass transport	+	+	+	0 to +	Benefits will depend somewhat on the transport mode targeted.
Increased active transport	++	-- to ++	++	++	Potential for very large benefits through multiple pathways, but possible increased risk of RTI if safe infrastructure is not provided.
Proximity planning and operational optimization	+	0 to +	0	0 to +	Seemingly few drawbacks, but not much health impact modeling.

Rated from "--" (strongly negative) to "++" (strongly positive) effects. "0" represents no significant effects.

Source: Modified from reference (13).

6

Fresh produce sold at the Crocker Galleria Farmer's Market in San Francisco, USA. (Credit: Brandon Doran/Flickr)

Chapter 6: Agriculture

Chapter highlights:

• Agriculture is the predominant source of anthropogenic methane emissions globally, with the livestock sector and rice cultivation being the two primary contributors.

• Agriculture is also a source of black carbon through the burning of agricultural waste and, to a lesser extent, the use of machinery.

• For agriculture, there are two broad types of SLCP mitigation measures: supply-side and demand-side measures.

• Key supply-side measures involve reducing methane emissions from rice paddies through the alternate wetting and drying of irrigated rice, improving the management of livestock manure, and reducing the burning of agricultural fields.

• A key demand-side SLCP mitigation action with large potential climate and health benefits is to facilitate a shift away from high-GHG foods – many of which are of animal origin – and towards healthy, low-GHG (often plant-based) alternatives. This strategy should target more affluent populations and not populations at risk of nutrient inadequacy.

• Reducing food waste is crucial to both supply-side and demand-side measures.

Introduction

Food production and dietary choice affects not only our heath, but also emissions of climate forcers: the agriculture sector (including forestry and land use) is responsible for an estimated 24% of global GHG emissions, while food-related risk factors comprised five of the 10 leading causes of death globally *(8, 165)*. Agricultural emissions also contribute substantially to the secondary formation of $PM_{2.5}$ *(39)*.

Emissions of SLCPs occur at every stage in a food's life cycle, from the farm field to the table (Figure 16). In this chapter, the key mitigation actions are separated into supply-side (production) and demand-side (consumption) measures, while acknowledging that some policies (e.g. food waste) are relevant to both.

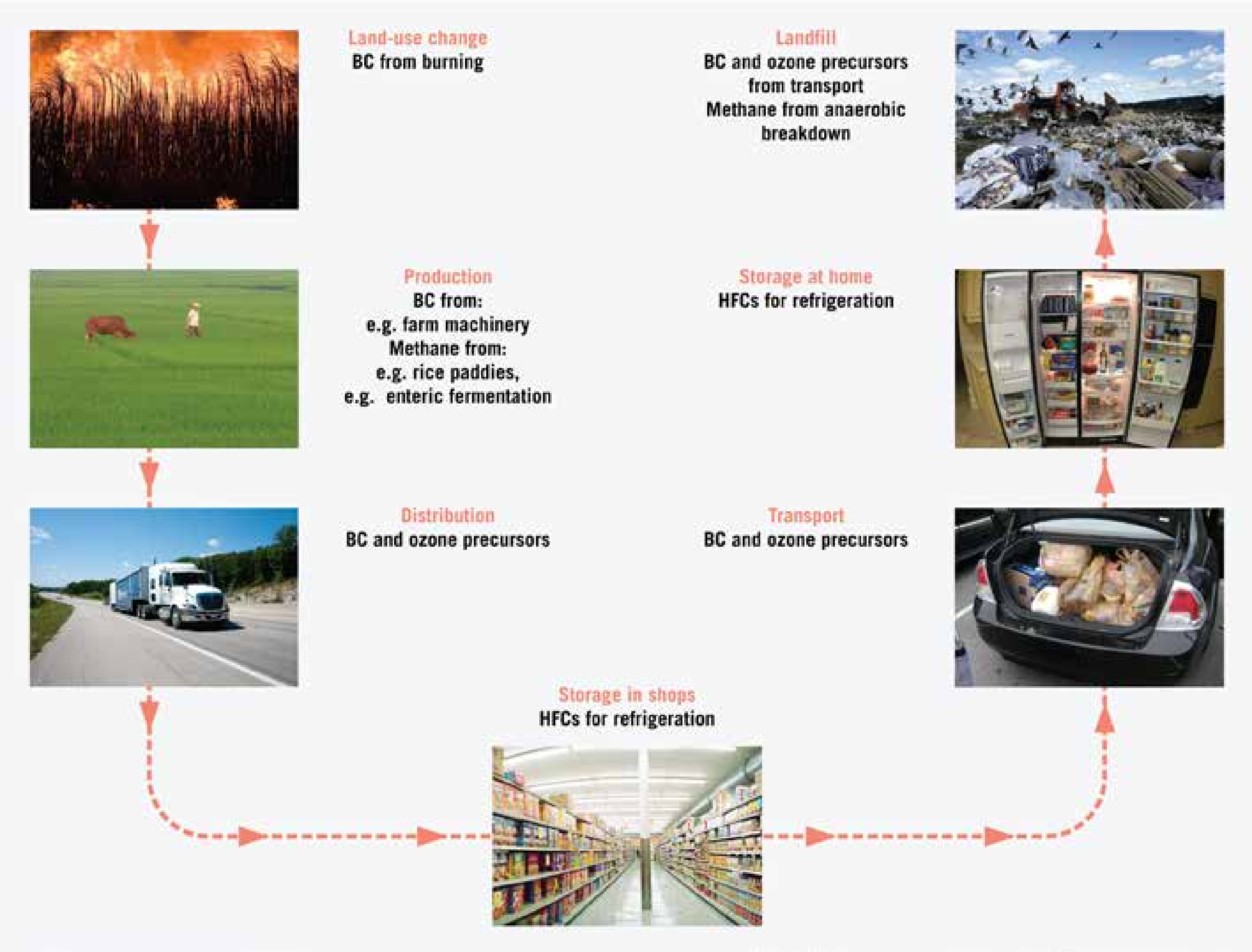


Figure 16. The farm-to-table (and then landfill) life-cycle of food and selected associated SLCP emissions
BC = black carbon, HFCs = hydrofluorocarbons. Source: All photos from Flickr licensed under Create Commons with credit to: UN Photo/Eskinder Debebe (land-use change), UN Photo/Evan Schneider (landfill), ILO/Trong Van Vi (production), MoDOT (distribution), Marleigh Jones (storage in shops), Harris Teeter (transport), Alexander Muse (storage at home).

Supply-side SLCP mitigation measures

Rice cultivation and livestock are the two agricultural industries most responsible for anthropogenic methane emissions, and both provide important opportunities for mitigation. Open burning of biomass, which often includes the burning of agricultural residues, is a key agriculture-related source of black carbon.

Alternate wet-dry irrigation (AWDI) of rice fields

Rice is the staple crop for approximately half of the world's population, and its production is estimated to be responsible for ~10% of global anthropogenic methane emissions through the anaerobic decomposition of organic matter *(40, 166)*. Studies have demonstrated that in place of continuous flooding, rice management that employs intermittent irrigation alternating between wet and dry periods can reduce methane emissions by 40% or more *(167, 168)*.

Alternating wet-dry irrigation (AWDI) may provide a number of indirect health benefits, although more research is urgently needed on this topic. One potentially important pathway is that AWDI has been identified as a strategy to control vector-borne diseases such as Japanese encephalitis and malaria in places where the vectors (mosquitoes) use rice paddies for breeding *(41, 42)*. In a (limited) number of studies, AWDI was found to reduce the densities of both immature (14-91%) and adult (55-70%) Culex mosquitoes, a vector for Japanese encephalitis *(42)*. In terms of controlling malaria vectors, AWDI has been shown to yield benefits in a number of settings (see Case study 2 for an example).

However, different vectors may respond differently to AWDI practices, and at least one study reported that the prevalence of Japanese encephalitis-carrying Culex and Anopheles mosquitoes was higher in AWDI systems compared to continuous flooding *(169)*. Researchers have also emphasized that AWDI must be practiced during the entire cropping season and must cover rice fields over a large area *(170)*.

Some studies also suggest that AWDI may be able to improve crop yields, with corresponding benefits for food security *(173, 174)*. However, the evidence is mixed, with one review finding that rice yields in AWDI systems generally do not increase and may decline, depending on the irrigation scheme and soil and hydrological conditions *(173)*. If water saved by AWDI is used to irrigate additional fields (or additional crops are grown in between rice-growing seasons), this may be another route to improving agricultural productivity and local income levels *(171)*. In some areas however, flooded rice fields are used as fish habitat, so intermittent draining could deplete an important food protein source *(175)*.

A potential drawbacks of AWDI is the need for a secure water supply for implementation (farmers will be reluctant to drain fields if they fear they cannot easily be flooded again). AWDI may also lead to increased emissions of nitrous oxide (N_2O, a long-lived greenhouse gas as well as air pollutant, used commercially as a surgical anaesthetic). Although nitrous oxide emissions may offset a portion of the gain through methane mitigation, AWDI is generally considered to produce a net climate benefit overall, assuming efficient application of nitrogen fertilizers *(168)*.

Case study 2. AWDI for malaria control in Sichuan Province, China

The expansion of alternating wet-dry irrigation practices was believed to have led to the virtual eradication of malaria in some parts of Sichuan Province, which had the fourth-highest level of malaria incidence in China prior to the 1960s *(171, 172)*. Although indoor residual spraying (IRS), the introduction of insecticide-treated nets, and improved case detection, treatment and surveillance gradually reduced the severity of epidemics in the 1970s and 1980s, these measures' limitations became apparent over time.

In the mid-1990s, expanded irrigation schemes that assured farmers of more reliable water access reduced Sichuan farmers' use of permanently flooded rice paddies. As a consequence, breeding habitats for malaria vectors dropped below the critical threshold level that triggers disease outbreaks. Along with improved public health, agricultural productivity increased significantly between 1995 and 2000, as farmers were able to cultivate a second crop, such as wheat or vegetables, during the cold season when flooded rice paddies had previously remained fallow *(171)*.

Rice terrace farming in China. Rice management that employs wet-dry irrigation practices as opposed to continuous flooding can reduce methane emissions and help control disease vectors. (Credit: Doron/Wikimedia Commons)

Livestock manure management

Improved manure management seeks to minimize methane emissions, and, when biogas is produced, to displace fossil fuel use, leading to avoided CO_2 emissions. It may also reduce fertilizer-based emissions of N_2O, a long-lived greenhouse gas which produces more than 250 times more radiative forcing than CO_2 *(18, 176)*.

Simple approaches to mitigate manure methane emissions include: cooling or covering manure sources, separating solids from liquids, and more precisely timing manure applications to crop lands. Composting the manure using anaerobic digestion (whereby the manure biodegrades in the absence of oxygen) leads to the release of methane gas (often known as biogas) which can be captured and burned as a cooking or heating fuel, thereby displacing the use of fossil or biomass fuels. Biogas production may be done at scales ranging from industrial-sized plants that also refine the fuel further, to simple small-farm installations that produce cooking fuel from the wastes of a few cattle or pigs as well as from household sewage.

The IPCC notes that the climate mitigation potential from manure management overall is fairly modest, as a relatively small proportion of the methane emitted in the livestock sector is from manure management - most is released through animal digestion – and most manure excretion occurs in the field where it is hard to capture *(165, 177)*.

Potential health benefits may be important if captured biogas – a relatively clean fuel – replaces coal or biomass fuel use in poor households which is associated with adverse cardiorespiratory effects (also see Chapter 7). A limitation, however, is that most household-level biogas installations provide enough energy for cooking only, while coal, wood or other biomass may additionally be needed for home heating. They may also be expensive for low-income farming households.

Manure management can also reduce infectious disease risks. Composting can help kill pathogens, and proper handling of manure, learned as part of improved management practices, also can help limit human exposure to both pathogens and toxic substances such as agrochemicals. If improved sanitation (e.g. latrines) accompanies improved manure management, which may be true of certain biogas interventions, potential health benefits are well-known and can be large, including reductions in diarrhea and helminth infections (also see Chapter 10) *(58, 59)*. Finally, biogas digestate (slurry) has better fertilizer qualities compared to traditionally managed manure *(178)* and may help improve agricultural yields and food security for poor farmers.

Farmers around the world burn crop residues to clear land and fertilize the soil, however such practices emit large amounts of black carbon. (Credit: Neil Palmer/CIAT International Center for Tropical Agriculture)

Reduced burning of agricultural waste

BC is not often the focus of mitigation policies in the agriculture sector, where emissions of methane and N2O dominate most estimates of radiative forcing. One area where substantial BC emissions occur is open burning of agricultural residues. The emission estimates and climate effects of black carbon from open burning are somewhat more uncertain than for other source categories for a number of reasons, including insufficient data, the heterogeneous composition of what is burnt, as well as high concentrations of co-emissions *(23)*. However, recent research increasingly indicates that burning agricultural waste could produce net warming, and thus may represent a viable target for SLCP mitigation activities, particularly near snow and ice covered regions *(77, 78)*.

There is not the same uncertainty regarding the negative health impacts of agro-waste burning, as burning agricultural waste can lead to large and locally dominant levels of particulate air pollution. For example, in Brazil it is still common practice in many areas to burn sugarcane fields before harvest; this enables easier access to the cane and clears fields of undesirable wildlife. Source apportionment studies from sugarcane-growing regions indicate that biomass burning is the predominant source of $PM_{2.5}$ during the burning season (about seven months per year), and data from air pollution monitors demonstrate that particle concentrations in adjacent cities can increase by 100% or more during burning *(179-182)*. Time-series analyses have linked sugarcane straw burning with hospital admissions for hypertension, asthma, and general respiratory complaints. However, in response to these concerns, legislative and voluntary actions have substantially reduced sugarcane burning in recent years in favor of mechanized harvesting *(179, 180, 183, 184).*

Demand-side SLCP mitigation measures

Different foods have very different embodied GHG emissions *(12, 165, 185-187).* Animal-sourced foods – from ruminants in particular – tend to be GHG-intense compared to many fruits, vegetables, and grains (though some types of fresh produce requiring air transport and refrigeration also have relatively high emissions) (Figure 17) *(12, 165, 185-187).* This demonstrates the considerable potential for climate-health co-benefits in the agriculture sector: millions of premature deaths globally are attributable to diets too low in

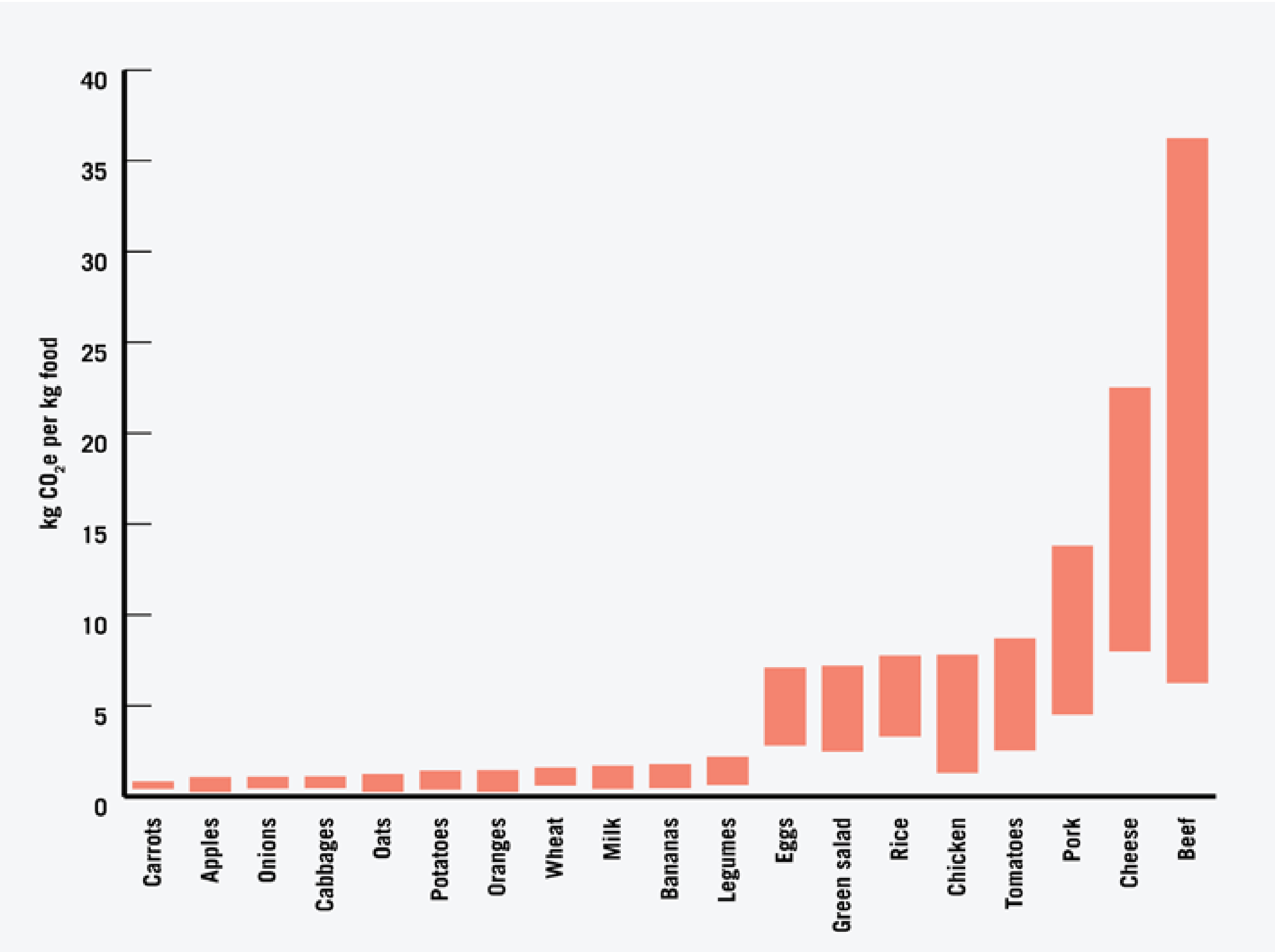


Figure 17. GHG intensity of selected foods based on four European studies. The color bars represent the approximate range (low and high) of GHG emissions in terms of Co_2e. CO_2e = carbon dioxide equivalents (a measure that includes non-CO_2 climate forcers such as methane). See Appendix III for further information about the figure. Sources: (12, 165, 185-187, 191).

Fresh produce sold at the Farmer's Market in Union Square, New York City, USA. (Credit Brandon Doran/Flickr)

fruits, vegetables, whole grains, and nuts and seeds. Meanwhile, nearly a million premature deaths annually are attributable to over-consumption of processed meat, and tens of thousands more premature deaths annually are associated with over-consumption of red meat; over-consumption of both types of meat are linked to colorectal cancer, diabetes mellitus, and, for processed meat, ischemic heart disease. See also Appendix 1 *(8, 188)*. Conversely, diets high in fruits, vegetables, nuts, seeds and fibres are also considered to be protective against man health conditions (Box 5). Related to this, a recent review concluded that a diet of minimally processed plant-based foods is "decisively associated with health promotion and disease prevention" *(43, p83)*.

Therefore, food choices for health and for sustainability are largely aligned *(189)*. Accordingly, recent reviews, including systematic review, *(11, 12)* have reported that the vast majority of modeling studies exploring this issue find that in affluent populations, shifting towards diets based on careful adherence to public health recommendations – including reduced consumption of red and processed meat and/or other animal-sourced foods in favor of healthier plant-based alternatives – has the potential to both reduce GHG emissions and improve population health (See Box 5 and Table 15 for a sample of recent studies). Low-GHG diets also have the capacity to reduce demand for land, thus potentially facilitating CO_2-based climate mitigation activities such as reforestation or cultivation of future-generation bioenergy crops *(11, 165, 190)*.

Reducing the demand for high-GHG foods will not be easy, as people make dietary choices for a variety of reasons and because, on the whole, the demand for meat and dairy has been increasing *(192)*. Nevertheless, a variety of policy tools exist to encourage dietary shifts. Experimental and modeling studies demonstrate that food pricing interventions have the ability to influence food choice, though caution is needed to avoid unexpected food substitutions *(94, 193, 194)*. Briggs et al. (2013) modeled the impact on chronic disease in the UK of taxing all food and drinks with above-average GHG emissions, concluding that a tax of £2.72/tCO_2e per 100g

Fresh vegetable market in Uttar Pradesh, India. (Credit: Ariel Charney) product would result in 7770 deaths averted, would save nearly 19 000 ktCO_2e/year, and create an annual revenue of £2 billion *(195)*. Others have also modeled the impacts of targeted food taxes and found the potential for large reductions in dietary GHG emissions *(196, 197)*. There is also some evidence demonstrating success in education campaigns that promote healthy eating *(198-201)*.

It is of course important to support consumption of animal-sourced foods in populations that depend on these foods as a vital source of nutrition, both for protein, energy and micronutrients, including small landholders, pastoralists and other rural or low income groups, as well as children undergoing rapid development.[VIII] Yet particularly higher-income countries where the consumption of red and processed meat is disproportionately high and many food choices are available, nutritious choices including more plant-based foods, could help reduce pressure of demands for increasing production food products that produce high levels of methane as well as other climate emissions.

Box 5. Dietary shifts: health and climate impacts

The livestock sector has an enormous impact on the planet. According to the Food and Agriculture Organization (FAO), it is the single largest anthropogenic user of land, is one of the primary sources of water pollution, and has a range of adverse effects on wildlife and ecosystems *(192)*. It is also responsible for about a quarter of anthropogenic methane emissions, mainly from enteric fermentation, and is the leading source of nitrogen dioxide – a long-lived climate pollutant that, like methane, has a global warming potential much higher than that of CO_2 *(40, 202)*. Deforestation caused by demand for pasture also releases short- and long-lived climate pollutants into the atmosphere and reduces the ability of forests to absorb CO_2. These facts are reflected in the GHG footprint of animal-sourced foods (e.g. particularly red meat and cheese), which are generally higher than many other foods even without considering land-use changes (see Figure 17 in main text).

In addition to their climate impact, intake of red and processed meats has been linked to adverse health outcomes including cancer, diabetes, and heart disease *(8, 188, 203, 204)*; an estimated 40 000 and 840 000 deaths globally are attributable to diets high in red and processed meats respectively, while some studies have attributed millions of premature deaths to insufficient intake of fruits, vegetables, fibre and legumes and other types of plant-based foods (see main text). As a result, a number of modeling studies have explored the potential climate and health (or dietary) impacts of moving towards more diets that are rich in plant-based foods and nutrients, generally finding that dietary shifts have the ability to produce positive benefits in both realms *(11, 205, 206)*. Table 15 below summarizes a number of these individual studies, presented to illustrate the variety of scenarios and assumptions that have been modeled. Recent systematic reviews provide more in-depth analysis of this issue *(11, 12, 205, 206)*. It is important to note that studies considering dietary options primarily through the climate/environment lens may not fully capture their health implications. The presentation of such studies here represents a survey of the literature, but not endorsement of any specific dietary regime. Designing healthy diets for particular populations, age groups, and individuals thus requires further reference to national and international nutrition standards, beyond the scope of this review.

The livestock sector is responsible for about a quarter of anthropogenic methane emissions. (Credit: Stephanie Schupska/University of Georgia, College of Agricultural & Environmental Sciences, USA)

[VIII] It should be noted that fish-based foods are outside the scope of this review; these are important sources of nutrition for billions of people – with a diverse and complex array of environmental impacts, depending on whether fish are harvested sustainably or not.

Reducing food waste


Household food waste in New York, USA (Credit: petrr/Flickr)

Another important issue in the agriculture sector relates to food waste, which can occur at any stage in the food supply chain, as well as in households *(207)*. Though estimates vary, food waste may be as high as 30-40% in some countries *(208, 209)*, but is variable across regions: a study by the FAO recently estimated per-capita food waste in Europe and North America of around 100 kg per year, whereas waste in sub-Saharan Africa and south/southeast Asia was estimated to be about 11 kg or less *(210)*. A different study from the USA concluded that food waste now stands at an average of about 1400 kcal per person per day – enough to satisfy the energy needs of a moderately active child – and in total accounts for the use of about 300 million barrels of oil per year *(209, 211)*.

Many factors contribute to food waste, but because emissions of climate forcers occur in the production, distribution, and storage of food, as well as from decomposition in landfills (Figure 16), many potential interventions are available that could affect climate and health. Awareness raising and incentives such as taxation are two examples. In a recent study, Smith et al. *(2013)* modeled impacts of different agricultural interventions and found that reducing losses in the food supply chain by 6% has a climate mitigation potential of 5.2-18.9 Gt of CO_2e per year, given assumptions about the use of the resulting spare land *(190)*. The authors also conclude that interventions of this sort could have a positive influence on food security.


Composting reduces landfill waste and associated methane emissions. Compost can be used as a soil fertilizer benefitting food production. (Credit: Philip N. Cohen/Flickr)

Table 15 Recent modeling studies assessing climate and/or health impacts of shifting towards low-GHG diets

Citation/aim/methods	Scenarios	Results
Westhoek et al. (2014) modeled alterative diets in the European Union compared to a reference diet *(212)*	Scenario 1: 50% reduction in beef and dairy, compensated by an increase in cereals Scenario 2: 50% reduction in pig, poultry and eggs, compensated by an increase in cereals Scenario 3: 50% reduction in all meat and dairy, compensated by an increase in cereals	Scenario 1: Up to 40% reduction in GHGe per year and about 25% reduction in saturated fat intake Scenario 2: Small reduction in GHGe and about 15% reduction in saturated fat intake Scenario 3: Up to 40% reduction in GHGe per year and about 40% reduction in saturated fat intake
Smith et al. (2013) modeled the GHG impact of agriculture-related changes in global land use *(190)*	Scenario: A global shift to a low-animal-product, nutritionally sufficient diet compared to reference diet	Scenario: Total global mitigation potential of 5.3-20.2 $GtCO_2e$ per year
Scarborough et al. (2012) modeled the impact of three diet scenarios on GHGe emissions and health in the UK *(213)*	Scenario 1: 50% reduction in meat/dairy replaced by fruit, vegetables and cereals Scenario 2: 75% reduction in beef and sheep meat replaced by pigs/poultry Scenario 3: 50% reduction in pigs/poultry replaced by fruit, vegetables and cereals	Scenario 1: 19% reduction in dietary GHGe, 37 000 premature deaths averted per year Scenario 2: 9% reduction in dietary GHGe, 2000 premature deaths averted per year Scenario 3: 3% reduction in dietary GHGe, 9000 premature deaths averted per year
MacDiarmid et al. (2012) modeled the GHG mitigation potential of UK diets that met the dietary requirements of an adult woman *(214)*	Scenario 1: A diet to maximize GHG reduction without acceptability constraints Scenario 2: Scenario 1 but with acceptability constraints	Scenario 1: 90% reduction in GHGe Scenario 2: 36% reduction in GHGe
Berners-Lee et al. (2012) modeled the climate impact of moving towards plant-based diets in the UK *(186)*	Scenario 1: Vegetarian diet Scenario 2: Vegan diet	Scenario 1: 22% reduction in dietary GHGe Scenario 2: 26% reduction in dietary GHGe
Popp et al. (2010) modeled, at the global level, the non-CO_2 impact of different future diets compared to baseline *(215)*	Scenario: Decadal reduction in demand for meat products of 25%	Scenario: 51% reduction in non-CO_2 GHGe in 2055
Friel et al. (2009) modeled future (2030) impacts in the UK and São Paulo, Brazil, from a dietary shift *(216)*	Scenario (both countries): A 30% reduction in livestock production (and intake of saturated fat and cholesterol)	Scenario (UK): A reduction of 9 $MtCO_2e$ from the agriculture sector, 15% reduction in health burden (DALYs) from ischemic heart disease Scenario (Sao Paulo): 16% reduction in health burden (DALYs) from ischemic heart disease
Stehfest et al. (2009) modeled, at the global level, the GHG impact of different future (2050) diets compared to a reference diet *(217)*	Scenario 1: No ruminant meat Scenario 2: No meat Scenario 3: No animal products Scenario 4: A "healthy diet" with less meat	Scenario 1: 48% reduction in land-use GHGe Scenario 2: 55% reduction in land-use GHGe Scenario 3: 67% reduction in land-use GHGe Scenario 4: 36% reduction in land-use GHGe

7

A women in India cooks food on a more efficient biomass cookstove. Improved biomass stoves are an important transition technology towards cleaner cookstoves. However, most improved biomass cookstoves still do not yet meet WHO guidelines for household fuel emissions. (Credit: Romana Manpreet/ Global Alliance for Clean Cookstoves)

Chapter 7: Household energy production and building design

Chapter highlights:

• Household solid fuel use is a major source of black carbon emissions and is the leading environmental risk factor for disease. It can also be a source of ozone precursor emissions (e.g. CO).

• Interventions to improve the efficiency of cookstoves and/or facilitate switching to cleaner energy sources therefore have potential for substantial climate and health benefits.

• Kerosene lamps are another important source of black carbon, and are associated with household air pollution, burns, and poisonings in low- and middle-income countries.

• There are many mitigation actions to reduce energy demand from buildings that also enhance indoor comfort, including use of higher-quality building materials and following passive design principles.

• Improved building design can reduce the need for energy derived from fossil fuels and/or biomass fuels, which emit black carbon and ozone precursors, as well as the use of air conditioning, which is a heavy power consumer and a major source of HFCs as well as a source of noise disturbance.

• Improved building design has the potential to reduce diseases associated with poor housing. These may include mortality and morbidity associated with exposure to heat or cold, allergies linked to mold and damp, and infections that spread as a result of poor ventilation.

Energy is consumed in the household for numerous reasons, including for activities that promote good health: energy is required to cook food, to keep warm, and to provide light. The type of fuel used in the household is strongly related to income, and populations at different levels of economic development will be exposed to different risks (Table 16).

As a result, the following discussion of household energy use is separated into two sections addressing lower- and higher-income areas. The final section discusses building design, mainly with regard to households but also other buildings, and how to ensure that building design minimizes the energy needed for comfortable, healthy living.

Table 16. Typical progression for household energy use.				
Energy Service	Developing countries households			Developing countries households
	<------------ Low-income ------------> <------------Middle-income ------------> <------------High-income ------------>			
Cooking	Wood (including wood chips straw, shrubs, grasses and bark), charcoal, agricultural residues, dung, coal and waste	Wood, agricultural residues, charcoal, LPD, coal, kerosene, and biogas	Wood, pellets, kerosene, biogas, charcoal, LPG, natural gas, electricity	Electricity, natural gas, LPG, charcoal (barbecue)
Lighting	Open fire, candles, kerosene (sometimes none)	Kerosene, batteries, electricity	Electricity	Electricity
Space heating	Wood, agricultural residues and dung (often none)	Wood, agricultural residues	Wood, coal, kerosene, pellets and electricity	Wood, pellets, oil, natural gas, LPG or electricity
Other needs (water, heating, recreation)	Wood, batteries (often none)	Wood, electricity, batteries	Wood, natural gas, LPG, electricity, batteries	Natural gas, LPG, electricity, batteries

Arrows indicate income levels, but other variables also influence fuel choice; thus households of varying incomes may span different fuels. Source: Sovacool (2012) as cited in Anenberg (2013). (46).

Household air pollution in developing countries

Some 2.8 billion people worldwide rely on burning solid fuel (e.g. biomass or coal) in the household for cooking, and approximately 4.3 million deaths annually are attributed to the associated household air pollution *(218)*, including:

- one-half of all pneumonia deaths globally among children under the age of 5;
- one-third of all premature deaths from chronic obstructive pulmonary disease;
- one-quarter of all deaths due to stroke;
- approximately 17% of adult lung cancer deaths and 15% of deaths from ischemic heart disease.

Household air pollution is the leading environmental risk factor for ill-health. Residential solid fuel use is also responsible for around 25% of global BC emissions – the majority from low- and middle-income countries – and has been identified as a potentially good mitigation opportunity due to the high proportion of BC emissions relative to co-emitted cooling particles *(23)*.

There are two complementary strategies for reducing the disease burden from household air pollution. The first is to reduce the air pollution that results from fuel combustion, while the second aims to reduce exposure without necessarily limiting emissions. The latter strategy, which includes, for example, the use of chimneys, is not discussed further as it does not affect total emissions. It is, however, important from a heath perspective, and is often a component of interventions that also reduce emissions, such as those described below.

The quantity of particulate air pollution – including BC – that is emitted from a stove depends largely on its combustion efficiency, which refers to how much of the energy and carbon in a fuel is converted to heat and carbon dioxide *(219)*. The more efficient the stove, the fewer emissions produced. Open fires and simple stoves burn fuel (usually solid fuels) inefficiently, leading to high levels of combustion-related pollution. Many interventions therefore have focused on improving combustion efficiency.

The potential BC mitigation and economic benefits of switching from open fires or simple stoves to advanced combustion cookstoves are well-established *(23, 44, 46, 47, 220, 221).* While certain types stoves perform better than others, studies have reported substantial reductions of BC emissions – sometimes by an order of magnitude – and there are similar findings for $PM_{2.5}$ *(45, 222-224).* It is important, however, to field-test different stove designs, as emissions reductions recorded in the laboratory may not always translate to real-life situations *(225)*. In fact, the most recent systematic review by WHO of household fuel combustion and health impacts indicates that no currently available and tested improved solid fuel stoves were achieving emission rates (Table 17) that would meet WHO air quality guideline levels for $PM_{2.5}$, and they should therefore be viewed as a transitional technology *(47, 226)*. This review was conducted in the context of new *WHO indoor air quality guidelines: household fuel combustion (47)*.

Table 17. *WHO guidelines for indoor air quality: household fuel combustion (47) Emission rate targets.*

WHO emission rate targets from household fuel combustion	
$PM_{2.5}$ (unvented)	0.23 (mg/min)
$PM_{2.5}$ (vented)	0.80 (mg/min)

Attainment of these targets would result in an estimated 90% of homes meeting WHO air quality guidelines for $PM_{2.5}$ (annual average – see Chapter 1, Table 9). There are also intermediate emission rate targets (not shown – see reference (47).

Many (though not all) epidemiological studies of cookstove interventions have reported reduced exposure to indoor air pollution and/or related disease compared to control groups, at least initially, while modeling studies have outlined the potential for health and climate benefits if implemented at a large scale *(221, 227, 228)*. For example, Wilkinson and colleagues (2009) modeled the impact of introducing 150 million low-emission cookstoves in India, and estimated that the intervention would result in a saving of 12 500 DALYs and 0.2 megatonnes of CO_2e per million population in one year. In terms of SLCPs in particular, the authors estimated a decadal reduction of 0.5 megatonnes of BC and 14 megatonnes of methane, as well as reductions in other ozone precursors.

Switching to cleaner fuels such as liquid petroleum gas, biogas, and ethanol is another option, and is generally viewed as an improvement over solid fuels in terms of climate and health benefits *(46, 229)*. However, few high-quality studies have field-tested their effectiveness *(47, 226)*, and they also have certain drawbacks. LPG, for example, is a fossil fuel and therefore associated with some CO_2 emissions, though its low-particulate content is important for BC mitigation. Crop-based ethanol fuels have raised health concerns about air pollution and food-insecurity through links with higher food prices *(136)*. In terms of lighting, kerosene lamps are now a top priority for SLCP mitigation due to their BC-rich emissions (Box 6).

Despite their potential benefits, uptake of clean cookstoves and alternative fuels is not straightforward, and there have been persistent challenges in implementing these interventions, including lack of affordability and cultural appropriateness *(46, 47, 230, 231)*. Uptake also does not guarantee reduced exposure and depends on stove design, how (and how often) it is used, and the fuel. The use of a new technology also does not necessarily preclude the continued use of the previous (traditional) stove. Nevertheless, if appropriately designed, these interventions can have important climate benefits and have the potential for some of the largest health benefits of any intervention discussed in this report, including some additional to emissions reductions (Box 7).

Switching to electricity is likely to be even more preferable than using liquid fuels, and this is also becoming increasingly feasible in many regions as electrification expands and the cost of electric cooking devices, such as portable induction cookstoves, falls *(232)*. Electric stoves are the cleanest fuel in terms of indoor health, but if the electricity is generated by conventional fossil fuel power plants, this will contribute to outdoor particulate emissions as well as GHGs (see Chapter 9).

Case Study 3. Clean and efficient cookstove initiatives

Clean and efficient cookstoves come in various forms, though their performance and cultural appropriateness vary. New *WHO guidelines for indoor air quality: household fuel combustion* set health-relevant benchmarks for evaluating stove performance *(47)*. As part of the CCAC Household Heating and Domestic Cooking Initiative industry standards and testing protocols are being developed to evaluate cook-stove technologies in terms of their BC, PM and other pollutant emissions, as well as other co-benefits to households (see Appendix 3 for link).

A variety of cookstoves from simple to more advanced designs (Credit: US EPA)

A complementary program, the Global Alliance for Clean Cookstoves, hosted by the UN Foundation and supported by UNEP and WHO as well as the CCAC, promotes the adoption of cleaner cooking solutions and has a target of fostering the adoption of such solutions by 100 million households by 2020. As part of the program, the Alliance and its partners are working to establish a thriving global market for clean cooking solutions by addressing the market barriers that impede the production, deployment, and use of clean and efficient cookstoves and fuels in developing countries.

The Energy and Resources Institute (TERI) provides rural indian household with electric lights charged by solar-powered PV stations as part of their "Lighting a Billion Lives" initiative. (Credit: TERI)

Box 6. The climate and health implications of kerosene lamp emissions

Recent research has demonstrated that kerosene lamps are a much more important source of BC than previously thought *(233, 234).* At least 270 000 tonnes are emitted annually worldwide, and unlike nearly all other sources of BC, particle emissions from kerosene lamps are almost entirely composed of black carbon, making them an excellent target for climate change mitigation *(23, 233, 234).* Moreover, there are already many affordable alternatives on the market *(233).*

Following systematic review, the new WHO guidelines for household fuel combustion discourage household use of kerosene, noting that studies have linked their emissions with impaired lung function and increased risks of asthma, cancer, eye problems, and infectious disease, as well as with risks of burns, fires and poisoning. However, due to the limited number of studies and variation in study quality, the review recommends further research into health impacts *(47)*. A unique challenge in understanding the health effects from kerosene lamp emissions is that, as noted above, emissions are almost exclusively BC. Therefore, while particulates in general are well-known to cause adverse health outcomes, it is not yet entirely clear which specific components are responsible. BC has been linked to ill heath in multiple systematic reviews (see Chapter 1 for a detailed discussion of these issues). It is also well known that kerosene is highly flammable (millions of people suffer severe burns from lamps each year) and that it can be a source of poisonings if the fuel is ingested *(47, 233, 235).* In South Africa alone, for example, treatment costs from kerosene-related burns and poisonings were estimated to be nearly US$30 million annually *(48, 49)*.

Kerosene lamps also emit CO_2, and studies comparing different lamp types note that CO_2 emissions from kerosene are generally higher per lumen than alternatives *(236, 237).*

A student in Afghanistan studies by a kerosene lamp. Despite the impacts of kerosene smoke on both health and climate, such lamps are widely used in the developing world. (Credit: Department of Foreign Affairs, Trade and Development Canada)

Women carrying firewood in southern Ethiopia. Collecting firewood can expose women to injuries and contribute to deforestation. (Credit: David Stanley)

Box 7. Indirect benefits of clean and efficient cookstoves and fuel switching

Cookstove and fuel switching interventions that lead to decreases in emissions of SLCPs, CO_2, and other particulates can have benefits that extend beyond climate and health. By increasing thermal efficiency, improved cookstoves can reduce fuel demand, potentially leading to economic benefits and time savings for households that collected their own fuel *(14, 229)*. Lower demand can also reduce exposure to hazards that may occur during fuel collection itself, such as injuries from carrying heavy loads or from interpersonal violence (14). In terms of climate, any reduction in deforestation (or increase in reforestation) will have positive consequences for provision of ecosystem services, including the uptake of atmospheric CO_2 by trees and other vegetation.

Household and building energy use in middle- and high-income settings

In high-income countries, a large proportion of the energy consumed is generated in power plants and supplied as electricity, a topic that is discussed in Chapter 9. However, there are also many households that rely on on-site fuel combustion systems for space heating and to heat water.

Where boilers or heating systems are based on relatively dirty fuels (e.g. diesel or coal) or inefficient wood stoves, outdoor emissions of BC and PM from households and other buildings may be high. Exposure is also potentially high, as emissions originating inside the household will be present in the neighborhood for a period of time, even if adequately vented.

Replacement of these systems with cleaner technologies can curb emissions, and addressing emissions from use of diesel and wood in particular has recently been highlighted as a potentially favorable BC-related climate mitigation opportunity *(23)*. Options include systems that:

- Use cleaner fossil fuels (e.g. boilers using natural gas or liquid petroleum gas),
- Rely upon more efficient energy production or distribution technologies (e.g. district heating systems that rely upon co-generation of heat and power, or gas/electric-powered heat pumps), and/or
- Use renewables to generate either thermal energy directly (e.g. solar hot water heaters) or as part of a PV-supported system (e.g. electric-powered heat pumps with solar support or very-low-emissions wood-burning stoves).

In heating with wood, technologies that have a high thermal efficiency compared to conventional wood stoves, such as pellet stoves, are now readily available in most high-income countries. The US Department of Energy, for example, considers pellet stoves the cleanest solid-fuel residential heating appliance, with certified models in the 70-83% efficiency range *(238)*. Introduction of pellet stoves and boilers was one of 16 interventions selected in the UNEP/WMO analysis that together are capable of reducing SLCP emissions by nearly 90% of the estimated maximum (see Chapter 4). Other higher-efficiency wood-burning technologies include masonry heaters and catalytic wood stoves.

In areas with at least moderate residential densities, implementing district heating systems based on co-generation can be one of the more environmentally favorable and cost-effective interventions for reducing emissions, as only a single boiler is required to provide both heat and power that can be distributed to a number of households. These systems are widespread in parts of Europe and the potential to optimize co-generation is one reason careful urban planning is critical to a low-emissions urban profile.

Efficiency gains occur because the co-production process simultaneously generates electricity and heat, whereas conventional electricity production discards a meaningful proportion of energy. In cases where "trigeneration" is feasible, chilled water for cooling can also be produced. Seasonal excess heat from the cogeneration system is used to drive an absorption chiller, which removes heat through an evaporative process. The system can be highly efficient compared to conventional air conditioning, and is able to use water as the refrigerant instead of HFCs. Small-scale power generation is further discussed in Chapter 9.

Buildings

While the previous section was concerned primarily with improving combustion efficiency and/or changing the type of fuel used, improvements in building design can reduce energy demand, which is another route to curbing emissions. Projections indicate that building energy use and related emissions from buildings could double or even triple over the coming decades if left unchecked. But there is also substantial mitigation potential: if implemented, already-established best practices and technologies could reduce energy use in absolute terms over the same time period *(239)*. In fact, building energy use has declined in many European countries, and evidence suggests that energy savings of up to 90% are achievable through deep retrofits *(239)*.

Construction workers adjust equipment for the photovoltaic solar power system on the roof of University Hospital Mirebalais, Haiti. (Credit: Jon Chew/Partners in Health)

It is clear that SLCP emissions from buildings come in many forms: as mentioned, buildings can be a major source of black carbon through fuel combustion, and are also a source of HFCs through the use of air conditioning and refrigerators. However, most of the research on buildings has focused on energy use and/or CO_2 emissions rather than SLCPs, and therefore this section necessarily follows suit. The first sub-section below explores mitigation through smart building design, the second looks at appliance use, and the third briefly describes how buildings can be transformed into sites of efficient energy production. These sections also highlight important health co-benefits of improved buildings, covered in detail in a WHO, 2011 publication (*Table A4; 368*), and which include:

- Improved thermal comfort, thus reducing risks of temperature-related morbidity and mortality
- Improved air quality from reduced energy use and adequate ventilation
- Reduced damp- and mold-related illnesses, such as allergies and asthma
- Reduced infections associated with poor air flow (e.g. tuberculosis or chickenpox) or cooling systems (e.g. legionella)

A summary of potential energy savings in buildings from different strategies, as outlined in the text below, can be found in Table 18. It is important to note that the effect on SLCP emissions and climate of the strategies discussed in this section will be largely dependent on what fuel is being used to supply energy to the building. If diesel or wood is common, it is likely that there be a positive net effect through reductions in BC emissions, but if conventional electricity is the source, this may not be the case (though longer-term climate benefits are probable through reductions in CO_2 emissions) *(23)*.

Table 18. Savings or off-site energy use reductions achievable in buildings for various end uses due to on-site active solar energy systems, efficiency improvements, or behavioural changes (system efficiency includes passive solar heating, cooling, ventilation and daylighting).

End use	On-site C-free energy supply	Device efficiency	System efficiency	Behavioural change
Heating	20-95%	30-80%	90%	10-30%
Hot water	50-100%	60-75%	40%	50%
Cooling	50-80%	50-75%	67%	50-67%
Cooking	0-30%	25-80%		50%
Lighting	10-30%	75-99.83%	80-93%	70%
Refrigerators	-	40	-	30-50%
Dishwashers	-	17+%	-	75%
Clothes washers	-	30%	-	60-85%
Clothes dryers	-	50+%	-	10-100%
Office computers and monitors	-	40%	-	-
General electrical loads	10-120%	-	-	-

Source: Adapted from IPCC 2014 (239) - see Appendix IV for details.

A double layer aluminum roof improves the "thermal envelope" of a house in Hunan Province, China helps to reduce heating requirements. (Credit: He Jianqing)

Building design

Design-based measures reduce the energy required to keep buildings dry and at a comfortable temperature, while also efficiently removing dangerous air pollutants. Appropriate construction will differ based on local conditions, but in colder climates usually involves ensuring a weather-tight building (thermal envelope) to reduce heat losses out of joints, walls, foundations, and ceilings. Ventilation is still required, however, to prevent poor indoor air quality *(240)*. In tropical areas, the aim is to allow for passive air flow and circulation during hot periods, while the use of reflective materials and landscaping interventions can also facilitate cooling (also see Chapter 11). Reducing the need for cooling reduces energy demand and emissions of HFCs, which are powerful SLCPs and are used in air conditioning. In all areas, the use of climate-appropriate building materials, insulation, and window placement are key strategies, as is building orientation (see Case study 4 for examples). These strategies are imperative in new buildings that have a long lifespan, but retrofitting existing stock is also essential *(239)*.

In two randomized community trials in New Zealand, researchers found that installing insulation and improved heating systems in old houses where residents had respiratory diseases reduced energy consumption and/or low indoor temperatures, and also reduced self-reported symptoms of ill health *(241)*. Evidence from England also suggests that old, poorly heated homes with low energy efficiency are associated with ill health *(242)*. In a study modeling the impact of improved energy efficiency in UK homes, Wilkinson et al. (2009) examined the impacts of separate fabric and ventilation improvements on six health-related exposures ($PM_{2.5}$, radon, carbon monoxide, environmental tobacco smoke, mold, and cold) and associated health outcomes, finding a net positive health impact from both interventions as well as an overall reduction in carbon dioxide emissions *(221)*.

Policy instruments to facilitate energy efficiency in building design include *(239)*:

- Building codes
- Mandatory energy audits
- Building labels and certificates
- Fiscal tools (taxes, subsidies, and loans)
- Awareness raising and information campaigns

Appliances


Appliances account for significant building and household electricity usage. Air conditioning, in particular, is a heavy power consummer and key source of HFCs. (Credit: Stilfehler/Wikimedia Commons)

In addition to heating and cooling, a large proportion of energy use in buildings is from appliances, often accounting for 20% or more of electricity usage, with large appliances responsible for much of the consumption *(239)*. Mitigation of SLCPs from appliance use will depend largely on the fuel used to supply power. Diesel generators, for example, can be an important source of BC, but the climate benefits of reducing energy demand from conventional power plants will mainly come from CO_2 reductions (see Chapter 9).

The two main interventions capable of reducing the energy consumed by appliances are to increase their efficiency and to change people's behaviour regarding how and when appliances are used. Table 18 illustrates some of the potential savings in energy consumption from these different strategies, showing that both are important. Appliances have already become much more efficient, often surpassing recommended standards, while many of the most important behaviour changes are straightforward. Examples include turning off lights and appliances when not in use, running dishwashers and washing machines only when full, and opening windows instead of using air conditioners. Households similar in size and in similar climates sometimes show differences in energy use of an order of magnitude or more, illustrating how energy-efficient buiding design, including improved use of natural ventilation for cooling, is critical. Such strategies could reduce energy demand by up to 50% by mid-century *(239)*. Health benefits from appliance interventions can include reduced noise pollution (e.g. from air conditioning) and improved indoor air quality if natural ventilation is feasible and used effectively.

Energy infrastructure in buildings

As this section overlaps significantly with Chapters 9 and 11 on mitigation actions from electricity generation and in cities, respectively, readers should refer to those chapters for more detail. In brief, however, buildings offer a range of options for reducing demand or increasing efficiency through energy infrastructure. Buildings (including houses) can be sites for small-scale renewable electricity generation – for example, by fitting photovoltaic panels or instituting district heating systems. Solar water heaters are another option. The fitting of direct-current (DC) connections within buildings alongside alternating-current (AC) connections would allow for DC appliances to connect to DC power sources, eliminating conversion losses. Significant local health benefits can be realized in terms of improved air quality and energy security associated with shifts to renewable energy and efficiency measures.

Roof-mounted solar water heater. (Credit: Wikipedia, Cachogaray)

Case study 4. Low-emission passive design and natural ventilation in health-care settings can reduce building-related emissions and disease transmission

A 2009 WHO systematic review found that well-designed natural ventilation systems in health-care settings are an effective means to reduce airborne infections, and that under the right conditions can achieve higher air exchange rates when compared to mechanical alternatives *(243).* A study of eight hospitals in Lima, Peru, found that if properly operated (by keeping windows and doors open), ventilation rates were higher and infection risks lower in naturally ventilated clinical rooms compared to mechanically ventilated rooms *(51).* Facilities built more than 50 years ago performed best: predicted infection risks were 3.5 times higher in mechanically ventilated facilities and 3 times higher in modern naturally ventilated facilities compared to the older natural ventilation designs.

To take another example, a study from Nguru, Nigeria, compared the impacts on temperature and patient care in two neonatal facilities where babies were vulnerable to hyperthermia – one control facility and one facility redesigned to incorporate passive design principles for thermal regulation *(244).* The latter included lowering floors 120 cm below ground, raising roof heights, creating double walls, placing windows for cross-ventilation, and adding cotton window blinds. The redesigned facility had substantially lower indoor temperatures on peak heat days (33 °C vs 39 °C), less overheating of incubators, and a much lower rate of baby water-sponging. A third site that underwent a less-extensive renovation performed between the control and the fully redesigned facility.

These studies illustrate how energy-efficient buildings can reduce demand for power generation as well as yield health benefits. WHO is supporting efforts to further define how the health sector can improve energy efficiencies and energy access for better health services delivery.

The design of a new South African health facility aims to curb cross-infection of patients with drug resistant TB using natural ventilation. (Credit: Council for Scientific and Industrial Research in South Africa)

8

Billions of bricks are produced per year, many in traditional kilns that pollute the air through the release of fine particulate matter, including black carbon. (Credit: Program on Energy Efficiency in Artisinal Brick Kilns in Latin America to Mitigate Climate Change (Program EELA), funded by the Swiss Development Corporation and implemented by Swisscontact.)

Chapter 8:
Industry

Chapter highlights:

• Industrial processes that emit large amounts of black carbon include brick production and the use of coke ovens.

• Traditional brick kilns and coke ovens can be a major cause of high particle concentrations in certain locations, particularly in Asia, and exposures can be particularly high among workers.

• Technologies exist that can substantially reduce emissions from both industries.

• The fossil fuel industry is a key source of methane emissions, which contribute to tropospheric ozone.

• Recovery and use of gas released during fossil fuel production and distribution can reduce methane emissions and the production of ozone.

The industrial sector includes a heterogeneous mix of activities, not all of which can be discussed here. The use of solid fuels for industrial purposes is an important source of BC, though not all industries present good climate mitigation opportunities because of cooling co-emissions *(23)*. Targeted action, however, may produce benefits, and emissions from brick kilns and coke ovens have been identified as worth taking action to address *(9, 23)*; both industries are discussed below, as are fossil fuel extraction and distribution because they are major sources of methane.

Brick kilns

Every year, billions of bricks are produced globally, with China and India the two top producers *(245, 246)*. India alone has an estimated 100 000 kilns that employ around 10 million people *(246)*. Kiln designs vary widely, but in many low-income countries, bricks are often fired in traditional (artisanal) kilns that release high levels of heath-relevant pollutants, including $PM_{2.5}$ and BC, worsening local air quality and leading to high occupational exposures (56, 245, 247-249). The kiln fuel is generally wood or coal. Although few studies have explored the health effects associated with brick kiln emissions specifically (as opposed to PM in general), there have been reported associations with adverse respiratory symptoms *(248, 250)*. A World Bank modeling study from Dhaka, Bangladesh, estimated that kilns were the major source of particulate air pollution in the city and were responsible for about 750 premature deaths annually *(249)*.

Acambaro, León, Mexico. Artisanal brick kiln in operation. Credit: (Photo is from the Program on Energy Efficiency in Artisinal Brick Kilns in Latin America to Mitigate Climate Change (Program EELA), funded by the Swiss Development Corporation and implemented by Swisscontact.)

Improved kiln designs generally focus on increasing combustion efficiency and reducing exposures through chimney design. In an analysis of 13 South Asian brick kilns, researchers found that emission factors differed widely between kiln types – sometimes by an order of magnitude – and that the most commonly used kilns had the highest emissions *(247)*. Programs and legislation have been implemented in a number of countries to move towards improved brick kilns (Figure 18), but these interventions generally have high capital costs and may entail replacement of the kiln *(9, 245)*. Lower-tech (and cost) options include the use of alternative fuels or measures to facilitate adoption of improved operating practices, such as education campaigns (Case study 5) *(251)*.

Coke ovens

Coke is a fuel produced by heating coal to high temperatures in an oxygen-free furnace or oven, normally between 1000-2000 °C. The fuel product (coke) has few impurities and is often used in iron smelting and steel production. The industry is concentrated in China, which is responsible for about 60% of global coke production *(254)*.

As with brick kilns, inefficient low-technology coke ovens are widespread in many developing countries and are characterized by high emissions when

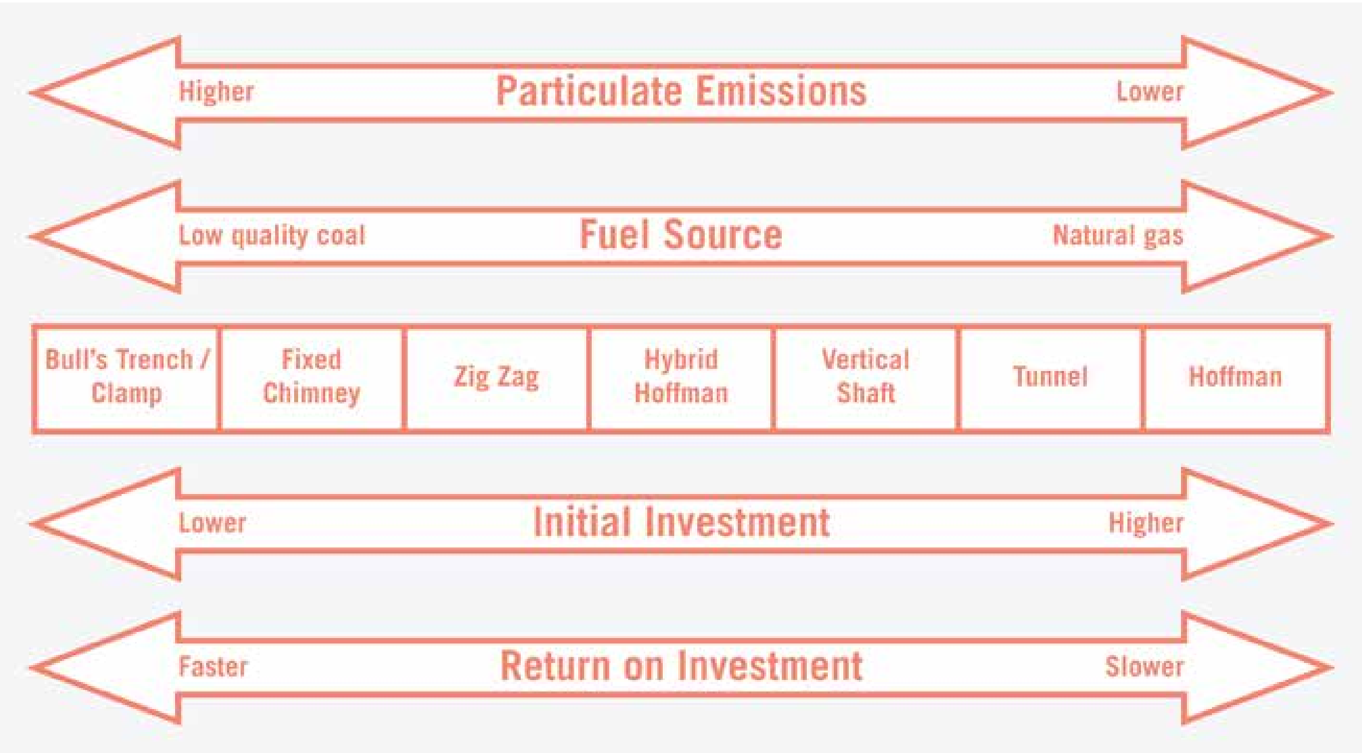


Figure 18. Relative particulate emissions, fuel sources and investment requirements for various brick kiln technologies, assuming good operating practices. In most cases, lower particulate emissions equate to lower BC emissions. Source: Recreated from reference (251) and based on information from Ijaz Hossain and Sameer Maithel (with permission).

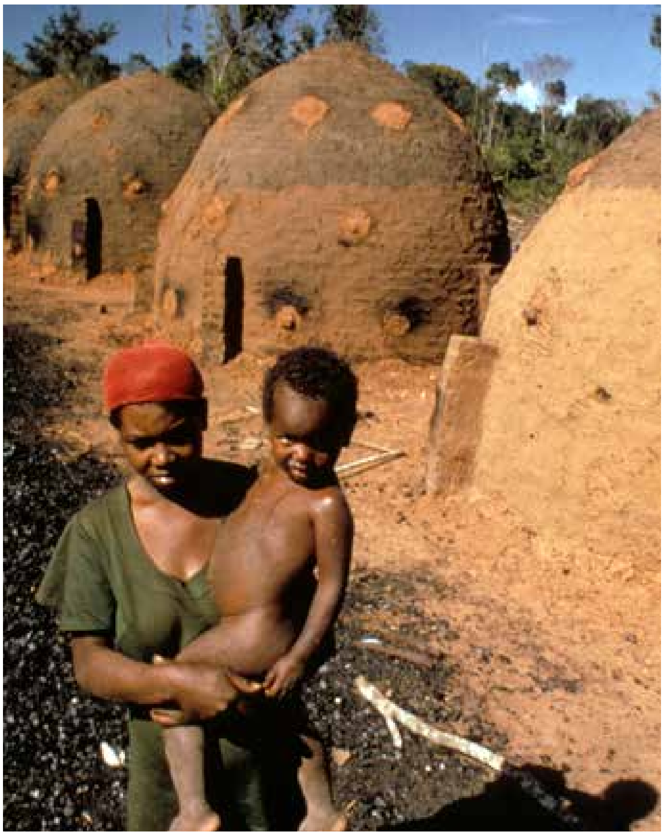
Case study 5. A brick production initiative

The Government of Bangladesh gave their brick kiln owners an ultimatum in early 2014: Convert to clean, modern technologies for production by July, or face tough legal action. Black carbon from nearly 7000 kilns in the country was impacting the health of Bangladesh's people, as well as harming their mango and rice crops. With the help of a large fund provided by the government in conjunction with the Asian Development Bank, the World Bank, and the UN Development Programme, modernization of the Bangladesh brick sector is on track *(252).*

Part of the stimulus for this decision was a CCAC initiative to reduce black carbon and other pollutants from brick production, while improving local and regional air quality *(253).* Beginning in 2013, a Policy and Advocacy Network (PAN) was launched globally and through two regional networks in South Asia and Latin America and the Caribbean. An awareness-raising toolkit as well as training nodes and manuals to help implement proven technologies have been developed and are shared via an online clearinghouse. The focus is on developing strategies to engage small producers and to create more formal policies for the sector, which is largely unregulated and relies on informal workers. Special attention is also given to demonstrating health and livelihood impacts to transform the sector. As part of a holistic mitigation strategy, considerations will go beyond improving the brick production process and go towards considering building materials more broadly (e.g. use of hollow bricks).

(See Appendix III for more details.)

compared to more modern production processes. Replacing traditional coke ovens (such as the common "beehive" kiln) with more modern designs using pollution abatement technologies is the main strategy to reduce emissions. There are relatively few observational studies on health effects associated with coke ovens, but some research in occupational settings, mainly from higher-income countries, has connected coke work with adverse physiological responses. There is evidence of links with certain cancers; the International Agency for Research on Cancer lists coke production as a group 1 carcinogen *(35, 255-257)*. $PM_{2.5}$ and other emissions that are released from ovens are known to be harmful from studies in other contexts (see Chapter 1) *(2, 4)*.

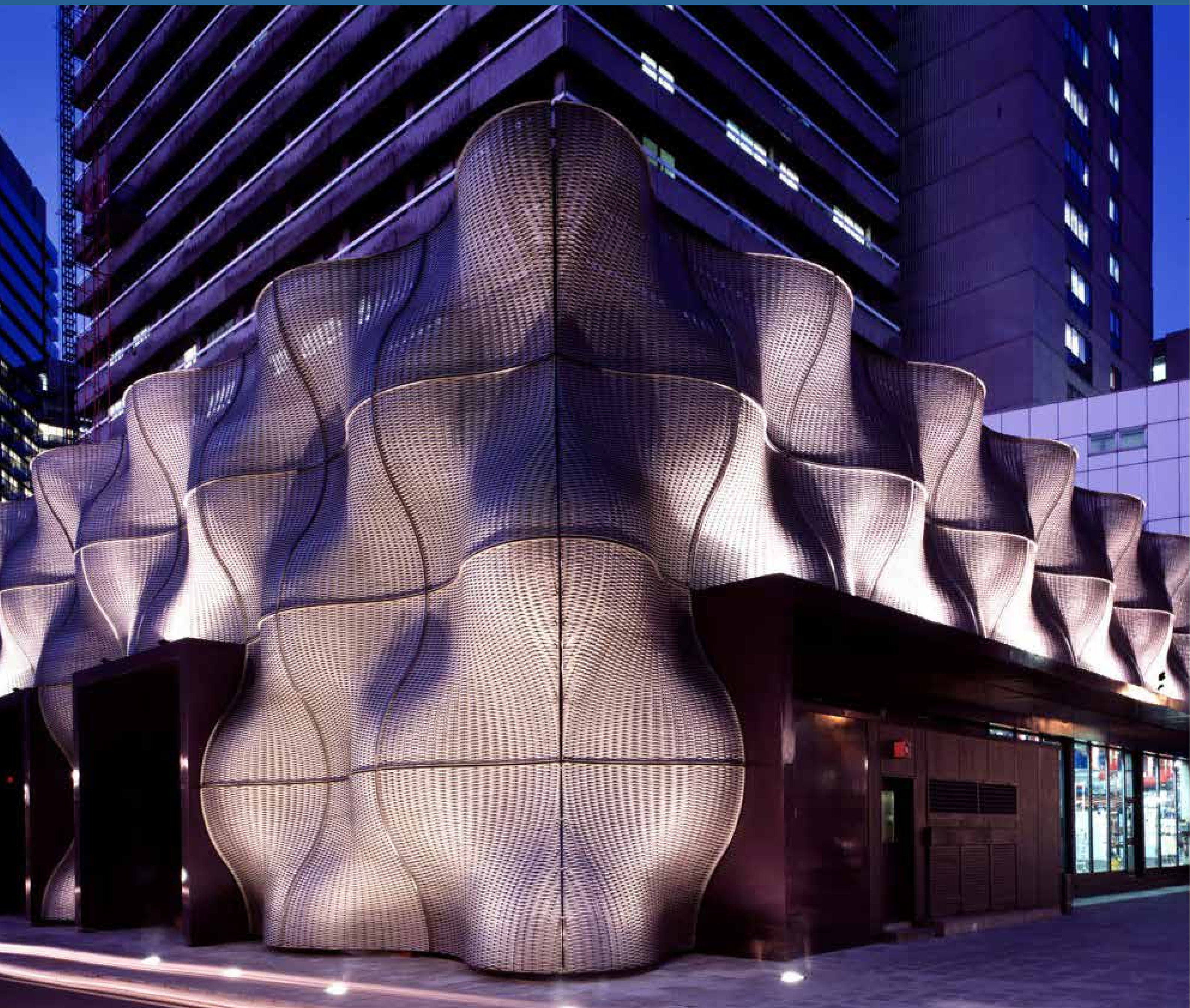


The modernization of traditional coke ovens is one strategy to reduce black carbon emissions. (Credit: UN Photo/Sebastiao Barbosa)

The fossil fuel industry

Fossil fuel extraction and processing are major sources of methane emissions and are regularly identified as major climate change mitigation opportunities *(9, 57)*. Specific actions include the recovery and use of methane from coal mines and in oil and natural gas production processes, and reducing leakages, including during pipeline distribution *(9, 57)*. Although climate impacts could be large, assessments indicate that mitigation is unlikely to produce a major direct public health benefit, though there may be modest gains through reductions in ambient ozone (methane is a precursor) *(9)*. Post-recovery flaring of methane from oil and gas production processes - which transforms the methane into CO2 and water, thereby reducing its warming potential - is a "second-tier" mitigation action. It is problematic, however, insofar as it also creates more emissions of particulate matter including black carbon; flaring is a poorly understood source of black carbon, but it is estimated to account for about 4-5% of the anthropogenic total globally *(9, 23)*.

9



London's Guy's and St Thomas' NHS Foundation Trust Hospital, United Kingdom, cut pollution and carbon emissions with an energy-efficient combined heat and power system, which captures waste heat from on-site power generation for building uses. (Credit: Edmund Sumner/heatherwick.com)

Chapter 9:
Electricity generation

Chapter highlights:

• Large-scale burning of fossil fuels in power plants is, in general, not considered a key area for SLCP mitigation, though technologies exist that can lead to large reductions in CO_2 and improve air quality.

• However, at a smaller scale, replacing diesel generators with cleaner energy sources (e.g. photovoltaic panels) has the potential to reduce black carbon emissions.

• Other climate (mainly CO_2) mitigation actions in the sector include switching from fossil fuels to renewables, building decentralized power grids, and increasing efficiencies during electricity transmission and distribution.

This section focuses on energy supply, and electricity in particular. Electricity accounts for about 17% of total final energy consumption *(57)* and is a major driver of outdoor air pollution. However, the potential climate benefits from reducing black carbon emissions from power plants may be offset by the reduced cooling effect of co-emitted particles (e.g. sulfates) and is therefore a poor mitigation opportunity in that respect *(23)*. Nevertheless, in light of the potential health benefits and overall climate impacts when also considering long-lived climate forcers, there is wide agreement that this sector requires significant policy action. Additionally, at a smaller scale, if diesel generators are being used for electricity production, there may be BC-related mitigation opportunities (Case study 6) *(23)*.

The main mitigation actions in this sector involve fuel switching and technological fixes. Therefore, unlike some other sectors where mitigation actions affect many different risk factors for ill health, the co-benefits of mitigation actions associated with electricity generation are limited primarily to changes in air quality and, in some cases, to occupational injuries.

This chapter is divided into three sections. The first focuses on mitigation actions addressing power plants. The second broadens the discussion to include the storage, transmission, and distribution of electricity. The final section turns to the potential benefits of decentralized power systems.

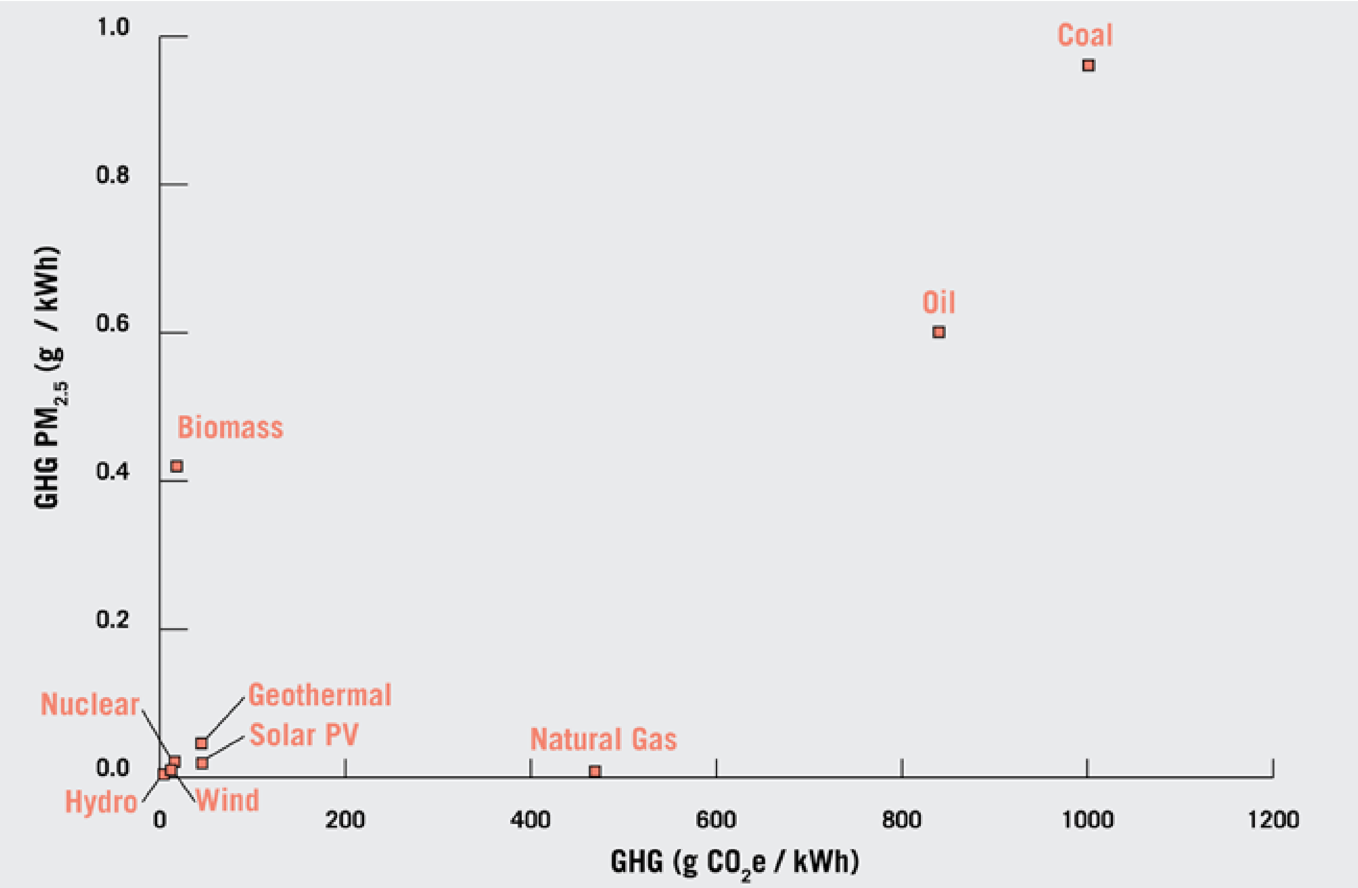


Figure 19. Life-cycle GHG and $PM_{2.5}$ emissions of selected electricity generation technologies. Data for GHG is presented as the median reported value, while for $PM_{2.5}$ is the midpoint between the minimum and maximum reported values. Carbon capture and storage is not considered. PV = photovoltaic. Source: Sathaye et al., 2011 (258).

Power plants

The dominant mode of electricity generation today is from conventional large-scale power plants using fossil fuels. In general, coal, and oil produce high levels of both GHG emissions and fine particulate matter, whereas natural gas performs substantially better, particularly with regard to $PM_{2.5}$ (Figure 19). It is possible to mitigate fossil fuel emissions somewhat through technological solutions (e.g. carbon capture and storage), but the benefits are likely to be smaller than those from switching away from coal and oil to other energy sources, namely by increasing the share of natural gas, nuclear, and renewables in particular.

Like coal and oil, and unlike renewable energy sources, natural gas is a fossil fuel and therefore exhaustible. Discoveries of new gas reserves have spurred a large increase in its use, and its advocates also note potentially important environmental benefits when compared to coal and oil, including reduced GHG and $PM_{2.5}$ emissions (Figure 19). Other concerns have been raised, however, particularly with regard to the recent growth in extraction of "unconventional" gas, which includes processes that use large amounts of undisclosed chemicals and can create local air quality concerns *(259, 260)*. Also, when leakages occur during extraction or distribution, these may increase levels of tropospheric ozone (also see Chapter 8).

The emissions of both GHGs and $PM_{2.5}$ from nuclear power are negligible (Figure 19) and reserves of uranium are large, likely sufficient to meet global energy demand for at least a century or more *(57)*. Nevertheless, nuclear energy currently only accounts for about 11% of the world's electricity supply, and most of this is concentrated in a small number of countries *(57)*. Despite very low day-to-day health impacts, impediments to expansion include high capital costs and anxieties about nuclear waste disposal and the possibility of an accident (or attack) at a nuclear facility.

Renewable energy sources, which include hydropower, wind, geothermal, solar, and biomass energy, comprise only a small proportion of total energy supply, though this may be changing: in 2012 over half of new installed capacity was from renewables *(146)*. Reasons for the recent growth include improved technology, lower costs, and the often substantial environmental and health benefits. There are still challenges in rolling out renewable energy on a large scale; for example, ensuring constant supply, but recent calculations indicate that the technical potential of renewables far exceeds total demand *(57)*. The most appropriate renewable technologies will vary by location and not all sites will be ideal, but in most places there are significant opportunities to increase deployment *(57)*. However, a distinction needs to be made between modern renewables and the traditional use of solid fuels (e.g. wood, dung), which are also considered renewable but tend to be burned inefficiently and can lead to high levels of particulate and black carbon emissions (see chapter 7). From an air quality perspective, (modern) renewable energy sources generally have far fewer impacts than coal or oil, though natural gas compares more favorably (Figure 19).

A transition to renewable energy production may also lead to a reduced burden of occupational injuries and diseases (e.g. respiratory diseases and cancers) commonly associated with fossil fuel extraction and use *(261, 262)*. More indirectly, renewable electrification of small workshops and cottage industries can bring occupational health benefits to the informal workforce by permitting greater worker productivity and fewer accidents, through better illumination and small electronic devices *(262)*. At the same time, renewable energy technologies can introduce some new risks for workers, such as exposure to nanoparticles or hazardous chemicals in certain types of solar panel production, as well as risks to the wider population through potential exposure to toxic waste products from discarded materials; these risks need to be assessed and mitigated as the industry grows and develops *(262-264)*.

Conversion, transmission, and distribution

The energy supply sector has large inefficiencies in its conversion, transmission, and distribution processes. For fossil fuel power, efficiency is estimated at only 37%, meaning that the majority of energy produced is lost *(57)*. Combined heat and power plants, which utilize the heat that is considered waste in electricity-only plants, have an estimated efficiency of 58% (though much higher if state-of-the-art) *(57)*. Efficiency from district heat generation using fossil fuels is 83% *(57)*. Losses occur in cables and transformers, so improved design can improve efficiencies *(57)*. Losses are also a function of the geographical layout of the system, which can vary widely between countries. The loss of energy during long-range transmission is one argument for decentralized systems, the topic of the next section.

Decentralized power systems

The rapid increase in the use of stand-alone diesel generators to respond to the soaring demand for power in regions that are off-grid or have unreliable access to grid electricity is a trend that has been noted with concern by scientists, as well as some policy-makers, as a rapidly growing source of both pollution and noise. Similarly, the CCAC's Scientific Advisory Panel has noted that these generators are a growing source of black carbon emissions in countries where recent economic growth and demand for electricity have not been matched by power supply (e.g. Nigeria, India, Nepal, etc.) *(265)*. Expansion of smaller-scale electricity generation at the community or single-building level has many advantages. Losses from transmission are reduced, people are less vulnerable to disruptions that occur far away, and power can be accessed by more remote communities without the need for as much distribution infrastructure. As mentioned above, the appropriate energy sources will depend on financing and local conditions, but many low-impact sources are available. For example, photovoltaic panels can be fixed to roofs of large institutional buildings, providing electric power to the facility in peak demand periods, and selling the surplus to utilities or nearby communities in off-peak periods. Households can also install panels for personal use; such systems are described as "distributed energy generation" since energy production occurs at multiple, diverse points in the grid. In settings that are currently off grid, "microgrids", which are a smaller-scale version of large-scale electrical networks – can be used to develop a community power supply. For homes, schools, health clinics and small businesses, micro-grids that make effective use of renewable energy sources can provide clean sources of light and power compared to fossil-fuel based systems while advancing broader development goals such as reading opportunities, entrepreneurial activities, and access to a variety of modern technologies. *(266-268)* Highly efficient combined heat and power systems are another decentralized option, and one that is being used by health facilities around the world (see Case study 6 for examples of decentralized energy solutions, including CHP and renewables, providing reliable power in the health-care sector).

Case study 6. Alternative energy in the health-care sector

Example 1. Capturing the sun's benefits for health care

Health-care facilities require particularly reliable power sources, and yet some 26% of health clinics in sub-Saharan Africa have no power at all, while only 33% of hospitals have what can be defined as a "reliable" power source *(267)*.

Stand-alone diesel generators are often the default power solution in such settings, despite being expensive to fuel and maintain. They are also among the most polluting sources available per kWh; they produce BC-rich emissions of $PM_{2.5}$ as well as CO_2. Substitution or supplementation of such generators with appropriately sized photovoltaic solar power systems can, however, substantially reduce emissions as well as cost. A series of recent modeling studies looking at clinic settings in Africa illustrate quantitatively how efficiently managed hybrid or fully renewable power systems have the potential to reduce PM and CO_2 (Table 19) *(268-272)*. High initial costs may be a barrier in some locations, but rapid declines in the price of renewables are closing the gap. Additionally, careful assessment of the longer-term savings inherent to hybrid or renewable systems (where fuel costs are significantly reduced) can also make the initial capital outlay for renewables much more attractive as evidenced in comparisons of capital versus net present costs of alternative power generation systems (Table 19).

Table 19. Comparative emissions of power supply options for a hypothetical health clinic in rural Kenya with energy efficient devices. Source: (272).

Configuration	Pollutant emissions (kg/yr)				Capital cost	Net present cost
	PM	CO_2	NO_x	CO		
Generator only	0.94	5 023	111.0	12.40	1 700	53 285
PV + generator	0.45	2 424	53.4	5.98	8 244	34 034
Generator + battery	0.50	2 658	58.6	6.56	5 160	29 799
PV + battery	0	0	0	0	8 460	10 305
PV + generator + battery	0.04	195	4.3	0.48	7 702	10 233

Notes: Net present costs include the cost of fuel, batteries, labor etc. assuming a 25-year time horizon and 7.5% discount rate. PM refers to total particulate emissions.

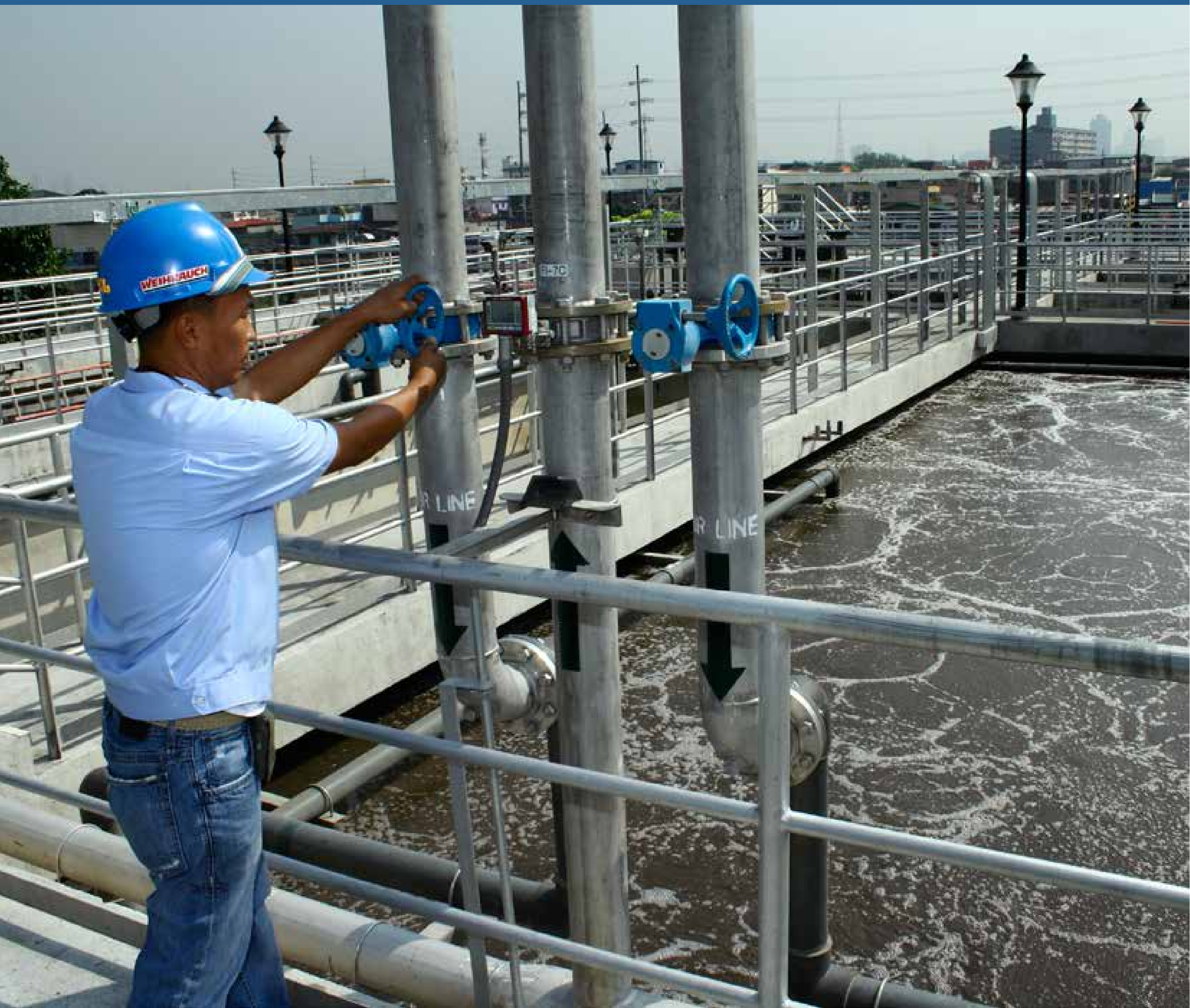
An aerial view of University Hospital of Mirebalais, Haiti reveals 1,800 solar panels on the hospital's rooftop. (Credit: Rebecca E. Rollins/Partners in Health)

Example 2. Combined heat and power (CHP) for storm resilience

In the USA, the Mississippi Baptist Medical Center, a 624-bed facility in Jackson, Mississippi, lost grid power for 52 hours in 2005 in the wake of Hurricane Katrina. A CHP system allowed the hospital to continue full operations – it was the only hospital in the area to do so – and to extend emergency aid to patients from other hospitals that lost power, as well as providing shelter and food to displaced community residents *(273).* Similarly, during Superstorm Sandy that hit the northeastern US in 2012, a number of major New York City institutions were able to maintain power during the storm because of their CHP systems, including Long Island's South Oaks 26-acre hospital campus, which isolated itself from the grid and operated for five days on its CHP system when grid power was unavailable. It then operated independently for another 10 days after power was restored to the surrounding area, at the request of the crisis-besieged Long Island Power Authority *(274).* These are but two examples of how large hospitals in developed countries, and in some emerging economies, are turning to CHP systems so as to improve their resilience in extreme weather, related emergency response capacity, and also reduce utility costs for both power and heat. Since conventional grid power generation is inherently inefficient, with significant losses of energy through waste heat, CHP systems can both reduce air pollution associated with power generation as well as climate emissions and energy costs for large institutional buildings. Shifting to CHP can also reduce reliance upon backup diesel power systems that large hospitals are usually required to maintain, thus emissions of black carbon *(272)*.

Gas compressor installed as part of New York-Presbyterian Hospital's Combined Heat and Power system. (Credit: New York-Presbyterian Hospital)

10



A wastewater treatment plant in Manila, Phillipines. Upgrading primary wastewateer treatment to secondary/tertiary treatment with gas recovery can help reduce methane emissions. (Credit: Danilo Pinzon/World Bank)

Chapter 10:
Waste management

Chapter highlights:

• The waste management sector is a major contributor to global methane emissions.

• Key mitigation actions include reducing the amount of waste produced (e.g. through recycling) and using technologies that capture methane at landfills and wastewater treatment plants.

• Less methane in the atmosphere can reduce health burdens from tropospheric ozone.

• If a mitigation action includes increased sanitation coverage, health benefits are potentially large.

This chapter focuses on post-consumer waste and sewage/wastewater. Other forms of waste are discussed in other chapters; for example, agricultural/ food waste (Chapter 5) and industrial by-products (Chapter 8).

Compared to most of the sectors discussed in this report, few studies have assessed the potential health benefits from waste management. Reasons may include the relatively small contribution of the sector to total global GHG emissions (estimated at around 5%) or the fact that some of the evidence on associations with health is inconclusive (see Box 8 for more on health effects of waste management) *(275-277)*.

Nevertheless, from the perspective of SLCPs and near-term climate, waste management remains an important target for mitigation as it is a major source of methane. Methane is the most important GHG in this sector, with CO_2 and N2O more minor contributors (HFC emissions may also occur after disposal of appliances and certain foams) *(275)*. A number of mature, cost-effective technologies are capable of reducing these emissions *(275)*. The IPCC AR4 report estimated that the future (2030) total global economic mitigation potential of methane was 70% of projected emissions, a large proportion of which would be achievable at low or even negative costs *(275)*. Accordingly, emissions from waste have already stabilized or even declined in some high-income countries *(275)*. Finally, despite the methodological challenges associated with epidemiological studies of solid waste management (Box 8), there are some strong associations between waste and health, of which the link between sanitation and infectious disease is perhaps the most well-known example.

The amount of waste produced per capita varies widely and is tightly correlated with affluence. In urban Africa, for example, average waste generation is about 0.65 kg/capita/day, but ranges from <0.01 to 3 kg *(277)*. The average in OECD countries is 2.2 kg. These differences will influence the choice of the appropriate mitigation actions, as will cost considerations. The following discussion is separated into four sections. The first describes mitigation technologies available at waste disposal sites, while the second takes a more upstream perspective to discuss strategies to reduce waste creation. The third section addresses sewage/wastewater, and the fourth briefly touches on open burning, which is a source of local air pollution, including BC. Examples of policies for mitigation across the different sub-sectors are summarized.

Solid waste mitigation technologies

The main GHG (methane) mitigation technologies in solid waste management – landfill gas recovery and incineration – affect emissions in two related ways. First, fewer climate forcers are released when using these technologies compared to conventional landfilling *(275)*. And second, combusting landfill gas and incinerating waste are both sources of energy if utilized, meaning that GHG emissions can be indirectly avoided by reducing reliance on energy produced elsewhere. Figure 20 summarizes the disposal options for solid waste in terms of sustainability in what is referred to as the “waste hierarchy.”

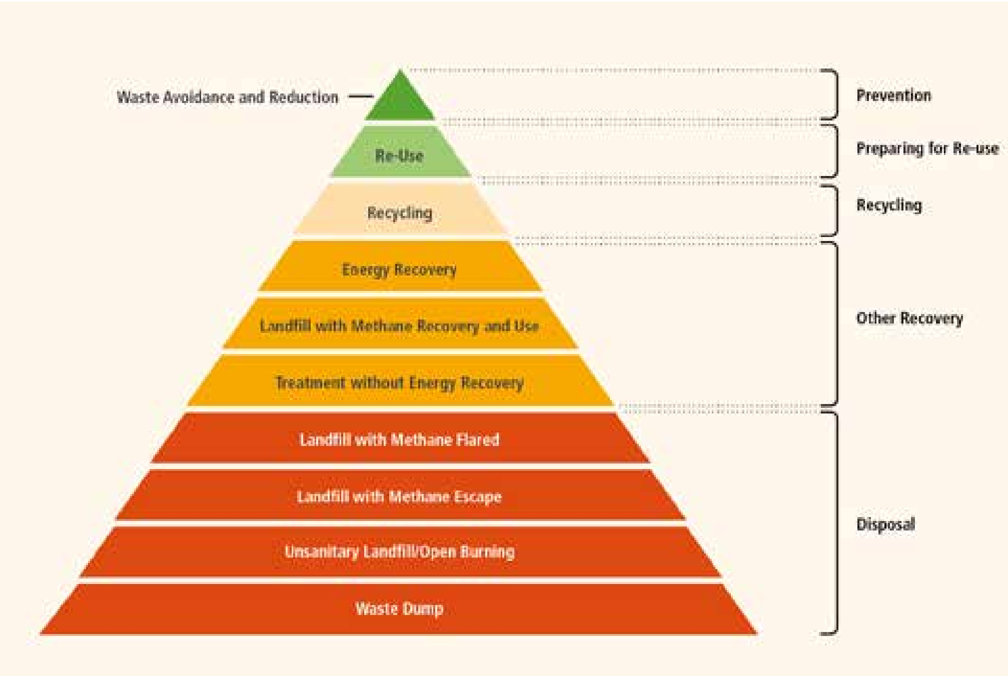


Figure 20. The hierarchy of waste management. The priority order and color coding are based on the waste hierarchy classification outlined by the European Commission and listed at right. Source: IPCC, 2014 (281) - see Appendix IV for details.

The recovery (and utilization or as a second option, flaring) of landfill gas is generally considered the most important mitigation action in the sector. Landfill methane is the main source of GHG emissions in waste management, and established technologies are already in wide use in many countries *(275)*. The approach generally involves constructing vertical wells or horizontal collection pipes and recovery of more than 90% of the gas is theoretically achievable *(275)*. The main potential health co-benefit is a reduction in ozone production.

Incineration reduces the total amount of waste that is landfilled, thus lessening the quantity of hazardous material potentially ending up in soil or water. However, it has high capital and operating costs, and only dry waste can be incinerated. Another drawback of incineration is that it only addresses new waste, whereas landfill gas can also be recovered from old waste; gas can be produced for decades after disposal. Additionally, incineration produces local air pollution, including particulates, though if the best available technologies are used, combustion is efficient and emissions will be small and unlikely to meaningfully affect background levels of these pollutants *(276)*. The non-hazardous ash output of incinerated waste can be used as a construction material, while the hazardous component will be landfilled or treated further.

Waste minimization and recycling (including composting)

Complementary to any technological approach that limits emissions are strategies that reduce the amount of waste generated. The potential for waste reduction is evident from international comparisons: for example, per capita waste generation is about 40% lower in Japan and the EU compared to the USA *(281)*. Policies to reduce post-consumer waste may target producers (e.g. through regulations on packaging) or households (for example, by legislating for garbage separation and recycling). In some countries, recycling of certain types of waste now exceeds 50% (Figure 21), and even where recycling is not mandated, cash incentives often spur informal recycling *(282, 283)*. With the exception of possible implications for occupational health and safety, minimizing waste through reuse and recycling is unlikely to have a negative impact on population health.

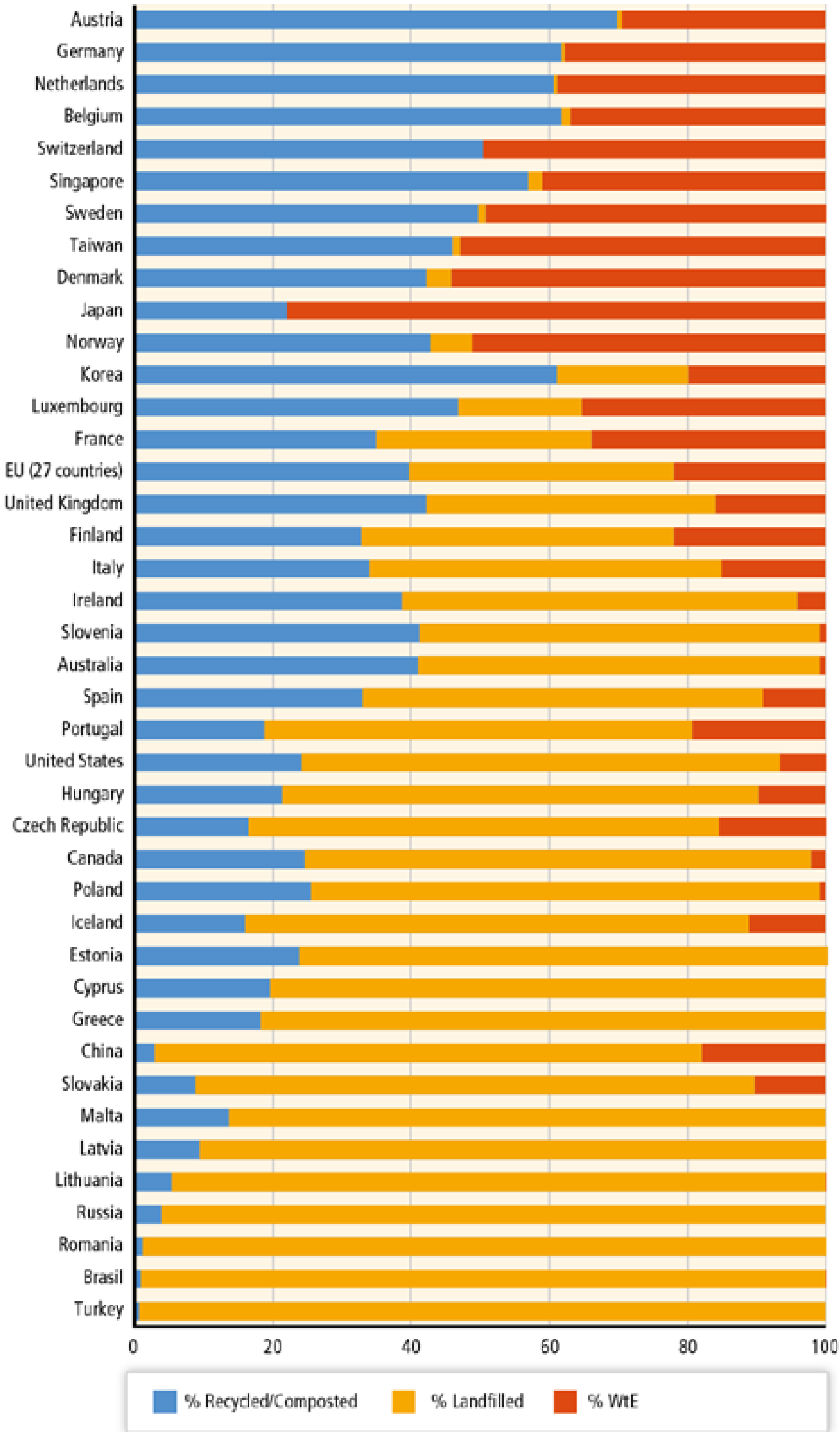


Figure 21. Management practices concerning municipal solid waste in several nations (WtE = waste-to-energy). Source: IPCC, 2014 (281) – see Appendix IV for details.

Less total waste reduces the need for landfilling and/or incineration and associated emissions. It also conserves raw materials and the energy needed to produce them, which for some metals, glass, and plastics can be considerable. Some countries are even attempting to move towards "circular economies" which aim to minimize total throughput by closing the flow of materials and ultimately producing zero waste *(275, 284)*.

Composting has also become an increasingly popular technology in the waste management sector. Composting is similar to recycling in that it reduces the amount of landfill waste, but focuses on biodegradable (organic) matter. Compost has applications in agriculture, horticulture and landscaping.

Wastewater / sewage

Approximately 2.5 billion people do not have access to proper sanitation, which refers to the safe disposal of human excreta *(285)*. Lack of sanitation is a strong risk factor for many infectious diseases, and untreated wastewater can also threaten freshwater resources and ecosystem integrity *(58, 59, 275, 286)*. Providing adequate sanitation (including sewage treatment) would therefore have multiple health and environmental benefits. The provision of sanitation is a part of Millennium Development Goal #7.

The majority of people without access to sanitation live in under-resourced settings in developing countries. As a result, ensuring adequate sanitation and wastewater treatment will involve a mix of technologies. Transport and processing at central sites has benefits, including the ability to apply a more modern treatment regime, but on-site sanitation is cheaper and may be more practical in many areas. On-site treatment includes pit latrines, composting toilets, and septic tanks. The health benefits of improving sanitation are evident from epidemiological studies, with systematic reviews finding strongly beneficial effects on a range of diseases, including diarrhea and helminth infections *(58, 59).* In terms of high-income countries where sanitation coverage is near-universal, technologies exist to capture and treat or utilize biogas emissions, an intervention evaluated in the UNEP/WMO study of SLCP reduction (see Chapter 4) but not assessed for sanitation-related health co-benefits *(9, 281).*

Sludge, the main solid byproduct of wastewater treatment, has applications in agriculture and landscaping. If it replaces other inputs (e.g. fertilizer), energy and raw materials are saved through substitution. It is important to ensure that hazards remaining in the sludge are within acceptable levels. Treated wastewater (as opposed to solid sludge) is also a valuable material for agricultural and industrial applications.

A note on open burning of waste

So-called "backyard burning" occurs in countries at all income levels. Reasons include inadequate provision of waste collection, economic rationales, and convenience. The unregulated open burning of solid waste produces local air pollution, including particulate matter and BC, though the exact emissions will be partly determined by the components of garbage, which vary widely *(287, 288).* Dioxin emissions are a particular health concern *(289)*. It is not clear whether open burning of garbage has a net cooling or warming effect, so this has not been pinpointed as a necessarily good climate mitigation opportunity *(23)*.

Table 20. Examples of policies and measures for the waste management sector.

Policies and measures	Activity affected	GHG affected	Type of instruments
Reducing landfill CH_4 emissions			
Standards for landfill performance to reduce landfill CH_4 emissions by capture and combustion of landfill gas with or without energy recovery	Management of landfill sites	CH_4	Regulation Economic incentive
Reduction in biodegradable waste that is landfilled	Disposal of biodegradable waste	CH_4	Regulation
Promoting incineration and other thermal processes for waste-to-energy			
Extended Producer Responsibility (EPR)	Manufacture of products Recovery of used products Disposal of waste	CO_2 CH_4 F-gases	Regulation Voluntary
Unit pricing/ Variable rate pricing/ Pay-as-you-throw (PAYT)	Recovery of used products Disposal of waste	CO_2 CH_4	Economic incentive
Landfill tax	Recovery of used products Disposal of waste	CO_2 CH_4	Regulation
Separate collection and recovery of specific waste fractions	Recovery of used products Disposal of waste	CO_2 CH_4	Subsidy
Promotion of the use of recycled products	Manufacturing of products	CO_2 CH_4	Regulation Voluntary
Wastewater and sludge treatment			
Collection of CH_4 From wastewater treatment system	Management of wastewater treatment system	CH_4	Regulation Voluntary
Post-consumer management of fluorinated gases			
Substitutes for gases used commercially	Production of fluorinated gases	F-gases	Regulation Economic incentive Voluntary
Collection of fluorinated gases from end-of-life products	Management of end-of-life products	F-gases	Regulation Voluntary

Source: IPCC (275) – see Appendix IV for details.

Box 8. Waste management: evidence of health effects

Solid waste

Electricity generators use landfill gas as fuel in Edmonton, Canada. (Credit: Pembina Institute)

Health concerns about solid waste management sites stem from the possibility that hazardous pollutants (metals, chemicals, pathogens) will enter the environment and make people sick. The main routes of exposure are likely to be from emissions into the air, the contamination of food grown near treatment sites or where end-products (e.g. compost or sludge) have been applied to agricultural fields, or through direct contact with contaminated water or soil *(276)*.

For a variety of reasons, it is difficult to design and conduct reliable, high-quality studies on associations between solid waste management and health *(276)*. Data is generally poor on the mix of pollutants present at a given site, as is information about how much is released into the wider environment. Confounding control is also a problem, both at the individual level and in terms of the area: waste management sites are often located near other potential sources of pollutants. Taken together, exposure classification in epidemiological studies is a huge challenge.

Partly as a result, a 2007 WHO report concluded that the evidence on health effects associated with landfills and incinerators is generally inconclusive *(276)*. There is an indication of a link between landfills and reproductive outcomes and cancers, particularly for the former, though it is so far insufficient to assign causality. The evidence is similar for incineration sites, though there is the added complexity that some studies may no longer be applicable as technologies have improved over time. More recent reviews broadly support these conclusions *(278-280)*. However, researchers have noted that despite the uncertainties in the literature, even small risks could contribute high population health burdens due to the large numbers of people potentially exposed *(276)*.

A power generator that uses captured landfill gas in China. (Credit: Yang Aijun/WorldBank)

Sewage / wastewater

Sewage (as opposed to solid waste) treatment is an important component of sanitation, which is strongly associated with the reduced risk of infectious disease, including diarrhea and helminth infections *(58, 59)*. In addition to a lack of sanitation facilities, exposure to hazards in wastewater can occur from spillages, discharges into water sources, or when inadequately treated wastewater is applied as an input in the agricultural sector.

It is also again worth mentioning that methane – released from landfills and during wastewater treatment – is an ozone precursor, and that ozone is a hazardous air pollutant *(5)*.

11

Vancouver, Canada is known among North American cities for its dense and mixed-use planning, which minimize travel distances and encourages sustainable forms of transport, such as walking and cycling. (Credit: Magnus Larsson)

Chapter 11:
SLCP mitigation actions in cities

Chapter highlights:

• The world is urbanizing in terms of population and land use.

• Cities provide an opportunity to implement multiple SLCP mitigation actions simultaneously and to benefit from potential synergies.

This chapter is an "integrating chapter" in the sense that it describes how many of the mitigation actions discussed in previous chapters can be applied to urban areas. The chapter illustrates opportunities for climate-health co-benefits provided by cities, demonstrating how implementing multiple mitigation actions in the same location can enable city planners to take advantage of economies of scale and complementarities across policies.

Cities, climate forcers and health: a brief background

More than 50% of the world's population now resides in urban areas, up from less than 30% in 1950 *(290)*. Every day the urban population grows by an estimated 200 000 people, and the expansion in terms of land cover is even faster *(291)*. Urbanization is driven to a large extent by the promise of increased income, which correlates strongly with per capita GHG emissions *(291)*. Although difficult to estimate, urban areas are thought to account for between two-thirds and three-quarters of total global energy use and a similar level of CO_2 emissions *(291)*.

In cities where resources (economic and otherwise) are limited and/or poorly applied, conditions can be overcrowded, unhygienic, and generally unhealthy. Nowhere is unplanned urban growth more evident than in the emergence of slums (informal settlements), which are home to nearly a billion people worldwide and are characterized by poor living conditions and high rates of disease and premature mortality *(292)*.

With good planning, however, it is possible to design cities where per-capita emissions are relatively low and where the environment promotes good health. In general, though important intra-city disparities remain, health status in urban populations is often better than in their rural counterparts *(293-295)*. In the USA, for example, life expectancy at birth in metropolitan areas is two years longer than in non-metropolitan areas *(296)*. In Porto Alegre, Brazil, life expectancies and environmental indicators are similar to many urban areas in high-income countries, and much better when compared to most other Brazilian cities *(293, 297)*.

To highlight mitigation actions that would be particularly advantageous in cities, the following sections draw on the discussions in previous chapters, but with an urban focus.

Transport

Cities are inherently dense, with high concentrations of people, resources, and economic activity. Compared to rural areas, commutes and distances to activities, goods, and services are generally much shorter, and people tend to live in smaller dwellings situated more closely together. There is great diversity between cities in terms of their physical layouts and configurations, factors that have a direct impact on GHG and BC emissions from transportation *(291)*. The IPCC notes that urban forms can be characterized using four interrelated metrics: density, land-use mix, connectivity and accessibility. In general, increasing the level of each will act to lower per-capita GHG emissions, but addressing the four characteristics together is vital and can have synergistic positive impacts *(291)*. Density, for example, is regularly (negatively) correlated with transportation energy use and GHG emissions (Figure 22) *(291, 298-300)*. In a comparison of California households, Brownstone and Golob (2009) reported that a lower density of 1000 housing units per square mile implies an increase of 1200 miles driven per year and 65 more gallons of fuel used per household *(298)*.

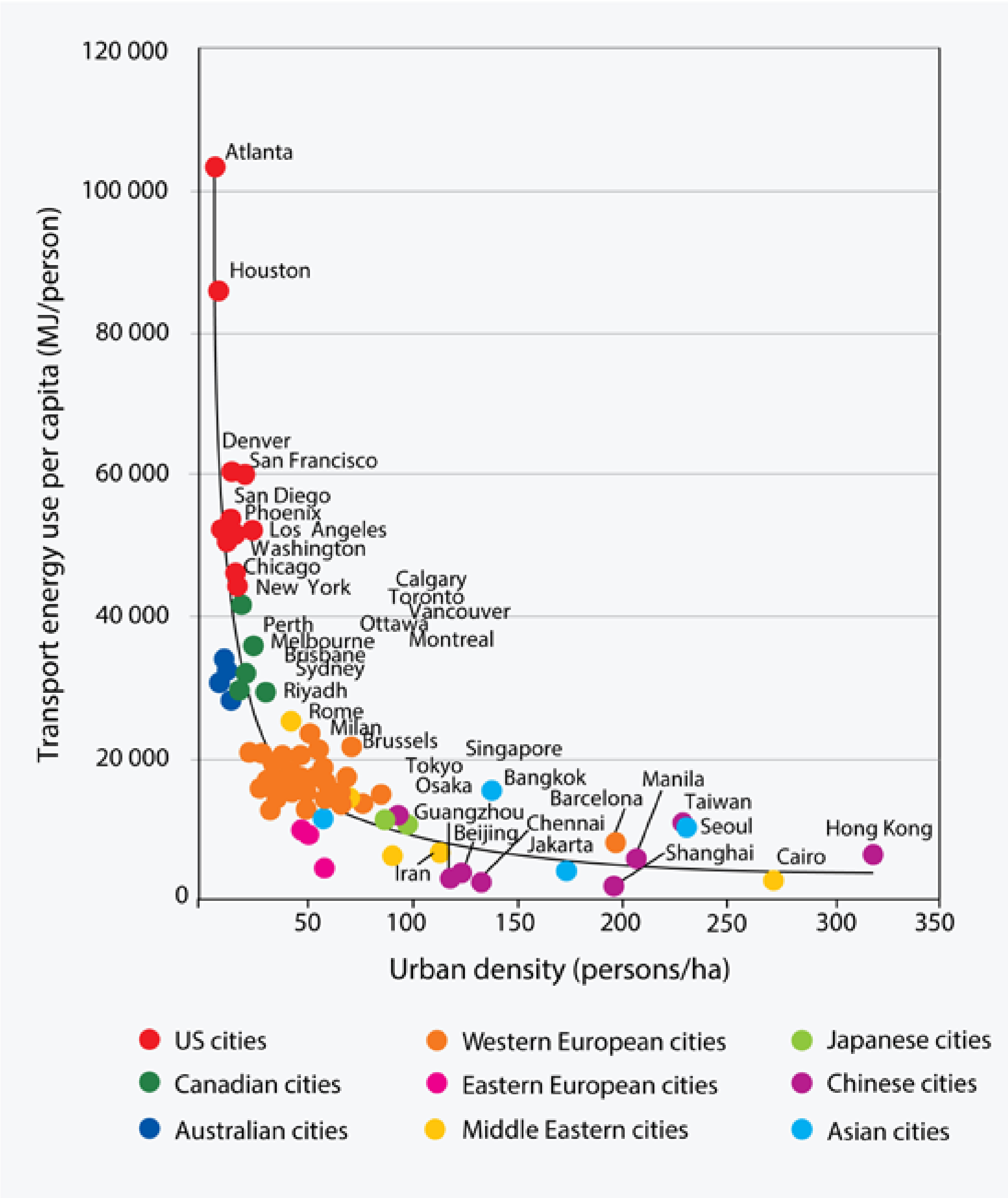


Figure 22. Urban density and transport-related energy consumption.
Source: International Association of Public Transport Providers, 2001 (301).

The importance of mass and active transport in SLCP reduction was already discussed in Chapter 6, as were the associated health benefits: improved air quality, reduced noise, fewer road traffic injuries, and an increase in physical activity. Where cities are new or expanding, it is important that safe, interconnected pedestrian and cycle routes and public transport are provided from the outset in order to prevent lock-in. However, recent initiatives such as the new high-speed bus system in Cape Town, South Africa (Case study 7), demonstrate that it is possible to provide innovative transport infrastructure, even in mature cities and neighborhoods.

Case study 7. Bus rapid transport in South Africa

A MyCiti bus in Cape Town adjacent to a well-maintained cycle path. (Credit: Transport for Cape Town)

In May 2011, a new bus rapid transit system named MyCiti launched in Cape Town, South Africa, the country's second-most-populous city. Similar to other initiatives launched throughout the country, MyCiti was implemented due to dissatisfaction with existing transport options, their inaccessibility in low-income communities, and environmental concerns *(13, 302)*.

Although still in its infancy, MyCiti's successes include: impressive growth in passenger numbers (an almost 90% increase on certain routes), improved on-time statistics that for many routes compare favorably with European systems, and continuing expansion into low-income neighborhoods *(302, 303)*. MyCiti allows bicycles on board, and the system was designed alongside a network of cycling paths and upgraded pedestrian walkways that connect to the buses *(302)*. All buses also comply with (at least) Euro 4 emission standards. The goal of MyCiti, and the city's wider Integrated Rapid Transit system, is to ultimately provide a "reliable, safe and cost-effective transport network within 500m of 75% of the homes in the city" *(304)*. This objective illustrates how transit systems can in turn stimulate active travel – simply by making it possible to walk or cycle daily to the bus or rail stop.

Buildings: residential and commercial

In addition to the mitigation actions discussed in Chapter 7, buildings in dense cities provide some distinct opportunities when compared to more rural areas. In multi-family homes and apartment buildings, building shells and walls are shared between neighbors, and have been shown to have lower residential energy use compared to single-family homes (smaller homes also use less energy) *(305, 306)*. District heating with co-generation of heat and power is a technology ideally suited for urban areas, and can result in substantial efficiency gains when compared to single-unit boilers or electricity-only power plants (see Chapter 7). When households rely on burning solid fuels to meet their energy needs, cleaner energy sources can provide large health benefits.

Tall buildings also provide shade to surrounding areas, while rooftops are available for many health-promoting uses: as substrate for photovoltaic panels, as space for home gardens, and/or as exercise areas. Green roofs can help regulate building temperatures and counteract the urban heat island effect (cities are usually hotter than the outskirts) in addition to providing an area to grow food and to relax *(307-309)*. Vegetation also absorbs carbon dioxide. Cool roofs that have high solar reflectance are a good alternative where green roofs are not feasible *(309-311)*. Interventions such as green and cool roofs (as well as green spaces, discussed below) which act to cool cities may also reduce ozone formation, which is temperature-dependent, and may lower the need for the HFCs associated with air conditioning *(239, 310, 312, 313)*.

One area where building design has special potential is in the upgrading of slums, which are partly defined by housing inadequacy (Case study 8). Slum households are often temporary structures built with unsatisfactory materials; therefore when resources become available to construct permanent housing, it is an opportunity to use environmentally optimized design techniques *(314)*.

Green space

Green spaces – parks, sports fields, etc. – are a fundamental component of any city. In addition to facilitating physical activity and relaxation (stress reduction), they can serve as refuges from noise and air pollution (315-318). They can also provide safe routes for walking and cycling, either for travel or recreation, and have been associated with neighborhood social cohesion and reductions in crime and violence (319-321). A recent cross-sectional study found that green space and tree canopy percentage was strongly inversely correlated with measures of depression, anxiety, and stress *(322)*.

Recent research has also shown that trees generally help remove particulate matter (including BC) from the air, providing a buffer between traffic pollution and residential areas; local urban design characteristics need to be considered so as to avoid accidentally increasing particle concentrations (for example, by reducing wind speeds and ventilation of street canyons) *(323-326)*. Tree planting programs (like green spaces) may also be effective in reducing the heat island effect through direct shading and evapotranspiration, and could therefore potentially reduce ozone concentrations, assuming low-VOC-emitting species are chosen *(309, 312, 327)*. In terms of energy savings, Akbari (2002) analyzed multiple US cities and estimated that for every tree strategically planted for shade, there could be a direct reduction of about 10 kg in carbon emissions from power plants through reduced demand for air conditioning *(328)*.

The Madrid Rio Park transforms a formerly neglected area in Madrid, Spain into a green space with paths for walkers and cyclists. (Credit: La-Citta-Vita)

Waste management

On average, urban residents produce more waste than those living outside of cities. Recent estimates suggest that cities generate 1.3 billion tonnes of solid waste per year, a figure expected to rise to 2.2 billion tonnes by 2025 *(277)*. Failure to adequately collect and dispose of solid waste presents numerous health risks, such as proliferation of vermin that carry disease and the poor air quality associated with open burning. A lack of access to sanitation also carries high risks of death and disease.

For the most part, reducing SLCP emissions from waste disposal involves technological solutions such as landfill gas recovery, modern incineration, and improved wastewater treatment. Therefore, action in cities will largely focus on the collection and transport of waste for processing. In resource-poor settings, sanitation programs are likely to be the most beneficial for health in this regard, and many people can be served with a single intervention. Where cities also have a particular advantage is in waste minimization. Efforts to promote recycling, reuse and composting can gather large quantities of usable material in relatively small spaces and times. Even in countries without mandatory recycling, informal recycling persists and can substantially reduce waste, though the benefits to health are questionable, as exposure to occupational hazards can be high *(282, 283)*.

An example of an intervention in this sector is the CCAC's Mitigating SLCPs from the Municipal Solid Waste Sector Initiative (see Appendix III for details), which works with cities to collect reliable data on waste and uses this data to design integrated waste management systems that reduce SLCPs, improve human health and sanitation, and create jobs. Specific activities include preventing organic/food waste, extending collection coverage, improving waste transport, source separation, extracting materials from waste, composting or digesting biodegradable waste, establishing sanitary landfills, and capturing and utilizing landfill gas. The initiative aims to reach 1000 cities by 2020 (see Appendix IV for more information).

Air quality standards

Air quality standards were presented and discussed in Chapter 1, and are an important policy tool for regulating air pollution. The World Health Organization provides guideline values for short- and long-term concentrations of both ozone and particulate matter (as well as other substances), while many countries and economic areas (e.g. the European Union) have their own standards or limits. There are no air quality standards for black carbon in particular, but researchers have recently suggested that it may be a useful indicator of primary combustion-related particles *(20)*.

Although it can be difficult to assess the effectiveness of air quality standards because many factors affect changes in emissions, improvements in air quality have often followed the adoption of standards *(329)*. However, in many countries, including high-income countries, cities often have air pollution levels above the WHO air quality guidelines. Among cities monitoring air pollution, only about 12% of urban residents worldwide enjoy air quality that meets WHO guideline levels for particulate air pollution (Figure 23).

Mitigation actions in cities: necessary ingredients

As this chapter has shown, SLCP mitigation actions in cities aim to counteract the main drivers of emissions of climate forcers through smart urban planning measures and by increasing efficiencies. Implementing mitigation actions, however, is not easy. In addition to financing, it requires good governance capability as well as technical capacity, as well as public support and engagement, all of which vary widely between cities and countries. Elaborating on these factors and how to obtain them is beyond the scope of this report and has been discussed in more detail elsewhere *(e.g. 292)*. Case study 8 demonstrates the level of success achievable given the right combination of attributes, profiling Curitiba, Brazil, as a benchmark in terms of its climate-friendly and health-promoting policy-making. Case study 9 profiles the "Healthy Cities" approach to climate mitigation and public health in Paris, focusing on the transport sector.

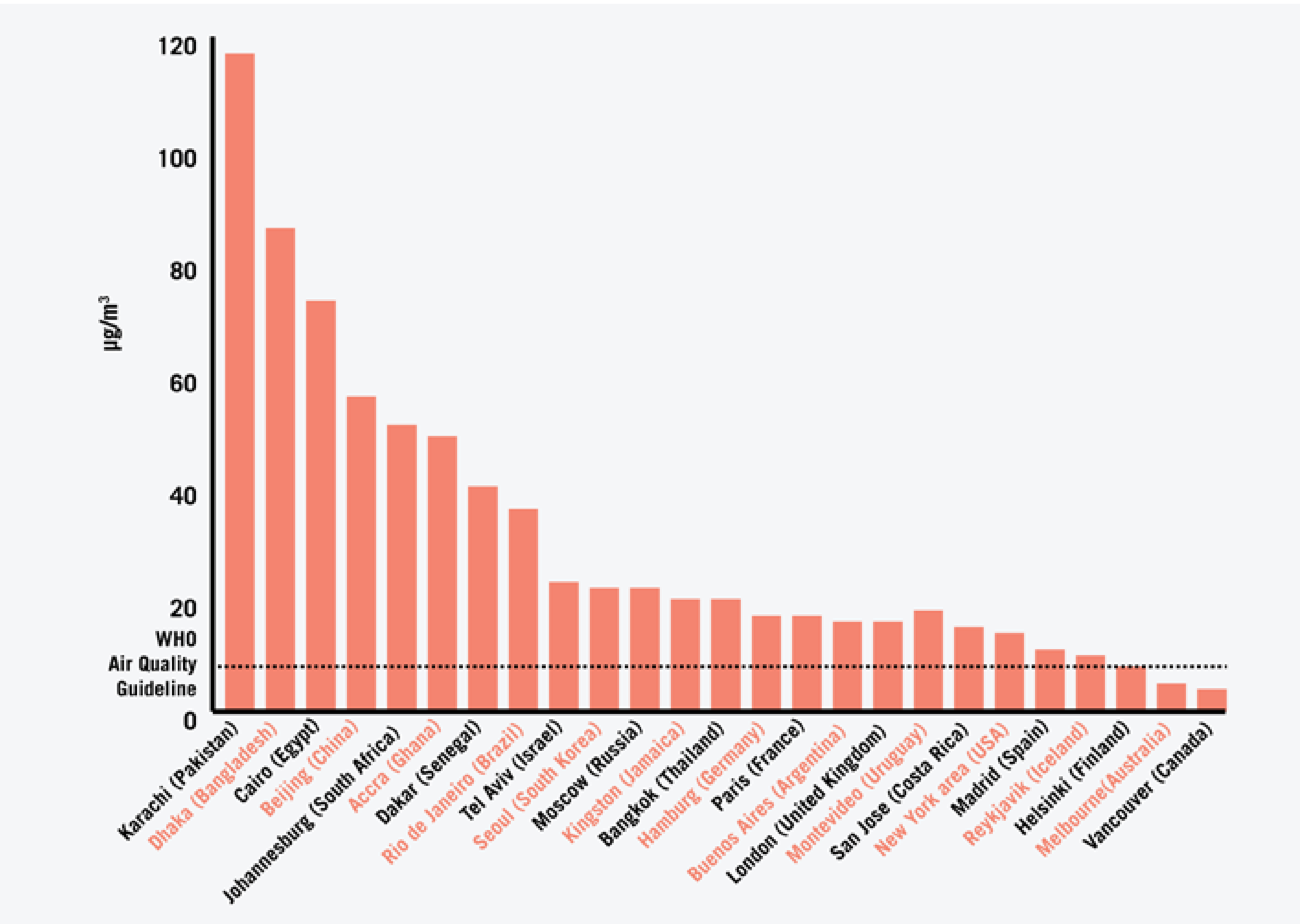


Figure 23. Annual average concentration of $PM_{2.5}$ for selected cities, 2008-2013. The black horizontal line is WHO's guideline value (10 µg/m³). Source: WHO Ambient Air Pollution database, 2014 (330).

Case study 8. Curitiba, Brazil: integrating slum rehab with urban development

Lacking at least one of the following assets constitutes the UN-HABITAT's definition of a slum: access to safe water, sanitation, secure residential status, or satisfactory housing. The environmental conditions common in slums thus contribute, directly and indirectly, to health risks among slum residents. Furthermore, as slums result from unplanned growth and are characterized by a lack of high-quality infrastructure, the upgrading of a slum is an opportunity for governments and planners to design low-emission, health promoting communities, as exemplified by Curitiba, Brazil.

Bus-rapit transit in Curitiba, Brazil. (Credit: whl.travel/Guilherme Mendes Thomaz)

The success of Curitiba's slum rehabilitation initiative is due, among other factors, to the development of a long-term master plan by 1966. Over the last 50 years, the city has seen a five-fold increase in population and become more than four times more dense, while managing to drastically expand the amount of green space per resident and create a widespread transport system that is used regularly by an estimated 72% of the population *(331, 332)*. More than 1.5 million trees have been planted; over 50% of paper, metal, glass, and plastic is recycled; and there is an extensive network of pedestrian walkways *(331)*. In terms of health, life expectancy in Curitiba (76.3 years) is two years longer than the national average, and the city also has relatively low infant mortality and fertility rates *(333)*. These achievements have occurred despite a proportion of the population living in slums, which is in part a result of ongoing in-migration spurred by the city's good reputation.

Part of Curitiba's success is the result of a development strategy that included a number of initiatives directly aimed at low-income and slum residents *(332)*, such as:

- The provision of social housing in mixed-income neighborhoods;
- A program where garbage can be exchanged for bus tickets and/or vegetables (affecting nutrition and sanitation);
- Ensuring access to public transport;
- Increasing green spaces in areas vulnerable to flooding;
- Free medical and dental care for low-income residents.


Barigui Park is one of the largest in Curitiba, Brazil. It has a number of amenities, including cycle tracks, exercise equipment and sports facilities. (Credit: hb_cwb/Flickr)

Case study 9. "Healthy cities" approach to reduce pollution and SLCPs

France has one of the highest proportions of diesel cars on the road in Europe, as well as nagging problems with urban air pollution *(123, 334, 335)*. An EU-supported study of pollution levels throughout European cities recently estimated that in Paris, 5.8 months of life expectancy, on average, could be gained if $PM_{2.5}$ levels, now averaging about 16 µg/m³ annually, were reduced to the WHO guideline levels of 10µg/m³ (see Figure 24 below). Specific health benefits would include declines in the incidence of stroke, heart disease, lung cancer, and respiratory diseases.

Rising French concerns about air pollution recently led to a major policy shift in the Paris city government that will change the way Parisians travel. The city's new anti-pollution plan, centered on a series of transport measures, represents one of the more comprehensive set of measures addressing diesel pollution emissions to be implemented by a major city.

Key elements of the Parisian plan include *(337, 338)*:

- Reducing the number of diesel vehicles on city roads, mandating diesel filters, and banning diesel cars made before 2011 by 2020.
- Certain areas, such as the Rue de Rivoli and Champs-Élysées, will be dedicated to ultra-low-emission clean vehicles. The first four arrondissements will be transformed into semi-pedestrian areas, barring all but residents' vehicles, deliveries, and emergency services.
- Cycling lanes will be doubled by 2020 and the city will fund an extended electric bike-share program.
- Other government incentives include free parking for electric and hybrid vehicles, a one-year Autolib (self-service electric car) subscription for newly licensed drivers, and a one-year Navigo pass (public transit smart card) for Parisians who get rid of their diesel vehicle.

The French plan's multifaceted strategy reflects an approach to stimulating healthier physical activity while reducing both pollution and climate emissions. This is one of the principles also being promoted by WHO in its work supporting healthy cities, urban health, and healthy urban transport.

This work seeks to address the widespread problems cities face with soaring air pollution, as well as the health impacts from unsustainable transport, energy-inefficient buildings, lack of green spaces, and other factors that create health risks in cities.

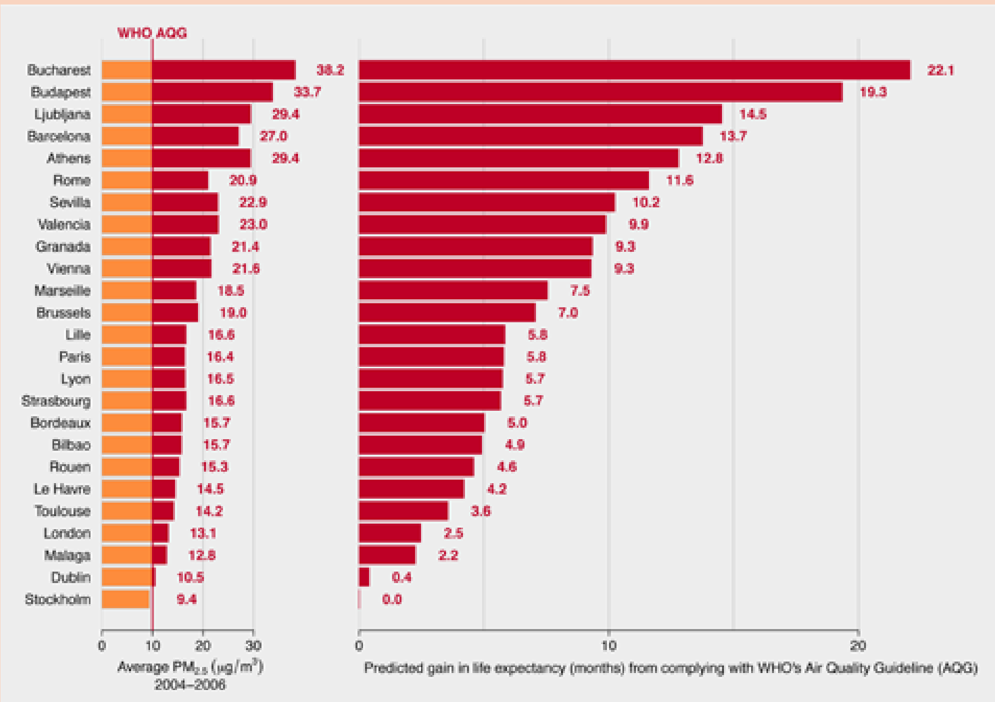


Figure 24. Expected gain in life expectancy (in months) in selected cities from a decrease in average $PM_{2.5}$ to 10 µg/m³, the WHO air quality guideline. Source: Aphekom project-InVS, 2008-2011 (336).

PART III

Urban gardens like this one in San Francisco, United States provide multiple health benefits: fresh produce, physical activity and green spaces that filter and absorb air pollutants. (Credit: Spur/Flickr)

Part III:
Conclusions and research directions

The reduction of SLCP emissions can have important near-term climate benefits while also contributing to improved population health. From a policy standpoint, the appeal of SLCP mitigation is that much of the benefit (for both climate and health) occurs near the mitigation action site and is felt relatively rapidly, which is not true of many other climate initiatives. However, it must again be stressed that long-term climate change will be largely determined by CO_2, and therefore SLCP mitigation should be viewed as a complementary strategy to CO_2-based measures, not as an alternative.

SLCPs are emitted from a variety of sources and therefore a range of mitigation opportunities exist, many of which were discussed in this document. The question then is how to identify which of the potential actions will be most effective, and to determine how to scale them up quickly enough to maximize their climate and health benefits. Table 21 allows for a qualitative comparison of some key SLCP reduction strategies in terms of their climate and health merits.

It is important to note that the evidence in the table should be viewed as preliminary, as SLCP-related associations with climate and health are emerging research areas. Nevertheless, certain mitigation actions – those that score high in terms of potential climate and health benefits – show particular promise. Examples include the promotion of healthy plant-based diets; prioritizing active (and mass) travel over private vehicle use; and programs to provide and promote the use of clean and efficient cookstoves or cleaner energy sources to households that currently rely on solid fuels. These interventions could also provide CO_2 co-benefits, another important consideration when designing any climate policy. The specific policy bundle that should be adopted will depend on local needs and conditions, and must account for additional factors such as cultural acceptability and affordability. Still, it is clear that many cost-effective policies are available that can simultaneously reduce SLCPs and improve health.

The report has also highlighted a number of priorities for further research. While all sectors would benefit from more empirical investigation, what stands out is the need for more systematic analyses aimed at identifying the health interventions that would have the greatest climate impact and vice versa. Most of the evidence is currently piecemeal, and it is therefore difficult to transparently and rigorously weigh the relative advantages of different policies. Furthermore, this report has shown that for certain mitigation actions, some of the largest improvements in population health are possible for reasons independent of reduced air pollution, but these more indirect pathways to health are sometimes the least understood.

What is clear is that facilitating policy action requires comprehensive accounting of the benefits versus costs of SLCP mitigation actions. Specifically, the co-benefits approach implicitly assumes that governments will prioritize policies fulfilling multiple objectives in parallel. This requires strong cross-sector collaboration and inclusive decision-making. Similarly, integrated development can enhance synergies. For example, cities designed to be compact and pedestrian-friendly, with complementary goods and services located in close proximity, can reduce traffic (and pollution), enable safe walking and cycling, and allow for efficient energy supply and cost-effective delivery of essential services, such as waste collection and medical care.

Finally, it is imperative that we reject the belief that many of the environmental and health challenges we face are the inevitable result of exercising personal choice. Lifestyle choices do not arise in a vacuum, and are legitimate subjects for democratic debate and government action. What we eat, how we travel, and the energy sources we use are functions of policy decisions, institutions and infrastructure, none of which are fixed.

Table 21. Potential magnitude of climate and health impacts of selected mitigation actions (see Appendix I for details)

Sector and mitigation action	Certainty of major SLCP-related climate benefit[1]	Aggregate level of potential health benefit[2]	Main health benefits (red = direct benefits of reduced air pollution; blue = indirect benefits of reduced air pollution; green = ancillary health benefits)	Potential level of CO_2 reduction co-benefit
Transport				
Support active (and rapid mass) transport	High	High	Improved air quality Less crop damage and extreme weather Increased physical activity Reduced noise Fewer road traffic injuries[3]	High
Ultra-low-sulfur diesel with diesel particle filters	Medium-high	Medium	Improved air quality Less crop damage and extreme weather	None
Higher vehicle emissions/ efficiency standards	High[4]	Medium-high	Improved air quality Less crop damage and extreme weather	High[4]
Agriculture				
Alternate wet/dry rice irrigation	Medium-high[5]	Low-medium	Less crop damage and extreme weather Reduced vector-borne disease	Low[5]
Improved manure management	Low-medium	Low-medium	Reduced zoonotic disease Improved indoor air quality	Low
Reduced open burning of agricultural fields	Medium	Low-medium	Improved air quality Less crop damage and extreme weather	Low
Promoting healthy diets low in red meat and processed meats and rich in plant-based foods[6]	High	High	Less crop damage and extreme weather Reduced obesity and diet-related non-communicable diseases	Medium-high[7]
Reducing food waste	Medium-high	Low-medium	Less crop damage and extreme weather Reduced food insecurity/undernutrition	Medium-high[7]

Table 21 (continued)

Household air pollution and building design				
Low-emission stoves and/or fuel switching to reduce solid fuel use	Medium-high	High	Improved air quality Less crop damage and extreme weather Lower violence and injury risk during fuel collection Fewer burns	Medium[7]
Improved lighting to replace kerosene lamps	Medium	Medium	Improved air quality Less crop damage and extreme weather Fewer burns Fewer poisonings	Low-medium
Passive design principles	Low-medium	Medium	Thermal regulation Improved indoor air quality	Medium
Energy supply/electricity				
Switch from fossil fuels to renewables for large-scale power production[7]	Low	High (coal/oil) Low-medium (gas)	Improved air quality Less crop damage and extreme weather Fewer occupational injuries	High (coal/oil) Medium-high (gas)
Replacement or supplementation of small-scale diesel generators with renewables	Low-medium	Low-medium	Improved air quality Less crop damage and extreme weather Reduced noise	Low-medium
Control of fugitive emissions from the fossil fuel industry	High	Low	Improved air quality Less crop damage and extreme weather	Low-medium[8]
Industry				
Improved brick kilns	Low-medium	Medium	Improved air quality Less crop damage and extreme weather	Low-medium[7]
Improved coke ovens	Low-medium	Medium	Improved air quality Less crop damage and extreme weather	Low-medium[7]
Control of fugitive emissions from the fossil fuel industry	High	Low	Improved air quality Less crop damage and extreme weather	Low-medium
Waste management				
Landfill gas recovery	Medium	Low	Improved air quality Less crop damage and extreme weather	Low-medium[9]
Improved wastewater treatment (including sanitation provision)	Medium	Medium-high	Improved air quality Less crop damage and extreme weather Reduced infectious disease risk	Low-medium[9]

See Appendix I for details.

[1] Incorporates both the potential for major emissions reductions as well as the certainty that those reductions will have the desired climate effect. For example, reducing BC emissions from BC-rich sources (e.g. diesel) will have less uncertainty than reducing BC from sources higher in co-emitted cooling agents (e.g. open burning). Near-term refers to anytime over the next few decades, though some climate benefits may occur almost immediately. [2] Assessed at the population level. [3] Assumes provision of safe infrastructure. [4] Increased efficiency may induce increased travel (a 'rebound') so should be combined with the complementary interventions (e.g. fuel taxes). [5] Note that potential climate benefit could potentially be offset by increases in nitrous oxide emissions, a long-lived greenhouse gas. [6] Avoid where there is a high risk of nutrient inadequacy. [7] Includes potential of CO_2 uptake by reforested land or use for bioenergy crops. [8] Does not include fugitive emissions, which are considered separately. [9] Includes potential displacement of fossil fuels by utilizing captured gas.

Appendix I: Explanations of ratings provided in Table 8 (and Table 21)

This material summarizes the rationale for the qualitative ratings assigned to the different mitigation actions displayed in Table 8 (and Table 21) of the main report. The explanations are provided separately for each of the three relevant columns (Columns 2, 3, and 5 of the main table). Note that the list of potential mitigation actions includes only some of the more promising actions in each sector but is not comprehensive. It also does not explicitly consider costs. The framework and ratings assessment was first published in a multi-authored peer-reviewed journal article *(34)*; however, a few additional mitigation actions were assessed solely by the author, albeit subject to expert review. In some cases, further research is needed to confidently determine the extent of potential health gains as well as the real-world effectiveness of different interventions.

Abbreviations:

BC: black carbon

CO: carbon monoxide

CO_2: carbon dioxide

IARC: International Agency for Research on Cancer

NOx: oxides of nitrogen

GHG: greenhouse gas

PM: particulate matter

SLCP: short-lived climate pollutant

Section 1. Certainty of a major SLCP-related climate benefit

For a given mitigation action to have a high certainty of producing a major SLCP-related climate benefit, it must fulfill two criteria. First, the intervention must address an activity that is a major source of SLCP emissions. And second, there must be good evidence that reductions in those emissions will have the desired impact – a cooling effect (or lack of warming). This latter criterion is primarily relevant to mitigation actions targeting black carbon, as co-emissions sometimes make the net climate impact uncertain *(23)*. Table A1 summarizes the evidence on each of the two issues separately. Methane is the only ozone precursor directly targeted, because as a strong GHG itself, it provides the best opportunity for climate change mitigation. However, in Table A2, which details the potential SLCP-related climate benefits of each mitigation action, we also note whether other ozone precursors are likely to be meaningfully affected.

Table A1. Description of different emission sources in terms of the (global) magnitude of the source and whether or not it provides a favorable mitigation opportunity.

SLCP	Emission source	Major source of SLCP emissions	Likelihood of SLCP-related net cooling effect[1]
Black carbon	Diesel engines	Diesel engines are the second-biggest source of BC emissions from energy-related combustion, and contributed about 20% of total global BC emissions in 2000 *(23)*. Both on-road and off-road engines are important sources, but particularly the former.	Diesel emissions are rich in BC and their reduction has been identified as a particularly good mitigation opportunity *(9, 23)*.
Black carbon	Gasoline vehicles	Gasoline vehicles produce BC but contribute much less than diesel vehicles to total emissions due to lower emission rates per vehicle *(23)*.	As with diesel engines, emissions from gasoline engines are rich in BC and are likely to present a good mitigation opportunity *(23)*.
Black carbon	Agriculture	Open biomass burning comprises a large proportion of global emissions (~40%) *(333)*. The open burning of agricultural fields makes up a relatively small, albeit non-trivial component *(333)*. Emissions from engines in farm machinery is another contributor	The heterogeneous composition of what is burnt, combined with cooling co-emissions, makes the climate effects of open burning uncertain, though recent studies indicate that it may be a better mitigation opportunity than previously thought *(77, 78, 333)*. Emissions from diesel engines are a good mitigation opportunity (see above).

Table A1 (continued)

Black carbon	Household solid fuel use	Household solid fuel use (for cooking and heating) is the leading source of energy-related black carbon emissions and contributed about 25% of total global BC emissions in 2000 *(23)*.	Solid fuel use has been identified as one of the better black carbon mitigation opportunities, but some uncertainty persists *(23)*. Cooking interventions may be more favorable than heating interventions, but heterogeneous technologies and fuels make generalizations difficult *(23)*.
Black carbon	Brick kilns and coke ovens	Small industry makes up a small but non-negligible source of global BC emissions, comprising about 9% of global emissions *(23)*. Brick kilns and coke ovens are two of the more important components. In some specific locations, emissions are a major source of BC. In general, there is a lack of data on the two industries.	Emissions from traditional brick kilns and coke ovens are rich in BC and it seems likely that their reduction would have a net climate benefit, although uncertainty persists, in part because of data constraints *(23)*.
Black carbon	Kerosene lamps	Though not as big a source as diesel or industrial coal, recent research has demonstrated that kerosene lamps are a much more important source than previously thought (233, 234). Around 270 000 tons are estimated to be emitted annually worldwide *(233)*.	Unlike almost all other BC sources, particle emissions from kerosene lamps are almost entirely black carbon, making them an excellent target for mitigation (23, 233, 234).
Black carbon	Power plants	Power plants comprise a small fraction of total BC emissions *(23)*.	Emissions from power plants are not rich in BC *(23)*.
Methane	Agriculture	Agriculture is one of the three main anthropogenic sources of methane globally, and the livestock sector is the primary contributor *(40, 165, 192)*. Important sources include enteric fermentation of livestock, rice cultivation and, to a lesser extent, manure management. Demand for livestock products is projected to increase in the future, as are diet-related methane emissions if dietary trends continue *(192, 215)*.	There is unambiguous evidence that methane produces a strong warming effect and that reducing methane emissions will have a beneficial climate impact *(61, 339)*.
Methane	Fossil fuel extraction and distribution	One of the three main anthropogenic sources of methane globally *(40)*. Emissions from waste disposal in landfills – currently responsible for ~50 Mt of methane annually – are expected to increase over the next decade *(281)*. Wastewater accounts for about 40% of GHG emissions in the waste sector (a large proportion from methane) and total GHG emissions from wastewater have approximately doubled in the last 30 years *(281)*.	
Methane	Waste	One of the three main anthropogenic sources of methane globally *(40)*. Emissions from waste disposal in landfills – currently responsible for ~50 Mt of methane annually – are expected to increase over the next decade *(281)*. Wastewater accounts for about 40% of GHG emissions in the waste sector (a large proportion from methane) and total GHG emissions from wastewater have approximately doubled in the last 30 years *(281)*.	
Methane	Household solid fuel use	Though not as big a source as the three listed above, biomass burning including biofuels is a key contributor to global methane emissions *(40)*.	

[1] When emissions of black carbon occur near snow and ice-covered regions, they are more likely to produce warming (or to produce more warming)

Note: There are other sources of both black carbon and methane, but these are not listed because they are not the target of any of the mitigation actions.

Table A2. Detail about the SLCP-related climate benefit of specific mitigation actions

Mitigation action	Main emission source targeted	Comment	Magnitude of potential benefit
Promoting healthy plant-based diets	Methane from agriculture	Many studies have found that animal-sourced foods have relatively high levels of embodied emissions *(12, 165, 185-187, 191)*. Similarly, modeling studies have demonstrated the potential for GHG savings from eating fewer animal products, though the level of impact will depend on which alternatives are selected *(11, 12, 186, 212, 213, 215)*. A recent study reported much lower diet-related emissions in individuals that eat little or no meat compared to those with higher meat intake *(340)*.	Medium-high
Alternate wet/dry rice irrigation	Methane from agriculture	Studies of alternate wetting and drying have demonstrated methane reductions of 40% or more compared to continuous flooding (167, 168).	Medium-high
Improved manure management	Methane from agriculture	The IPCC notes that the climate mitigation potential from manure management is modest, as a small proportion of the methane emitted in the livestock sector is from this source and because most manure excretion occurs in the field where it is difficult to manage *(165, 177)*.	Low-medium
Reduced open burning of agricultural fields	Black carbon from agriculture	As noted above, the heterogeneous composition of what is burnt, combined with cooling co-emissions, makes the climate effects uncertain, though recent studies indicate that it may be a better mitigation opportunity than previously thought *(77, 78, 333)*.	Medium
Reducing food waste	Methane from agriculture and landfills	Up to 40% of food may be wasted in some countries *(208, 209)* and food waste comprises a large fraction of waste that goes to landfills *(277, 281)*. The level of emissions reductions from reducing food waste will depend not only on the quantity of waste, but also on the type of food wasted, which varies and is not well known in many places. Few studies have quantified embodied emissions in food waste or emissions changes resulting from associated reductions in food demand, but the available evidence indicates that savings could be large *(165, 190, 208, 209)*.	Medium-high
Support active (and mass) transport	Black carbon from diesel and gasoline vehicles, ozone precursors	Modeling studies of SLCP-related interventions in the transport sector (e.g. emission standards) have reported the potential for important climate benefits, though these have generally not looked specifically at active/mass travel *(9, 131)*. Nevertheless, as black carbon emissions from vehicles appear to produce net warming,*(23)* avoiding journeys should have a beneficial climate impact. Transport is also a major source of ozone precursors, particularly NOx and CO *(5, 9)*.	High
Diesel particle filters	Black carbon from diesel vehicles	More work is needed to assess the in vivo impacts of diesel particle filters, but evidence indicates potentially large reductions in PM overall and BC in particular *(117-119, 341)*. This was one of a group of interventions included in a large modeling study that, in aggregate, showed important potential SLCP-related climate benefits *(9)*.	Medium
Higher vehicle emissions/ efficiency standards	Black carbon from diesel and gasoline vehicles, ozone precursors	A large modeling study of tighter vehicle emission standards that included impacts from both black carbon and ozone precursors showed potential for substantial SLCP-related climate benefits *(131)*. For efficiency improvements specifically, some potential benefits may be offset by the “rebound effect” whereby low travel costs induces people to travel more, though the size of the effect varies and can be minimized with complementary interventions such as fuel taxes *(342-344)*.	High
Improved cookstoves/ fuel switching to reduce solid fuel use	Black carbon from solid fuels (mainly), methane	Although the intervention is likely to have benefits through black carbon alone, if methane and/or CO also are reduced, the likelihood of a net climate benefit increases *(23)*. The level of impact will depend on the original fuel used as well as the substitute fuel if fuel switching is considered, as different fuels produce different emission profiles. Successful implementation of some cookstove initiatives has proven challenging for socioeconomic reasons *(230, 345)*. Solid fuel interventions were included in a large modeling study that showed important potential SLCP-related climate benefits *(9)*. The beneficial climate impact of interventions in some areas (e.g. South Asia) may be greater and more certain due to proximity to elevated/glaciated regions *(9)*.	Medium-high
Improved lighting to replace kerosene lamps	Black carbon from kerosene lamps	Different lamp types have different emission factors, but because emissions are almost entirely black carbon, climate benefits are almost certain *(23, 233, 234)*. There are already many affordable alternatives on the market *(233)*.	Medium

Table A2 (continued)

Passive design principles	Black carbon and ozone precursors from fuel combustion	Impacts will depend on the fuel source that was (would be) required to compensate for less-efficient designs (e.g. for heating/cooling/ventilation). If design features reduce the use of diesel or solid fuels, net climate impacts from black carbon mitigation could occur *(23)*. The reduction in use of various fuel types (e.g. fossil fuels) can lower emissions of ozone precursors, while reduced demand from some other sources (e.g. wind or solar) would have a negligible impact.	Low-medium
Switch from fossil fuels to renewables	Black carbon, ozone precursors from fossil fuel combustion	Climate benefits from black carbon are unlikely. Some beneficial impacts may occur through reductions in ozone precursors *(5, 346)*. In theory, there could also be some benefits through reductions in fugitive methane emissions, but this is considered separately (see next row).	Low
Replacement or supplementation of diesel generators with renewables	Black carbon	Although not currently one of the larger source of black carbon emissions, stand-alone generators are growing in importance, particularly in countries where recent economic growth and demand for electricity have not been matched by power supply (e.g. Nigeria, India, Nepal, etc.) *(265)*	Low-medium
Control of fugitive emissions from the fossil fuel industry	Methane from fugitive emissions	Despite data uncertainties with regard to the extent of fugitive methane emission, this has been identified as an important mitigation opportunity in the energy supply sector because leakage is likely to be high enough to have a meaningful adverse climate impact *(9, 57)*. Modeling studies have shown that the climate implications of the natural gas industry are strongly dependent on assumed leakage rates, and that assuming high (but not necessarily unrealistic) rates could make gas as or more problematic than coal or oil *(347, 348)*. This intervention was the largest contributor to methane emissions controls in a large modeling study that showed the potential for important climate benefits *(9)*.	High
Improved brick kilns	Black carbon from fuel combustion	This was one of a group of interventions included in a large modeling study that, in aggregate, showed important potential SLCP-related climate benefits *(9)*. As there is a concentration of traditional brick kilns in South Asia, climate benefits may be greater and more certain than they would be otherwise due to proximity to the Himalayas *(9)*.	Low-medium
Improved coke ovens	Black carbon from fuel combustion	Similar to the above, this was one of a group of interventions included in a large modeling study that, in aggregate, showed important potential SLCP-related climate benefits *(9)*. Coke ovens in proximity to elevated/glaciated regions (e.g. the Himalayas) are more likely to produce climate benefits, which is relevant due to their high concentration in south and east Asia *(9)*.	Low-medium
Landfill gas recovery	Methane from landfills	This was one of a group of interventions included in a large modeling study that, in aggregate, showed important potential SLCP-related climate benefits *(9)*.	Medium
Improved wastewater treatment (including sanitation)	Methane from wastewater	As above, this was one of a group of interventions included in a large modeling study that, in aggregate, showed important potential SLCP-related climate benefits *(9)*.	Medium

Note: The proposed ratings should be interpreted in conjunction with the information in Table A1.

Section 2. The aggregate level of potential health benefit

For a given mitigation action to have a high likelihood of producing a major health benefit, it must reduce population exposure to risk factors that are associated with substantial disease burdens. Recent estimates of disease burdens from the targeted exposures are reported below (Table A3). Details of these estimates can be found in the source references, but a prerequisite for the risk factor to be assessed is that there was convincing evidence for a robust association with ill-health, which normally entailed at least one systematic review and/or analysis of a very large epidemiological study. In addition to considering (a) the burden of disease (Table A3), the proposed ratings also consider (b) the relevant pathways to health and (c) the strength of evidence for health impact (Table A4).

Table A3. Annual mortality burden from the targeted exposures.
Note that most exposures also lead to substantial morbidity (8,31, 349).

Risk factor	Mortality burden[a]	Year estimated	Reference
Household particulate air pollution	4.3 million	2012	*(7)*
Ambient particulate air pollution	3.7 million	2012	*(6)*
Ambient ozone air pollution	152 000 (52-267)	2010	*(8)*
Diets low in fruits	4.9 million (3.8-5.9)	2010	*(8)*
Diets low in nuts and seeds	2.5 million (1.6-3.2)	2010	*(8)*
Diets low in vegetables	1.8 million (1.2-2.4)	2010	*(8)*
Diets low in whole grains	1.7 million (1.3-2.1)	2010	*(8)*
Diets high in processed meat	841 000 (189-1500)	2010	*(8)*
Diets high in red meat	38 000 (11-66)	2010	*(8)*
Undernutrition (in aggregate)[b]	3.1 million	2011	*(31)*
Low physical activity	3.2 million (2.7-3.7)	2010	*(8)*
Malaria	1.2 million (0.9-1.5)	2010	*(350)*
Japanese encephalitis	13 600 – 20 400	2006-2009	*(351)*
Road traffic injuries	1.3 million (1.1-1.7)	2010	*(350)*
Occupational injuries	481 000 (364-640)	2010	*(8)*
Burns	265 000	2012	*(352a)*
Poisonings	180 000 (130-240)	2010	*(350)*
Inadequate sanitation	244 000 (6-478)	2010	*(8)*
Mold	No global assessment	-	-
Noise	No global assessment	-	-
Temperature-related mortality	No global assessment	-	-

[a] Per year, rounded. Uncertainty intervals are provided in parentheses where reported. [b] Includes fetal growth restriction, stunting, wasting, and deficiencies of vitamin A and zinc along with suboptimum breastfeeding.

Note that where pathways to health overlap, attributable burdens from individual risk factors cannot be summed; the joint effects are often much lower than the crude sum of individual effects.

Table A4. Detail on pathways to health and strength of evidence for health impact.

Mitigation action	Main risk factor targeted	Comment on pathways to health and strength of evidence	Decision (potential benefit)
Promoting healthy plant-based diets	Dietary risk factors	Red and processed meats are associated with certain cancers and diabetes *(8, 204, 352, 353)*. Diets high in fruits, vegetables and nuts and seeds are protective against certain cancers *(8, 204)*. Some of those diets are also protective against obesity, diabetes, heart disease and/or stroke *(8, 204)*. A recent review concluded that diets comprised predominantly of plants were healthiest *(43)*. Modeling studies of the impacts of lowering red meat intake (and substituting with other foods) generally report the potential for substantial health benefits *(216, 354)*.	High

Table A4 (continued)			
Alternate wet/dry rice irrigation	Vector-borne disease	Alternate wetting and drying has been shown to reduce vectors for diseases including malaria and Japanese encephalitis *(41, 42)*, though others have suggested that vectors could increase *(169)*. There is little empirical research tying it directly to reduced disease incidence in humans. Rice cultivating regions are generally not the same as the areas with the greatest malaria burdens. Evidence is mixed about the effects of alternate wetting and drying on yields and food security *(173, 174)*.	Low-medium
Improved manure management	Household particulate air pollution, infectious disease	Potential health benefits may be important if captured biogas replaces the household use of solid fuels, as air pollution exposures to PM in people using solid fuels are extremely high *(44)*. Composting can help kill pathogens, and proper handling of manure can help limit human exposure to both pathogens and toxic substances. If improved sanitation (e.g. latrines) accompanies improved manure management, potential health benefits are well-known *(58, 59)*.	Low-medium
Reduced open burning of agricultural fields	Outdoor particulate air pollution	Particulate air pollution is a well-known risk factor for disease and combustion-related particles may be more harmful than other types of particles *(1, 3, 20-22)*. Epidemiological studies have linked the burning of agricultural fields specifically with adverse cardiovascular and respiratory outcomes *(179, 180, 183, 184, 355, 356)*. An assessment of the health impacts of landscape fire smoke estimated an annual mortality burden of 339,000 deaths globally, although agricultural waste burning comprises a small proportion of total emissions from landscape fires *(357, 358)*.	Low-medium
Reducing food waste	Undernutrition	Systematic reviews and meta-analyses report that child undernutrition is associated with significantly elevated risks of death overall and from certain infectious diseases in particular *(359, 360)*. In addition to the mortality burdens, child undernutrition can lead to life-long disabilities, including cognitive impairment *(361)*. However, lack of food is only one cause of undernutrition *(32, 91)*. There has been little research explicitly quantifying how reducing food waste may improve food security and nutrition, though researchers have suggested this *(190)*.	Low-medium
Support active (and mass) transport	Physical inactivity, outdoor air pollution (ozone and particulate), road traffic injuries, noise	It is well established that physical activity helps prevent a range of chronic diseases and likely improves mental health *(362-364)*. Epidemiological studies have reported that cycle commuters have significantly reduced risks of premature death, and interventions to encourage active travel are known to be effective *(153-155)*. Using mass transport also appears to increase physical activity *(150)*. Combustion-related particles may be more harmful than other types of particles, and a recent study also suggests that transport-derived particles may be responsible for a large proportion of PM-related ill health *(3, 20-22, 115)*. Vehicles are also one of the main sources of (non-methane) ozone precursors *(5, 346)*. To reduce road traffic injuries from active travel, safe infrastructure must be provided, otherwise increases are possible *(38, 157)*. Environmental noise has been linked to hypertension, annoyance, and reductions in some measures of cognition *(365, 366)*. Modeling studies of the health impacts of active travel have reported net positive impacts overall *(38, 158, 367)*.	High
Diesel particle filters	Outdoor particulate air pollution	Combustion-related particles may be more harmful than other types of particles, and a recent study also suggests that transport-derived particles may be responsible for a large proportion of PM-related ill health *(3, 20-22, 115)*. Vehicles are also one of the main sources of (non-methane) ozone precursors *(5, 346)*. A large modeling study recently demonstrated substantial benefits to air quality and associated population health from tightening vehicle emission standards, with estimated future annual benefits of US$0.6-2.4 trillion in avoided health damage *(131)*. Improvements in efficiency need to be coupled with complementary policies (e.g. fuel taxes) to minimize rebound effects.	Medium-high
Improved cookstoves/ fuel switching to reduce solid fuel use	Household particulate air pollution (mainly), ambient particulate air pollution	Exposures to PM in people using solid fuels are extremely high, and there is some evidence that combustion-related particles may be more harmful than other types of particles *(3, 20-22, 44)*. Many technologies exist to reduce household air pollution, and modeling studies have demonstrated the associated potential for major health benefits, although ensuring their appropriate and persistent use can be challenging *(9, 46, 221, 229, 230, 345)*. Other benefits may include reduced exposure to violence during fuel collection and less fatigue *(14)*. In addition to household air pollution, 12% of outdoor combustion-derived $PM_{2.5}$ is attributable to cooking with solid fuels *(44)*.	High

Table A4 (continued)			
Improved lighting to replace kerosene lamps	Particulate air pollution	Although more research is still needed to differentiate the relative toxicity of particle types, meta-analyses have associated black carbon – the main particle emission from kerosene lamps – with mortality and morbidity *(3, 20)*. A recent review noted that studies have linked kerosene lamps with impaired lung function and increased risks of asthma, cancer, eye problems, and infectious disease.*(235)* However, due to the limited number of studies and variations in quality, the authors did not consider the evidence to be robust. Kerosene is also highly flammable and millions of people suffer severe burns from lamps each year *(233)*. It is also one of the most comment agents involved in childhood poisonings in low- and middle-income countries *(48)*.	Medium
Passive design principles	Indoor and outdoor air quality (particulate, ozone, mold), thermal regulation	Passive design principles such as natural ventilation and passive heating and lighting have demonstrated ability to improve air quality and thermal comfort while using less energy *(51, 239, 243, 368)*. High and low ambient temperature is an established risk factor for a range of diseases *(54, 102-104)*. Health benefits could be particularly high where solid fuels are used for cooking or heating (see row above). Research specifically quantifying health benefits of passive design principles is lacking, but where general housing interventions have been studied, there are many potential health benefits *(221, 240, 368)*. A few modeling studies have reported the potential for health benefits through passive temperature control and/or improved air quality *(51, 369)*.	Medium
Switch from fossil fuels to renewables	Outdoor air pollution (ozone and particulate)	Both coal and oil generally have much higher PM emissions per kWh than renewables, and in many places power plants are a dominant source of PM *(258, 370, 371)*. There is some evidence that combustion-related particles may be more harmful than other types of particles, and evidence from modeling studies has demonstrated that health benefits could be achieved by reducing pollutant emissions from power plants *(3, 20-22, 370, 371)*. Natural gas-fueled power plants have low PM emissions, but there are a variety of additional questions regarding unconventional mining processes, such as potential exposure to the chemicals found in fracturing fluid *(258-260)*. Power plants are an important source of NOx – an ozone precursor – and their emissions increase ozone concentrations in some locations *(5)*. There are high injury rates in the fossil fuel industry, and coal miners in particular are also at risk of pneumoconiosis *(371)*.	High (coal/oil) Low-medium (gas)
Replacement or supplementation of diesel generators with renewables	Outdoor air quality, noise	Combustion-related particles may be more harmful than other types of particles *(3, 20-22)* and diesel exhaust is listed as a Group 1 carcinogen by IARC *(35)*. Modeling studies have shown the potential for large reductions in particulate matter emissions given replacement or supplementation of diesel generators with renewables *(268-270, 372)*. However, few studies have explored the direct impacts of diesel generators on health. Environmental noise has been linked to hypertension, annoyance, and reductions in some measures of cognition (365, 366).	Low-medium
Control of fugitive emissions from the fossil fuel industry	Outdoor ozone air pollution	Methane is an ozone precursor, but its reduction is not necessarily the best way to prevent ozone-related ill-health. Controlling fugitive methane emissions was included in a large modeling study of the impacts of SLCP mitigation actions, but compared to interventions focusing on black carbon, the methane-focused interventions produced only small air quality-related health benefits *(9)*.	Low
Improved brick kilns	Outdoor particulate air pollution	Though not one of the major sources of PM globally, traditional brick kilns have a large adverse impact on air quality and health in some locations (e.g. Dhaka) (9, 249). There is some evidence that combustion-related particles may be more harmful than other types of particles *(3, 20-22)*. The intervention was one of a group of measures included in a large modeling study of SLCP mitigation actions that, in aggregate, showed the potential to avoid 2.4 (0.7-4.6) million deaths annually by 2030 *(9)*.	Medium
Improved coke ovens	Outdoor particulate air pollution	The information in the row above also holds for coke ovens. In addition, coke production is listed as a Group 1 carcinogen by IARC *(35)*.	Medium
Landfill gas recovery	Outdoor ozone air pollution	Methane is an ozone precursor, but its reduction is not necessarily the best way to prevent ozone-related ill-health. Landfill gas recovery was included in a large modeling study of the impacts of SLCP mitigation actions, but compared to interventions focusing on black carbon, the methane-focused interventions produced only small air quality-related health benefits *(9)*.	Low

Table A4 (continued)			
Improved wastewater treatment (including sanitation)	Inadequate sanitation, outdoor ozone air pollution	The health benefits of adequate sanitation are well established, with systematic reviews finding strongly beneficial effects on a range of diseases including diarrhea and helminth infections *(58, 59)*. Reducing methane is not necessarily the best way to prevent ozone-related ill-health. The action was included in a large modeling study of the impacts of SLCP mitigation actions, but compared to interventions focusing on black carbon, the methane-focused interventions produced only small air quality-related health benefits *(9)*. Impacts from sanitation, however, were not quantified.	Medium-high
The proposed ratings should be interpreted in conjunction with the information presented in Table A3.			

Section 3. Potential for CO_2 co-reductions

Reducing CO_2 is required to prevent climate change over the long term. The magnitude of emissions reductions will correspond closely to the amount of future climate benefit that is estimated in Table A5 for the different mitigation actions.

Table A5. Level of CO_2 co-reductions that would be expected from SLCP mitigation actions under discussion

Sector and mitigation action	Potential CO_2 impact	Decision (potential benefit)
Promoting healthy plant-based diets	Changes in land-use can be either a source of CO_2, for example when a forest is converted to cropland, or a sink if it is allowed to reforest or is used for other CO_2 mitigation activities, such as the cultivation of bioenergy crops *(165, 190)*. The livestock sector is the largest anthropogenic user of land, and land used for grazing generally sequesters far less CO_2 than forests and other natural ecosystems *(140, 192)*. Producing the same amount of food energy from animal products also generally requires (much) more land when compared to other foods *(373)*. As a result, the sequestration of CO_2 in soils and biomass has been identified as a key CO_2 mitigation strategy, including through the use of land made available by changes in diet *(165)*. Modeling has shown that substantial CO_2 mitigation is possible from dietary changes given assumptions about how the newly spare land is used (165, 190).	Medium-high
Alternate wet/dry rice irrigation	Direct impacts on CO_2 are unlikely.	Low
Improved manure management	Manure application onto agricultural fields could reduce the fossil fuel use associated with the manufacture and distribution of inorganic fertilizers *(176)*. To the extent that biogas is captured and burned in place of fossil fuels, there could also be a CO_2 benefit. Large direct impacts are unlikely. (Note however that manure management can affect N2O (a long-lived GHG) production in a variety of ways) *(176)*.	Low
Reduced open burning of agricultural fields	If vegetation is allowed to regrow, burning is unlikely to have a strong influence on CO_2 fluxes and therefore reduced burning will not have a meaningful impact overall.	Low
Reducing food waste	As noted above, changes in land use can be either a source or sink of CO_2. The use of available agricultural land – the largest anthropogenic land-use – resulting from reductions in food waste has been identified as a key CO_2 mitigation strategy *(165)*. Modeling has shown that substantial CO_2 mitigation is theoretically possible through reducing waste, given assumptions about how the newly spare land is used (165, 190). There is also some fossil fuel use in agriculture, for example by farm machinery, which could be reduced if less food needs to be produced. A study from the USA estimated that food waste accounts for ~300 million barrels of oil per year (~4% of total consumption) *(209)*.	Medium-high
Support active (and mass) transport	The transport sector (land transport in particular) is one of the main contributors to global CO_2 emissions, responsible for approximately 23% of total energy-related CO_2 emissions in 2010 *(114)*. Direct CO_2 emissions from transport in 2050 are projected to be 40-80% higher than in 2010 in baseline modeling scenarios, and it could be the fastest growing energy end-use sector during that time period (in terms of CO_2 emissions) *(114, 339)*. Avoided journeys and modal shifts have been identified as key mitigation strategies in the sector *(114)*. Modeling studies have reported reductions in CO_2 emissions from these strategies, though for mass transport the magnitude of effect will depend on the efficiency of the public transport system *(16, 38, 374)*.	High

Table A5 (continued)		
Diesel particle filters	Diesel particle filters do not cause CO_2 co-reductions, and there is some evidence they may increase their emissions through slight reductions in efficiency (a "fuel penalty"), though any increase would likely be small *(341, 375)*.	None
Higher vehicle emission/ efficiency standards	The transport sector is one of the main contributors to global CO_2 emissions and is projected to increase (see "support active and mass transport" above). Improved vehicle and engine technologies have been identified as key mitigation strategies in the sector *(114)*. Modeling studies have found that improvements in vehicle efficiency and tighter standards can be effective in reducing CO_2 emissions *(374, 376)*. Improvements in efficiency in particular need to be coupled with complementary policies (e.g. fuel taxes) to minimize rebound effects.	High
Improved cookstoves/ fuel switching to reduce solid fuel use	The impact will depend somewhat on the type of fuel used. There is debate about the extent that fuelwood collection contributes to deforestation, *(377)* but deforestation leads to emissions of CO_2 while reforestation/afforestation can act to sequester it *(165)*. The amount of sequestration will depend on how the previously exploited land is used *(165, 190)*. Household coal use releases CO_2.	Medium
Improved lighting to replace kerosene lamps	Kerosene lamps emit CO_2, but are not a major global source. Studies comparing different lamp types note that CO_2 emissions from kerosene are generally higher per lumen than alternatives *(236, 237)*.	Low-medium
Passive building design principles	Buildings currently account for about 19% of global GHG emissions, with CO_2 a main contributor *(239)*. Under baseline scenarios, CO_2 emissions from buildings are projected to be about 50-95% higher in 2050 than they are currently *(239, 339)*. Many proven and cost-effective interventions exist in the sector, including passive design *(239)*. A difficulty is that the sector often faces significant "lock-in" due to the longevity of existing building stock. Studies have demonstrated substantial capacity to reduce energy demand and CO_2 emissions through the use of passive design *(378, 379)*. The magnitude of impact will depend on the type of fuel that supplies energy to the buildings.	Medium
Switch from fossil fuels to renewables	Energy supply is the largest GHG-emitting sector, and CO_2 is the predominant emission *(57)*. Emissions have been increasing rapidly over the past decade, and further growth is expected to continue under baseline scenarios *(57)*. Electricity generation from fossil fuels (and coal and oil in particular) emits far more GHGs per kWh than renewable alternatives *(258)*	High
Replacement or supplementation of diesel generators with renewables	Although not a dominant source globally, diesel generators produce levels of CO_2 emissions that are often higher per kWh than a power grid system *(380)*. Modeling studies have shown the potential for large reductions in CO_2 emissions given replacement or supplementation of diesel generators with renewables *(268-270, 372)*.	Low-medium
Control of fugitive emissions from the fossil fuel industry	This intervention specifically focuses on capturing methane, so direct impacts on CO_2 will be minimal. Some indirect CO_2 savings could occur if captured gas is used as a substitute for fossil fuels. The amount of CO_2 avoided will depend on the quantity of gas captured and also the fuel source that the gas substitutes for.	Low-medium
Improved brick kilns	Industry is a major emitter of CO_2, but brick kilns comprise a small proportion of the sector as a whole. When traditional brick kilns are improved or replaced, the amount of CO_2 avoided will depend in part on the fuel source used in the kiln. If it is wood, sequestration could occur if previously exploited land is allowed to reforest or is used for other CO_2 mitigation strategies, such as the cultivation of bioenergy crops *(165, 190)*. Coal is also widely used and therefore a contributor to CO_2 emissions *(246)*. However, there are substantial knowledge gaps about the brick kiln industry, in part because much of it is informal and unregulated *(9, 23, 245)*.	Low-medium
Improved coke ovens	The above description of the brick kiln intervention also holds here.	Low-medium
Landfill gas recovery	CO_2 is not a major emission in the waste sector, but some CO_2 savings could occur if captured gas is used as a substitute for fossil fuels. The amount of CO_2 avoided will depend on the quantity of gas captured and also the fuel source that the landfill gas substitutes for.	Low-medium
Improved wastewater treatment (including sanitation provision)	Description of the landfill intervention in the row above also holds here.	Low-medium

Appendix II: Literature review

To help inform the sector-by-sector analysis of mitigation actions capable of reducing SLCP emissions while also improving public health, a brief review of the recent peer-reviewed literature was conducted. Specifically, using the Ovid platform, the Medline and Global Health databases were searched with the multi-purpose keyword terms climat$ AND health ($ is a truncator). Results were limited to those studies with human subjects and written in English, by date to 2011-present, and to journal articles. The search was conducted on 24 June 2014. Figure A.1 illustrates the search strategy.

The titles (and abstracts if necessary) of all of 2902 results were searched for relevance – defined as a study presenting results of a quantitative health analysis of a climate mitigation action – and relevant articles were read for content. However, as the point of this review was to inform the discussion, rather than to present a comprehensive literature review, not every relevant article is cited in the main text.

The literature search described above was conducted in conjunction with a review of selected national and international agency documents, with a particular emphasis on WHO documentation and the IPCC AR5 reports. Additional support literature known by the author but not identified in these searches was also included where appropriate.

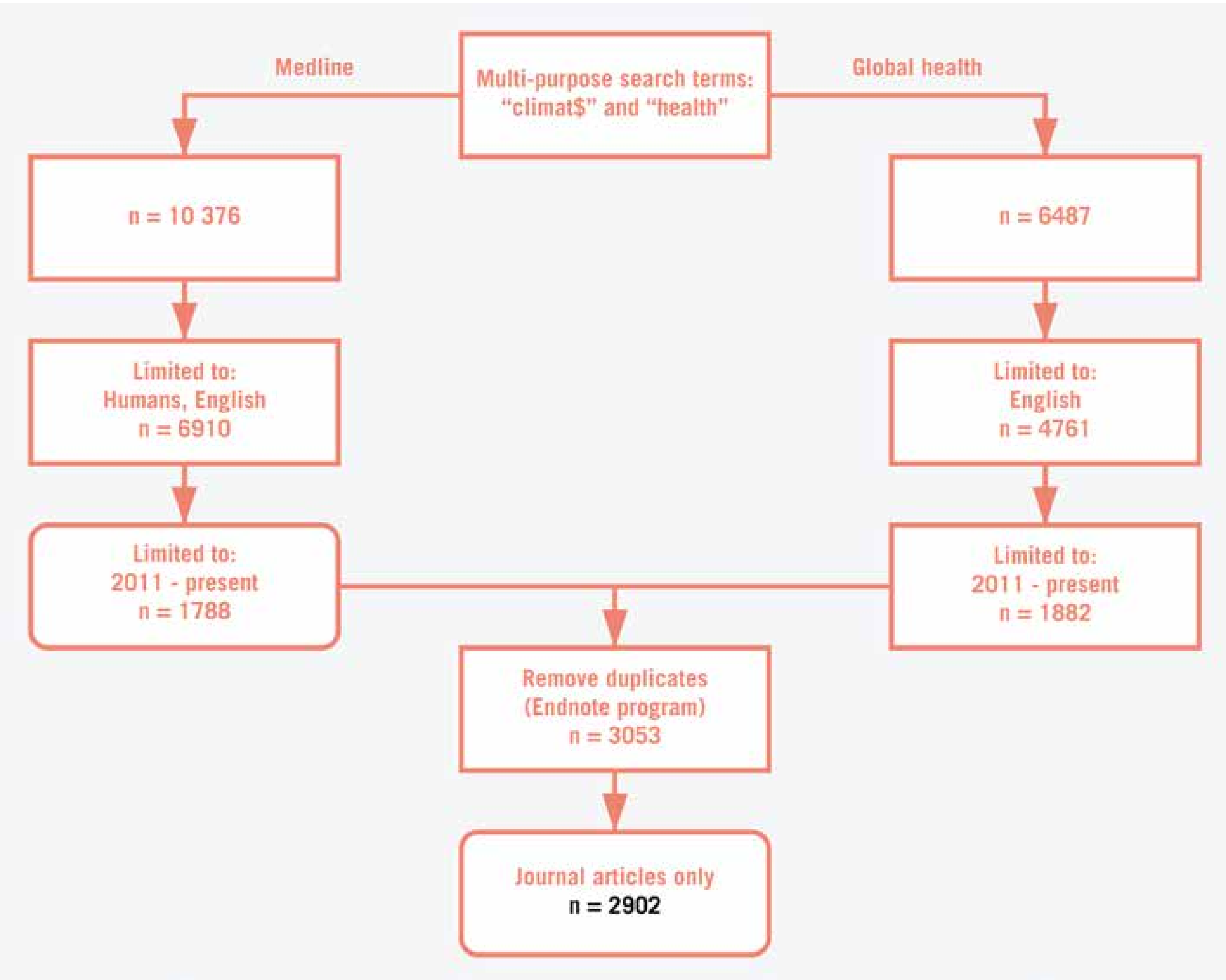


Figure A1. Search strategy, conducted on 24 June 2014 using the Ovid search platform.

Appendix III: The Climate and Clean Air Coalition initiatives

The Climate and Clean Air Coalition (CCAC; http://www.ccacoalition.org/) is involved with a number of initiatives around the world that aim to reduce SLCPs. Some of these have been described in the main text, but more information can be found at the following links.

Addressing SLCPs from Agriculture – see more at:
http://new.ccacoalition.org/en/initiatives/agriculture

Mitigating Black Carbon and Other Pollutants from Brick Production – see more at:
http://new.ccacoalition.org/en/initiatives/bricks

Reducing Black Carbon Emissions from Heavy-Duty Diesel Vehicles and Engines – see more at:
http://new.ccacoalition.org/en/initiatives/diesel

Reducing SLCPs from Household Cooking and Domestic Heating – see more at:
http://new.ccacoalition.org/en/initiatives/cookstoves

Mitigating SLCPs from the Municipal Solid Waste Sector – see more at:
http://new.ccacoalition.org/en/initiatives/waste

Realizing Health Benefits from Action on SLCPs in Cities – see more at:
http://new.ccacoalition.org/en/initiatives/health

Supporting National Action Planning on SLCPs (SNAP) – see more at:
http://new.ccacoalition.org/en/initiatives/snap

Appendix IV. IPCC Figures and Tables

Certain tables and figures in this report were taken from IPCC reports. In some cases the captions were modified and therefore the full IPCC captions are listed below along with web links to the original versions.

Table 18. Savings or off-site energy use reductions achievable in buildings for various end uses due to on-site active solar energy systems, efficiency improvements, or behavioural changes (system efficiency includes passive solar heating, cooling, ventilation and daylighting).
https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter9.pdf (p687)
The references underlying the estimated reductions can also be found at the above link.

Table 20. Examples of policies and measures for the waste management sector.
http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter10.pdf (p608)

Figure 14. Direct GHG emissions (shown here by transport mode) rose 250% from 2.8 Gt CO_2eq worldwide in 1970 to 7.0 Gt CO_2eq in 2010.
https://www.ipcc.ch/report/graphics/index.php?t=Assessment%20Reports&r=AR5%20-%20WG3&f=Chapter%2008

Figure 20. The hierarchy of waste management. The priority order and color coding are based on the waste hierarchy classification outlined by the European Commission and listed at right.
https://www.ipcc.ch/report/graphics/index.php?t=Assessment%20Reports&r=AR5%20-%20WG3&f=Chapter%2010

Figure 21. Management practices concerning municipal solid waste in several nations (WtE = waste-to-energy).
https://www.ipcc.ch/report/graphics/index.php?t=Assessment%20Reports&r=AR5%20-%20WG3&f=Chapter%2010

Appendix V. Methods for Figure 17

Figure 17 of the main text reports the embodied emissions in different foods based on four European studies (185-187, 191). It is important to note that methodologies differed somewhat between the studies; for example, which life-cycle stages were included. The figure reports estimates only for selected representative foods, and only if at least two estimates were available. The bars represent the minimum and maximum of the estimates. In one study, estimates were sometimes differentiated between production in the UK, Europe, and the rest of the world. Where more than one of these was reported for a given food, the average was taken.

References

1. Brook RD, Rajagopalan S, Pope CA, Brook JR, Bhatnagar A, Diez-Roux AV, et al. Particulate matter air pollution and cardiovascular disease an update to the scientific statement from the american heart association. Circulation. 2010;121(21):2331-78.
2. US Environmental Protection Agency. Integrated science assessment for particulate matter. Triangle Park; 2009.
3. Hoek G, Krishnan R, Beleen R, Peters A, Ostro B, Brunekreef B, et al. Long-term air pollution exposure and cardio- respiratory mortality: A review. Environ Health. 2013;12(43).
4. World Health Organization Regional Office for Europe. Review of evidence on health aspects of air pollution – REVIHAAP project. Copenhagen; 2013.
5. US Environmental Protection Agency. Integrated science assessment for ozone and related photochemical oxidants. Triangle Park; 2013.
6. World Health Organization. Mortality from ambient air pollution for 2012. Geneva; 2014 [cited 17 November 2014]; Available from: http://www.who.int/phe/health_topics/outdoorair/databases/en/.
7. World Health Organization. Mortality from household air pollution for 2012. Geneva; 2014 [cited 17 November 2014]; Available from: http://www.who.int/phe/health_topics/outdoorair/databases/en/.
8. Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: A systematic analysis for the global burden of disease study 2010. Lancet. 2012;380(9859):2224-60.
9. UNEP/WMO. Integrated assessment of black carbon and tropospheric ozone. Nairobi; 2011.
10. Shindell D. The contribution of short-lived climate pollutants to the post-2015 development agenda. Climate and Clean Air Coalition’s Working Group Meeting; September 8-10, 2015; Paris.
11. Hallström E, C-Kanyama A, Börjesson P. Environmental impact of dietary change: A systematic review. J Clean Prod. 2015 91:1-11.
12. Heller MC, Keoleian GA, Willett WC. Toward a life cycle-based, diet-level framework for food environmental impact and nutritional quality assessment: A critical review. Environ Sci Technol. 2013;47(22):12632-47.
13. Hosking J, Dora C, Mudu P. Health in the green economy: Health co-benefits of climate change mitigation – transport sector. Geneva; World Health Organization 2011.
14. Rehfuess E, Mehta S, Prüss-Üstün A. Assessing household solid fuel use: Multiple implications for the millennium development goals. Environ Health Perspect. 2006;114(3):373-8.
15. Shoemaker J, Schrag D, Molina M, Ramanathan V. What role for short-lived climate pollutants in mitigation policy? Science. 2013;342(6164):1323-4.
16. Chester M, Pincetl S, Elizabeth Z, Eisenstein W, Matute J. Infrastructure and automobile shifts: Positioning transit to reduce life-cycle environmental impacts for urban sustainability goals. Environ Res Lett. 2013;8(1):015041.
17. Chester M. Environmental life-cycle assessment of passenger transportation. [cited 22 August 2014]; Available from: http://www.transportationlca.org/.
18. Myhre G, Shindell D, Bréon FM, Collins W, Fuglestvedt J, Huang J, et al. Anthropogenic and natural radiative forcing. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, et al., editors. Climate change 2013: The physical science basis contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2013.

19. Janssen N, Girlofs-Nijland M, Lanki T, Salonen R, Cassee F, Hoek G, et al. Health effects of black carbon. Bonn: WHO - Europe; 2012.

20. Janssen N, Hoek G, Simic-Lawson M, Fischer P, van Bree L, ten Brink H, et al. Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM_{10} and $PM_{2.5}$. Environ Health Perspect. 2011;119(12):1691-9.

21. Lippmann M, Chen L, Gordon T, Ito K, Thurston G. National particle component toxicity (npact) initiative: Integrated epidemiologic and toxicologic studies of the health effects of particulate matter components. Boston: Health Effects Institute; 2013.

22. World Health Organization. Health relevance of particulate matter from various sources. Copenhagen; 2007.

23. Bond TC, Doherty SJ, Fahey D, Forster P, Berntsen T, DeAngelo B, et al. Bounding the role of black carbon in the climate system: A scientific assessment. J Geophys Res. 2013;118(11):5380-552.

24. World Health Organization Regional Office for Europe. Air quality guidelines: Global update 2005. Copenhagen; 2006.

25. Faustini A, Rapp R, Forastiere F. Nitrogen dioxide and mortality: Review and meta-analysis of long-term studies. Eur Respir J. 2014;44:744-53.

26. World Health Organization Regional Office for Europe. Health risks of air pollution in Europe - HRAPIE project. Copenhagen; 2013.

27. World Health Organization Regional Office for Europe. WHO expert meeting: Methods and tools for assessing the health risks of air pollution at local, national and international level. Bonn; 2014.

28. Stocker T, D Qin, GK. Plattner, LV Alexander, SK Allen, NL Bindoff, et al. Technical summary. In: Stocker TF, D. Qin, G.K. Plattner, M. Tignor, S.K. Allen, J. Boschung, et al., editors. Climate change 2013: The physical science basis contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2013.

29. World Health Organization. WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. Global update 2005: Summary of risk assessment. Geneva; 2006.

30. FAO. Food security indicators. 2015 [cited September 6 2015]; Available from: http://www.fao.org/economic/ess/ess-fs/ess-fadata/en/#.Vew8oxG6fIU.

31. Black RE, Victora CG, Walker SP, Bhutta ZA, Christian P, de Onis M, et al. Maternal and child undernutrition and overweight in low-income and middle-income countries. Lancet. 2013;382(9890):427–51.

32. Lloyd S, Kovats R, Chalabi Z. Climate change, crop yields, and malnutrition: A model to quantify the future impact of climate change on malnutrition. Environ Health Perspect. 2011;119(12):1817-23.

33. Van Dingenen R, Dentener FJ, Raes F, Krol MC, Emberson L, Cofala J. The global impact of ozone on agricultural crop yields under current and future air quality legislation. Atmos Environ. 2009;43(3):604-18.

34. Scovronick N, Dora C, Fletcher E, Haines A, Shindell D. Reduce short-lived climate pollutants for multiple benefits. The Lancet. 2015.

35. International Agency for Research on Cancer (IARC). Agents classified by the IARC monographs, volumes 1–111. 2014 [cited 31 October 2014]; Available from: http://monographs.iarc.fr/ENG/Classification/ClassificationsGroupOrder.pdf.

36. US Environmental Protection Agency. Report to congress on black carbon. Triangle Park; 2012.

37. Boulter P, Borken-Kleefeld J, Ntziachristos L. The evolution and control of nox emissions from road transport in Europe. In: Viana M, editor. Urban air quality in Europe. Berlin Heidelberg: Springer; 2013. p. 31-53.

38. Woodcock J, Edwards P, Tonne C, Armstrong BG, Ashiru O, Banister D, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: Urban land transport. Lancet. 2009;374(9705):1930-43.

39. Lelieveld J, Evans J, Fnais M, Giannadaki D, Pozzer A. The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature. 2015;525:367-71.

40. Ciais P, Sabine C, Bala G, Bopp L, Brovkin V, Canadell J, et al. Chapter 6: Carbon and other biogeochemical cycles. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, et al., editors. Climate change 2013: The physical science basis contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambrige and New York: Cambridge University Press; 2013. p. 465-570.

41. Qunhua L, Xin K, Changzhi C, Shengzheng F, Yan L, Rongzhi H, et al. New irrigation methods sustain malaria control in Sichuan province, China. Acta Trop. 2004;89:241-7.

42. Keiser J, Maltese MF, Erlanger TE, Bos R, Tanner M, Singer BH, et al. Effect of irrigated rice agriculture on Japanese encephalitis, including challenges and opportunities for integrated vector management. Acta Trop. 2005;95:40-57.

43. Katz D, Meller S. Can we say what diet is best for health? Annu Rev Public Health. 2014;35:83-103.

44. Smith KR, Bruce N, Balakrishnan K, Adair-Rohani H, Balmes J, Chafe ZA, et al. Millions dead: How do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. Annu Rev Public Health. 2014;35(1):185-206.

45. Kar A, Rehman IH, Burney J, Puppala SP, Suresh R, Singh L, et al. Real-time assessment of black carbon pollution in Indian households due to traditional and improved biomass cookstoves. Environ Sci Technol. 2012;46(5):2993-3000.

46. Anenberg SC, Balakrishnan K, Jetter J, Masera O, Mehta S, Moss J, et al. Cleaner cooking solutions to achieve health, climate, and economic cobenefits. Environ Sci Technol. 2013;47(9):3944-52.

47. World Health Organization. WHO air quality guidelines for indoor air quality: Household fuel combustion. Geneva; 2014.

48. Peden M, Oyegbite K, Ozanne-Smith J, Hyder A, Branche C, Fazlur Rahman A, et al. World report on child injury prevention. World Health Organization; 2008.

49. World Health Organization. Fact sheet on burns. 2014 [cited September 17 2015]; Available from: http://www.who.int/mediacentre/factsheets/fs365/en/.

50. Schwebel DC, Swart D, Hui S-kA, Simpson J, Hobe P. Paraffin-related injury in low-income South African communities: Knowledge, practice and perceived risk. Bull World Health Organ. 2009;87(9):700-6.

51. Escombe A, Oeser C, Gilman R, Navincopa M, Ticona E, Pan W, et al. Natural ventilation for the prevention of airborne contagion. PLoS Med. 2007;4:e68.

52. Bornehag C-G, Blomquist G, Gyntelberg F, Jarvholm B, Malmberg P, Nordvall L, et al. Dampness in buildings and health. Indoor Air. 2001;11(2):72-86.

53. McMichael AJ, Wilkinson P, Kovats RS, Pattenden S, Hajat S, Armstrong B, et al. International study of temperature, heat and urban mortality: The 'isothurm'project. Int J Epidemiol. 2008;37(5):1121-31.

54. Basu R. High ambient temperature and mortality: A review of epidemiologic studies from 2001 to 2008. Environ Health. 2009;8:40.

55. Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, Schwartz J, et al. Mortality risk attributable to high and low ambient temperature: A multicountry observational study. The Lancet. 2015;386(9991):369-75.

56. Guttikunda SK, Begum BA, Zia W. Particulate pollution from brick kiln clusters in the greater Dhaka region, Bangladesh. Air Quality, Atmosphere and Health. 2013;6(2):357-65.

57. Bruckner T, IA Bashmakov, Y Mulugetta, H Chum, A de la Vega Navarro, J Edmonds, et al. Chapter 7: Energy systems. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al., editors. Climate change 2014: Mitigation of climate change contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2014. p. 511-97.

58. Ziegelbauer K, Speich B, Mausezahl D, Bos R, Keiser J, Utzinger J. Effect of sanitation on soil-transmitted helminth infection: Systematic review and meta-analysis. PLoS Med. 2012;9(1):e1001162.

59. Fewtrell L, Kaufmann R, Kay D, Enanoria W, Haller L, Colford Jr J. Water, sanitation and hygiene interventions to reduce diarrhoea in less developed countries: A systematic review and meta-analysis. Lancet Infect Dis. 2005;5(1):42-52.
60. IPCC. Annex iii: Glossary. In: Planton S, editor. Climate change 2013: The physical science basis contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambrige University Press; 2013.
61. IPCC. Summary for policymakers. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, et al., editors. Climate change 2013: The physical science basis contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2013.
62. Field C, Barros V, Mastrandrea M, Mach K, Abdrabo M, Adger W, et al. Climate change 2014: Impacts, adaptation, and vulnerability: Summary for policymakers; 2014.
63. Smith K, Jerrett M, Anderson H, Burnett R, Stone V, Derwent R, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: Health implications of short-lived greenhouse pollutants. Lancet. 2009;374:2091-103.
64. Bahadur R, Praveen PS, Xu Y, Ramanathan V. Solar absorption by elemental and brown carbon determined from spectral observations. Proc Natl Acad Sci USA. 2012;109(43):17366-71.
65. Hales S, Kovats S, Lloyd S, Campbell-Lendrum D. Quantitative risk assessment of the effects of climate change on selected causes of death, 2030s and 2050s. Geneva: WHO; 2014.
66. Burnett R, Pope III C, Ezzati M, Olives C, Lim S, Mehta S, et al. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environ Health Perspect. 2014;122(4):397-403.
67. Karagulian F, Belis C, Dor C, Prüss-Üstün A, Bonjour S, Adair-Rohani H, et al. Contributions to cities' ambient particulate matter (PM): A systematic review of local source contributions at global level. Atmos Environ. 2015;120:475-83.
68. Putaud J-P, Raes F, Van Dingenen R, Brüggemann E, Facchini M-C, Decesari S, et al. A European aerosol phenomenology—2: Chemical characteristics of particulate matter at kerbside, urban, rural and background sites in Europe. Atmos Environ. 2004;38(16):2579-95.
69. Rückerl R, Schneider A, Breitner S, Cyrys J, Peters A. Health effects of particulate air pollution: A review of epidemiological evidence. Inhal Toxicol. 2011;23(10):555-92.
70. Krewski D, Jerrett M, Burnett RT, Ma R, Hughes E, Shi Y, et al. Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality. Boston: Health Effects Institute 2009.
71. Laden F, Schwartz J, Speizer FE, Dockery DW. Reduction in fine particulate air pollution and mortality: Extended follow-up of the Harvard six cities study. Am J Respir Crit Care Med. 2006;173(6):667-72.
72. Atkinson R, Kang S, Anderson H, Mills I, Walton H. Epidemiological time series studies of $PM_{2.5}$ and daily mortality and hospital admissions: A systematic review and meta-analysis. Thorax. 2014.
73. Levy JI, Diez D, Dou Y, Barr CD, Dominici F. A meta-analysis and multisite time-series analysis of the differential toxicity of major fine particulate matter constituents. Am J Epidemiol. 2012;175(11):1091-9.
74. Dai L, Zanobetti A, Koutrakis P, Schwartz JD. Associations of fine particulate matter species with mortality in the United States: A multicity time-series analysis. Environ Health Perspect. 2014.
75. Petzold A, Ogren J, Fiebig M, Laj P, Li S-M, Baltensperger U, et al. Recommendations for reporting "black carbon" measurements. Atmospheric Chemistry and Physics. 2013;13(16):8365-79.
76. Ramanathan V, Carmichael G. Global and regional climate changes due to black carbon. Nature Geoscience. 2008;1(4):221-7.
77. Saleh R, Hennigan C, McMeeking G, Chuang W, Robinson E, Coe H, et al. Absorptivity of brown carbon in fresh and photo-chemically aged biomass-burning emissions. Atmospheric Chemistry and Physics. 2013;13(15):7683-93.

78. Saleh R, Robinson ES, Tkacik DS, Ahern AT, Liu S, Aiken AC, et al. Brownness of organics in aerosols from biomass burning linked to their black carbon content. Nature Geoscience. 2014;7(9):647-50.

79. Bonjour S, Adair-Rohani H, Wolf J, Bruce N, Mehta S, Prüss-Ustün A, et al. Solid fuel use for household cooking: Country and regional estimates for 1980-2010. Environ Health Perspect. 2013;121(7):784-90.

80. Ji M, Cohan DS, Bell ML. Meta-analysis of the association between short-term exposure to ambient ozone and respiratory hospital admissions. Environ Res Lett. 2011;6(2):024006.

81. Anderson GB, Krall JR, Peng RD, Bell ML. Is the relation between ozone and mortality confounded by chemical components of particulate matter? Analysis of 7 components in 57 US communities. Am J Epidemiol. 2012;176(8):726-32.

82. Katsouyanni K, Samet J. Air pollution and health: A european and north american approach (aphena). Boston: Health Effects Institute; 2009.

83. World Health Organization Regional Office For Europe. Health risks of ozone from long-range transboundary air pollution. Copenhagen; 2008.

84. Bell ML, Peng RD, Dominici F. The exposure-response curve for ozone and risk of mortality and the adequacy of current ozone regulations. Environ Health Perspect. 2006;114(4):532-6.

85. Jerrett M, Burnett RT, Pope III CA, Ito K, Thurston G, Krewski D, et al. Long-term ozone exposure and mortality. N Engl J Med. 2009;360(11):1085-95.

86. Ashmore M. Assessing the future global impacts of ozone on vegetation. Plant, Cell & Environment. 2005;28(8):949-64.

87. Derwent R, Collins W, Johnson C, Stevenson D. Transient behaviour of tropospheric ozone precursors in a global 3-d ctm and their indirect greenhouse effects. Clim Change. 2001;49(4):463-87.

88. Burney J, Ramanathan V. Recent climate and air pollution impacts on Indian agriculture. Proc Natl Acad Sci U S A. 2014;111(46):16319-24.

89. FAO. Food balance sheets 2009. [cited May 29 2014]; Available from: http://www.fao.org/home/en/.

90. Smith L, Haddad L. Explaining child malnutrition in developing countries: A cross-country analysis. Washington D.C.: International Food Policy Research Institute; 2000.

91. Smith L, Haddad L. Reducing child undernutrition: Past drivers and priorities for the post-MDG era. Brighton: Institute of Development Studies; 2014.

92. Checkley W, Buckley G, Gilman RH, Assis AM, Guerrant RL, Morris SS, et al. Multi-country analysis of the effects of diarrhoea on childhood stunting. Int J Epidemiol. 2008;37(4):816-30.

93. Crompton DWT, Nesheim M. Nutritional impact of intestinal helminthiasis during the human life cycle. Annu Rev Nutr. 2002;22(1):35-59.

94. French SA. Pricing effects on food choices. J Nutr. 2003;133(3):841S-3S.

95. Green R, Cornelsen L, Dangour A, Turner R, Shankar B, Mazzocchi M, et al. The effect of rising food prices on food consumption: Systematic review with meta-regression. Br Med J. 2013;346:doi: 10.1136/bmj.f3703.

96. Iannotti LL, Robles M, Pachón H, Chiarella C. Food prices and poverty negatively affect micronutrient intakes in Guatemala. J Nutr. 2012;142(8):1568-76.

97. Scovronick N, Wilkinson P. The impact of biofuel-induced food-price inflation on dietary energy demand and dietary greenhouse gas emissions. Global Environ Change. 2013;23(6):1587-93.

98. Sari M, de Pee S, Bloem M, Sun K, Thorne-Lyman A, Moench-Pfanner R, et al. Higher household expenditure on animal-source and nongrain foods lowers the risk of stunting among children 0-59 months old in Indonesia: Implications of rising food prices. J Nutr. 2010;140(1):195S-200S.

99. Torlesse H, Kiess L, Bloem M. Association of household rice expenditure with child nutritional status indicates a role for macroeconomic food policy in combating malnutrition. J Nutr. 2003;133(5):1320-5.

100. Duffey K, Gordon-Larsen P, Shikany J, Guilkey D, Jacobs Jr D, Popkin B. Food price and diet and health outcomes: 20 years of the cardia study. Arch Intern Med. 2010;170(5):420-6.

101. Shindell D, Kuylenstierna JC, Vignati E, van Dingenen R, Amann M, Klimont Z, et al. Simultaneously mitigating near-term climate change and improving human health and food security. Science. 2012;335(6065):183-9.

102. Hajat S, Kosatky T. Heat-related mortality: A review and exploration of heterogeneity. J Epidemiol Community Health. 2010;64(9):753-60.

103. Kovats RS, Hajat S. Heat stress and public health: A critical review. Annu Rev Public Health. 2008;29:41-55.

104. Anderson BG, Bell ML. Weather-related mortality: How heat, cold, and heat waves affect mortality in the United States. Epidemiology. 2009;20(2):205-13.

105. Gasparrini A, Armstrong B, Kovats S, Wilkinson P. The effect of high temperatures on cause-specific mortality in England and Wales. Occup Environ Med. 2012;69(1):56-61.

106. Ahern M, Kovats RS, Wilkinson P, Few R, Matthies F. Global health impacts of floods: Epidemiologic evidence. Epidemiol Rev. 2005;27(1):36-46.

107. Lindell MK, Prater CS. Assessing community impacts of natural disasters. Natural Hazards Review. 2003;4(4):176-85.

108. Goldmann E, Galea S. Mental health consequences of disasters. Annu Rev Public Health. 2014;35:169-83.

109. United Nations Office for Disaster Risk Reduction. Disaster impacts / 2000-2012. 2013 [cited May 29 2014]; Available from: http://www.preventionweb.net/files/31737_20130312disaster-20002012copy.pdf.

110. United Nations Office for Disaster Risk Reduction. 2012 disasters in numbers. 2012 [cited May 29 2014]; Available from: http://www.preventionweb.net/files/31685_factsheet2012.pdf.

111. World Bank. Turn down the heat: Climate extremes, regional impacts, and the case for resilience. Washington D.C.: A report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics.; 2013.

112. Unger N, Bond TC, Wang JS, Koch DM, Menon S, Shindell DT, et al. Attribution of climate forcing to economic sectors. Proc Natl Acad Sci U S A. 2010;107(8):3382-7.

113. Fan J, Rosenfeld D, Yang Y, Zhao C, Leung LR, Li Z. Substantial contribution of anthropogenic air pollution to catastrophic floods in Southwest China. Geophysical Research Letters. 2015;42(14):6066-75.

114. Sims R., R. Schaeffer, F. Creutzig, X. Cruz-Núñez, M. D'Agosto, D. Dimitriu, et al. Chapter 8: Transport. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al., editors. Climate change 2014: Mitigation of climate change contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2014. p. 599-670.

115. Organisation for Economic Co-operation and Development (OECD). The cost of air pollution: Health impacts of road transport. Paris; 2014.

116. Dalkmann H, Brannigan C. Sustainable transport: A sourcebook for policy-makers in developing cities; 2007.

117. Dallmann TR, Harley RA, Kirchstetter TW. Effects of diesel particle filter retrofits and accelerated fleet turnover on drayage truck emissions at the port of Oakland. Environ Sci Technol. 2011;45(24):10773-9.

118. Biswas S, Vermaa V, JJ S, Sioutas C. Chemical speciation of pm emissions from heavy-duty diesel vehicles equipped with diesel particulate filter (DPF) and selective catalytic reduction (SCR) retrofits. Atmos Environ. 2009;43(11):1917-25.

119. Bergmann M, Kirchner U, Vogt R, Benter T. On-road and laboratory investigation of low-level PM emissions of a modern diesel particulate filter equipped diesel passenger car. Atmos Environ. 2009;43(11):1908–16.

120. Millstein DE, Harley RA. Effects of retrofitting emission control systems on in-use heavy diesel vehicles. Environ Sci Technol. 2010;44(13):5042-8.

121. Carslaw DC. Evidence of an increasing NO_2/NO_x emissions ratio from road traffic emissions. Atmos Environ. 2005;39(26):4793-802.

122. European Environment Agency. Air quality in Europe - 2014 report. Luxembourg; 2014.

123. Sundvor I, Balaguer N, Mar Viana X, Reche C, Amato F, Mellios G, et al. Road traffic's contribution to air quality in european cities. Biltoven: European Topic Centre on Air Pollution and Climate Change Mitigation; 2012.

124. Franco V, Sánchez FP, German J, Mock P. Real-world exhaust emissions from modern diesel cars. Berlin: International Council on Clean Transportation; 2014.

125. Schiermeier Q. The science behind the volkswagen emissions scandal. 2015 [cited 6 October 2015]; Available from: http://www.nature.com/news/the-science-behind-the-volkswagen-emissions-scandal-1.18426.

126. Weiss M, Bonnel P, Kühlwein J, Provenza A, Lambrecht U, Alessandrini S, et al. Will Euro 6 reduce the NO_x emissions of new diesel cars? – insights from on-road tests with Portable Emissions Measurement Systems (PEMS). Atmos Environ. 2012;62:657-65.

127. V. Ramanathan et al. Black carbon and the regional climate of California: Report to the California Air Resources Board; 2013.

128. Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants. Mexico launches new world-class heavy-duty vehicle emissions standards. [cited August 21 2015]; Available from: http://www.unep.org/ccac/Media/PartnersInFocus/Mexico-launchesnewworld-classheavy-dutyvehicle/tabid/794666/Default.aspx.

129. Miller J, Blumberg K, Sharpe B. Cost-benefit analysis of Mexico's heavy-duty emission standards (nom 044): International Council on Clean Transportation; 2014.

130. Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants. Initiatives [cited August 21 2015]; Available from: http://www.unep.org/ccac/Initiatives/tabid/130287/Default.aspx.

131. Shindell D, Faluvegi G, Walsh M, Anenberg SC, Van Dingenen R, Muller NZ, et al. Climate, health, agricultural and economic impacts of tighter vehicle-emission standards. Nature Clim Change. 2011;1(1):59-66.

132. Fontaras G, Martini G, Manfredi U, Marotta A, Krasenbrink A, Maffioletti F, et al. Assessment of on-road emissions of four Euro V diesel and CNG waste collection trucks for supporting air-quality improvement initiatives in the city of Milan. Sci Total Environ. 2012;426(1):65-72.

133. Reynolds CC, Grieshop AP, Kandlikar M. Climate and health relevant emissions from in-use Indian three-wheelers fueled by natural gas and gasoline. Environ Sci Technol. 2011;45(6):2406-12.

134. Myung C, Lee H, Choi K, Lee Y, Park S. Effects of gasoline, diesel, LPG, and low-carbon fuels and various certification modes on nanoparticle emission characteristics in light-duty vehicles. International Journal of Automotive Technology. 2009;10(5):537-44.

135. Turrio-Baldassarri L, Battistelli CL, Conti L, Crebelli R, De Berardis B, Iamiceli AL, et al. Evaluation of emission toxicity of urban bus engines: Compressed natural gas and comparison with liquid fuels. Sci Total Environ. 2006;355(1):64-77.

136. Scovronick N, Wilkinson P. Health impacts of liquid biofuel production and use: A review. Global Environ Change. 2014;24:155-64.

137. Anderson LG. Effects of biodiesel fuels use on vehicle emissions. Journal of Sustainable Energy & Environment. 2012;3:35-47.

138. Niven R. Ethanol in gasoline: Environmental impacts and sustainability review article. Renewable and Sustainable Energy Reviews. 2005;9(6):535-55.

139. Hill J, Polasky S, Nelson E, Tilman D, Huo H, Ludwig L, et al. Climate change and health costs of air emissions from biofuels and gasoline. Proceedings of the National Academy of Sciences, USA. 2009;106(6):2077-82.

140. Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science. 2008;319(5867):1235-8.

141. Rosegrant MW, Zhu T, Msangi S, Sulser T. Global scenarios for biofuels: Impacts and implications. Review of Agricultural Economics. 2008;30(3):495-505.

142. Delucchi MA. Impacts of biofuels on climate change, water use, and land use. Ann NY Acad Sci. 2010;1195:28-45.

143. Hill J, Nelson E, Tilman D, Polasky S, Tiffany D. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proc Natl Acad Sci USA. 2006;103(30):11206-10.

144. Hill J, Polasky S, Nelson E, Tilman D, Huo H, Ludwig L, et al. Climate change and health costs of air emissions from biofuels and gasoline. Proc Natl Acad Sci USA. 2009;106(6):2077-82.

145. Rosegrant M, Msangi S, Sulser T, Valmonte-Santos R. Biofuels and the global food balance. Washington DC: International Food Policy Research Institute; 2006.

146. Renewable Energy Policy Network for the 21st Century. Renewables 2013: Global status report. Paris: REN21 Secretariat; 2013.

147. Beck LF, Dellinger AM, O'neil ME. Motor vehicle crash injury rates by mode of travel, United States: Using exposure-based methods to quantify differences. Am J Epidemiol. 2007;166(2):212-8.

148. European Transport Safety Council. Transport safety performance in the eu: A statistical overview. Brussels; 2003.

149. World Health Organization. Global status report on road safety: Supporting a decade of action. Geneva; 2013.

150. Rissel C, Curac N, Greenaway M, Bauman A. Physical activity associated with public transport use—a review and modelling of potential benefits. Int J Environ Res Public Health. 2012;9(7):2454-78.

151. Ewing R, Cervero R. Travel and the built environment: A meta-analysis. J Am Plann Assoc. 2010;76(3):265-94.

152. Handy SL, Boarnet MG, Ewing R, Killingsworth RE. How the built environment affects physical activity: Views from urban planning. Am J Prev Med. 2002;23(2):64-73.

153. World Health Organization. Interventions on diet and physical activity: What works? Geneva; 2009.

154. Matthews CE, Jurj AL, Shu X-o, Li H-L, Yang G, Li Q, et al. Influence of exercise, walking, cycling, and overall nonexercise physical activity on mortality in Chinese women. Am J Epidemiol. 2007;165(12):1343-50.

155. Andersen LB, Schnohr P, Schroll M, Hein HO. All-cause mortality associated with physical activity during leisure time, work, sports, and cycling to work. Arch Intern Med. 2000;160(11):1621-8.

156. Andersen ZJ, de Nazelle A, Mendez MA, Garcia-Aymerich J, Hertel O, Tjønneland A, et al. A study of the combined effects of physical activity and air pollution on mortality in elderly urban residents: The Danish diet, cancer, and health cohort. Environ Health Perspect. 2015.

157. Macmillan A, Connor J, Witten K, Kearns R, Rees D, Woodward A. The societal costs and benefits of commuter bicycling: Simulating the effects of specific policies using system dynamics modeling. Environ Health Perspect. 2014;122(4):335-4.

158. Grabow ML, Spak SN, Holloway T, Stone Jr B, Mednick AC, Patz JA. Air quality and exercise-related health benefits from reduced car travel in the midwestern United States. Environ Health Perspect. 2012;120(1):68-76.

159. Pucher J, Dijkstra L. Making walking and cycling safer: Lessons from Europe. Transportation Quarterly. 2000;54(3):25-50.

160. Barías J, Browne J, Sanhueza E, Silsbe E, Winkelman S, Zegras C. Getting on track: Finding a path for transportation in the cdm. Manitoba: International Institute for Sustainable Development; 2005.

161. Edwards JB, McKinnon AC, Cullinane SL. Comparative analysis of the carbon footprints of conventional and online retailing: A "last mile" perspective. International Journal of Physical Distribution & Logistics Management. 2010;40(1/2):103-23.

162. Wiese A, Toporowski W, Zielke S. Transport-related CO_2 effects of online and brick-and-mortar shopping: A comparison and sensitivity analysis of clothing retailing. Transportation Research Part D: Transport and Environment. 2012;17(6):473-7.

163. Holmner A, Rocklov J, Nawi N, Nilsson M. Climate change and ehealth: A promising strategy for health sector mitigation and adaptation. Global Health Action. 2012;5(18428).

164. Gouge B, Dowlatabadi H, Ries FJ. Minimizing the health and climate impacts of emissions from heavy-duty public transportation bus fleets through operational optimization. Environ Sci Technol. 2013;47(8):3734-42.

165. Smith P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E.A. Elsiddig, et al. Chapter 11: Agriculture, forestry and other land use (afolu). In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al., editors. Climate change 2014: Mitigation of climate change contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2014. p. 811-922.

166. Pandey S, Byerlee D, Dawe D, Dobermann A, Mohanty S, Rozelle S, et al. Rice in the global economy. Los Banos, Phillipines: International Rice Research Institute 2010.

167. Sanchis E, Ferrer M, Torres AG, Cambra-López M, Calvet S. Effect of water and straw management practices on methane emissions from rice fields: A review through a meta-analysis. Environmental Engineering Science. 2012;29(12):1053-62.

168. Wassmann R, Hosen Y, Sumfleth K. Reducing methane emissions from irrigated rice. Washington DC: International Food Policy Research Institute (IFPRI); 2009.

169. Krishnasamy S, Amerasinghe FP, Sakthivadivel R, Ravi G, Tewari S, Van Der Hoek W. Strategies for conserving water and effecting mosquito vector control in rice ecosystems: A case study from Tamil Nadu, India. International Water Management Institute; 2003.

170. Keiser J, Maltese MF, Erlanger TE, Bos R, Tanner M, Singer BH, et al. Effect of irrigated rice agriculture on Japanese encephalitis, including challenges and opportunities for integrated vector management. Acta Tropica. 2005 7//;95(1):40-57.

171. Qunhua L, Xin K, Changzhi C, Shengzheng F, Yan L, Rongzhi H, et al. New irrigation methods sustain malaria control in Sichuan Province, China. Acta Tropica. 2004; 89(2):241-7.

172. World Health Organization. Malaria control: The power of integrated action. [cited 5 October 2015]; Available from: http://www.who.int/heli/risks/vectors/malariacontrol/en/index6.html.

173. Bouman B, Lampayan R, Tuong T. Water management in irrigated rice: Coping with water scarcity. Int. Rice Res. Inst.; 2007.

174. Li C, Salas W, DeAngelo B, Rose S. Assessing alternatives for mitigating net greenhouse gas emissions and increasing yields from rice production in China over the next twenty years. J Environ Qual. 2006;35(4):1554-65.

175. Halwart M, Gupta MV. Culture of fish in rice fields. Rome and Penang: FAO and WorldFish Center; 2004.

176. Chadwick D, Sommer S, Thorman R, Fangueiro D, Cardenas L, Amon B, et al. Manure management: Implications for greenhouse gas emissions. Animal Feed Science and Technology. 2011;166-167(23):514-31.

177. Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, et al. Agriculture. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L, editors. Climate change 2007: Mitigation contribution of Working Group 2 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambrdige and New York: Cambridge University Press; 2007.

178. Holm-Nielsen JB, Al Seadi T, Oleskowicz-Popiel P. The future of anaerobic digestion and biogas utilization. Bioresour Technol. 2009;100(22):5478-84.

179. Arbex M, Martins L, de Oliveira R, Pereira L, Arbex F, Cancado J, et al. Air pollution from biomass burning and asthma hospital admissions in a sugar cane plantation area in Brazil. J Epidemiol Community Health. 2007;61(5):395-400.

180. Cançado J, Saldiva P, Pereira L, Lara L, Artaxo P, Martinelli L, et al. The impact of sugar cane–burning emissions on the respiratory system of children and the elderly. Environ Health Perspect. 2006;114(5):725-9.

181. Fatima Alves de Oliveira B, Ignotti E, Artaxo P, do Nascimento Saldiva PH, Junger WL, Hacon S. Risk assessment of pm2. 5 to child residents in Brazilian amazon region with biofuel production. Environ Health. 2012;11(1):64-75.

182. Lara L, Artaxo P, Martinelli L, Camargo P, Victoria R, Ferraz E. Properties of aerosols from sugar-cane burning emissions in Southeastern Brazil. Atmos Environ. 2005;39(26):4627-37.

183. Arbex M, Bohm G, Saldiva P, Conceiçao G, Pope A, Braga A. Assessment of the effects of sugar cane plantation burning on daily counts of inhalation therapy. J Air Waste Manag Assoc. 2000;50(10):1745-9.

184. Arbex M, Saldiva P, Pereira L, Braga A. Impact of outdoor biomass air pollution on hypertension hospital admissions. J Epidemiol Community Health. 2010;64(7):573-9.

185. Audsley E, Brander M, Chatterton J, Murphy-Bokern D, Webster C, Williams A. How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050. FCRN-WWF-UK; 2009.

186. Berners-Lee M, Hoolohan C, Cammack H, Hewitt C. The relative greenhouse gas impacts of realistic dietary choices. Energ Policy. 2012;43:184-90.

187. Carlsson-Kanyama A, Gonzalez A. Potential contributions of food consumption patterns to climate change. Am J Clin Nutr. 2009;89(5):1704S-9S.

188. Chao A, Thun M, Connell C, McCullough M, Jacobs E, Flanders W, et al. Meat consumption and risk of colorectal cancer. JAMA. 2005;293(2):172-82.

189. Van Dooren C, Marinussen M, Blonk H, Aiking H, Vellinga P. Exploring dietary guidelines based on ecological and nutritional values: A comparison of six dietary patterns. Food Policy. 2014;44:36-46.

190. Smith P, Haberl H, Popp A, Erb Kh, Lauk C, Harper R, et al. How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Global Change Biol. 2013;19(8):2285-302.

191. Wallén A, Brandt N, Wennersten R. Does the Swedish consumer's choice of food influence greenhouse gas emissions? Environ Sci Policy. 2004;7(6):525-35.

192. Steinfeld H, Gerber P, Wassenaar T, Castel V, Rosales M, De Haan C. Livestock's long shadow. Rome: FAO; 2006.

193. Eyles H, Mhurchu C, Nghiem N, Blakely T. Food pricing strategies, population diets, and non-communicable disease: A systematic review of simulation studies. PLoS Med. 2012;9(12):e1001353.

194. Mytton O, Gray A, Rayner M, Rutter H. Could targeted food taxes improve health? J Epidemiol Community Health. 2007;61(8):689-94.

195. Briggs AD, Kehlbacher A, Tiffin R, Garnett T, Rayner M, Scarborough P. Assessing the impact on chronic disease of incorporating the societal cost of greenhouse gases into the price of food: An econometric and comparative risk assessment modelling study. BMJ open. 2013;3(10):e003543.

196. Edjabou LD, Smed S. The effect of using consumption taxes on foods to promote climate friendly diets–the case of Denmark. Food Policy. 2013;39:84-96.

197. Wirsenius S, Hedenus F, Mohlin K. Greenhouse gas taxes on animal food products: Rationale, tax scheme and climate mitigation effects. Clim Change. 2011;108(1-2):159-84.

198. Kroeze W, Werkman A, Brug J. A systematic review of randomized trials on the effectiveness of computer-tailored education on physical activity and dietary behaviors. Ann Behav Med. 2006;31(3):205–23.

199. Engbers L, van Poppel M, Chin A Paw M, van Mechelen W. Worksite health promotion programs with environmental changes: A systematic review. Am J Prev Med. 2005;21:61-70.

200. Knai C, Pomerleau J, Lock K, McKee M. Getting children to eat more fruit and vegetables: A systematic review. Prev Med. 2006;42(2):85-95.

201. Capacci S, Mazzocchi M, Shankar B, Macias J, Verbeke W, Pérez-Cueto F, et al. Policies to promote healthy eating in Europe: A structured review of policies and their effectiveness. Nutr Rev. 2012;70(3):188-200.

202. Blanco G, Gerlagh R, Suh S, Barrett J, Coninck HCd, Morejon CFD, et al. Chapter 5: Drivers, trends and mitigation. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al., editors. Climate change 2014: Mitigation of climate change contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, USA: Cambridge University Press; 2014. p. 351-411.

203. Jakobsen M, O'Reilly E, Heitmann B, Pereira M, Balter K, Fraser G, et al. Major types of dietary fat and risk of coronary heart disease: A pooled analysis of 11 cohort studies. Am J Clin Nutr. 2009;89(5):1425-32.

204. World Health Organization. Diet, nutrition and the prevention of chronic diseases. Geneva: Report of a joint WHO/FAO Expert Consultation; 2003.

205. Yip CSC, Crane G, Karnon J. Systematic review of reducing population meat consumption to reduce greenhouse gas emissions and obtain health benefits: Effectiveness and models assessments. Int J Public Health. 2013;58(5):683-93.

206. Joyce A, Hallett J, Hannelly T, Carey G, Hallett J, Hannelly T, et al. The impact of nutritional choices on global warming and policy implications: Examining the link between dietary choices and greenhouse gas emissions. Energy and Emission Control Technologies. 2014;2:33-43.

207. Parfitt J, Barthel M, Macnaughton S. Food waste within food supply chains: Quantification and potential for change to 2050. Philosophical Transactions of the Royal Society B: Biological Sciences. 2010;365(1554):3065-81.

208. Godfray J, Beddington JR, Crute IR, Haddad L, Lawrence D, Muir JF, et al. Food security: The challenge of feeding 9 billion people. Science. 2010;327(5967):812-8.

209. Hall KD, Guo J, Dore M, Chow CC. The progressive increase of food waste in America and its environmental impact. PLoS ONE. 2009;4(11):e7940.

210. FAO. Global food losses and food waste – extent, causes and prevention. Rome; 2011.

211. U.S. Department of Agriculture and U.S. Department of Health and Human Services. Dietary guidelines for Americans 2010. Washington D.C.; 2010.

212. Westhoek H, Lesschen JP, Rood T, Wagner S, De Marco A, Murphy-Bokern D, et al. Food choices, health and environment: Effects of cutting Europe's meat and dairy intake. Global Environ Change. 2014;26:196-205.

213. Scarborough P, Allender S, Clarke D, Wickramasinghe K, Rayner M. Modelling the health impact of environmentally sustainable dietary scenarios in the UK. Eur J Clin Nutr. 2012;66(6):710-5.

214. Macdiarmid JI, Kyle J, Horgan GW, Loe J, Fyfe C, Johnstone A, et al. Sustainable diets for the future: Can we contribute to reducing greenhouse gas emissions by eating a healthy diet? Am J Clin Nutr. 2012;96(3):632-9.

215. Popp A, Lotze-Campen H, Bodirsky B. Food consumption, diet shifts and associated non-CO_2 greenhouse gases from agricultural production. Global Environ Change. 2010;20(3):451-62.

216. Friel S, Dangour A, Garnett T, Lock K, Chalabi Z, Roberts I, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: Food and agriculture. Lancet. 2009;374(9706):2016-25.

217. Stehfest E, Bouwman L, van Vuuren DP, den Elzen MG, Eickhout B, Kabat P. Climate benefits of changing diet. Clim Change. 2009;95(1-2):83-102.

218. World Health Organization. Household air pollution and health. 2014 [cited 15 July 2014]; Available from: http://www.who.int/mediacentre/factsheets/fs292/en/.

219. Venkataraman C, Sagar A, Habib G, Lam N, Smith K. The Indian national initiative for advanced biomass cookstoves: The benefits of clean combustion. Energy Sustain Dev. 2010;14(2):63-72.

220. Bruce N, Perez-Padilla R, Albalak R. Indoor air pollution in developing countries: A major environmental and public health challenge. Bull World Health Organ. 2000;78(9):1078-92.

221. Wilkinson P, Smith KR, Davies M, Adair H, Armstrong BG, Barrett M, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: Household energy. Lancet. 2009;374(9705):1917-29.

222. Jetter JJ, Kariher P. Solid-fuel household cook stoves: Characterization of performance and emissions. Biomass and Bioenergy. 2009;33(2):294-305.

223. Romieu I, Riojas-Rodríguez H, Marrón-Mares AT, Schilmann A, Perez-Padilla R, Masera O. Improved biomass stove intervention in rural Mexico: Impact on the respiratory health of women. Am J Respir Crit Care Med. 2009;180(7):649-56.

224. Roden CA, Bond TC, Conway S, Osorto Pinel AB, MacCarty N, Still D. Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves. Atmos Environ. 2009;43(6):1170-81.

225. Sambandam S, Balakrishnan K, Ghosh S, Sadasivam A, Madhav S, Ramasamy R, et al. Can currently available advanced combustion biomass cook-stoves provide health relevant exposure reductions? Results from initial assessment of select commercial models in India. EcoHealth. 2014;12(1):25-41.

226. Rehfuess E, Pope D, Bruce N. Who indoor air quality guidelines: Household fuel combustion - review 6: Impacts of interventions on household air pollution concentrations and personal exposure. Geneva; 2014.

227. Diaz E, Smith-Sivertsen T, Pope D, Lie RT, Diaz A, McCracken J, et al. Eye discomfort, headache and back pain among Mayan Guatemalan women taking part in a randomised stove intervention trial. J Epidemiol Community Health. 2007;61(1):74-9.

228. Dherani M, Pope D, Mascarenhas M, Smith KR, Weber M, Bruce N. Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: A systematic review and meta-analysis. Bull World Health Organ. 2008;86(5):390-8C.

229. Anenberg S. Technology: Clean stoves benefit climate and health. Nature. 2012;490(7420):343.

230. Lewis JJ, Pattanayak SK. Who adopts improved fuels and cookstoves? A systematic review. Environ Health Perspect. 2012;120(5):637-45.

231. Beltramo T, Levin D. The effect of solar ovens on fuel use, emissions an health: Results from a randomised controlled trial. Journal of Development Effectiveness. 2013;5(2):178-207.

232. Smith K. In praise of power. Science. 2014;345(6197):603.

233. Tedsen E. Black carbon emissions from kerosene lamps: Potential for a new CCAC initiative. Ecological Institute; 2013 [cited 14 November 2014]; Available from: http://www.ecologic.eu/10232.

234. Lam NL, Chen Y, Weyant C, Venkataraman C, Sadavarte P, Johnson MA, et al. Household light makes global heat: High black carbon emissions from kerosene wick lamps. Environ Sci Technol. 2012;46(24):13531-8.

235. Lam NL, Smith KR, Gauthier A, Bates MN. Kerosene: A review of household uses and their hazards in low-and middle-income countries. J Toxicol Env Heal B. 2012;15(6):396-432.

236. Mills E. Technical and economic performance analysis of kerosene lamps and alternative approaches to illumination in developing countries. Berkeley: Lawrence Berkeley National Laboratory 2003.

237. Mahapatra S, Chanakya H, Dasappa S. Evaluation of various energy devices for domestic lighting in India: Technology, economics and CO_2 emissions. Energy Sustain Dev. 2009;13(4):271-9.

238. US Department of Energy. Wood and pellet heating. 2013 [cited 25 August 2014]; Available from: http://energy.gov/energysaver/articles/wood-and-pellet-heating.

239. Lucon O., Ürge-Vorsatz D, Ahmed AZ, Akbari H, Bertoldi P, Cabeza LF, et al. Chapter 9: Buildings. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al., editors. Climate change 2014: Mitigation of climate change contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2014. p. 671-738.

240. Milner J, Shrubsole C, Das P, Jones B, Ridley I, Chalabi Z, et al. Home energy efficiency and radon related risk of lung cancer: Modelling study. BMJ. 2014;348.

241. Howden-Chapman P, Crane J, Chapman R, Fougere G. Improving health and energy efficiency through community-based housing interventions. Int J Public Health. 2011;56(6):583-8.

242. Wilkinson P, Landon M, Armstrong B, Stevenson S, McKee M. Cold comfort: The social and environmental determinants of excess winter death in England, 1986–1996. York: Joseph Rowntree Foundation; 2001.

243. Atkinson J, Chartier Y, Pessoa-Silva C, Jensen P, Li Y, Seto W. Natural ventilation for infection control in healthcare settings. Geneva: WHO; 2009.

244. Amadi H, Mohammed L, Kawuwa M, Oyedokun A, Mohammed H. Synthesis and validation of a weatherproof nursery design that eliminates tropical evening-fever syndrome in neonates. International Journal of Pediatrics. 2014;2014:9p.

245. Schimidt C. Modernizing artisinal brick kilns: A global need. Environ Health Perspect. 2013;121(8):a242-9.

246. Shakti Sustinable Energy Foundation. Brick kilns performance assessment: A roadmap for cleaner brick production in India. New Dehli; 2012.

247. Weyant C, Athaiye V, Ragavan S, Rajarathnam U, Lalchandani D, Maithel S, et al. Emissions from South Asian brick production. Environ Sci Technol. 2014;48(11):6477-83.

248. Joshi S, Dudani I. Environmental health effects of brick kilns in Kathmandu Valley. Kathmandu Univ Med J. 2008;6:3-11.

249. World Bank. Introducing energy-efficient clean technologies in the brick sector of Bangladesh. Washington, DC; 2011.

250. Shaikh S, Nafees A, Khetpal V, Jamali A, Arain A, Yousef A. Respiratory symptoms and illnesses among brick kiln workers: A cross sectional study from rural districts of Pakistan. BMC Public Health. 2012;12(999).

251. US Environmental Protection Agency. Reducing black carbon emissions in South Asia: Low-cost opportunities. Washington D.C.; 2012.

252. Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants. Mitigating black carbon and other pollutants from brick production. [cited August 21 2015]; Available from: http://www.ccacoalition.org/docs/pdf/Fact_Sheet_05-Bricks_1.5_Web.pdf.

253. Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants. Brick production. [cited August 21 2015]; Available from: http://www.unep.org/ccac/Initiatives/ImprovedBrickProduction/tabid/794080/Default.aspx.

254. Huo H, Lei Y, Zhang Q, Zhao L, He K. China's coke industry: Recent policies, technology shift, and implication for energy and the environment. Energ Policy. 2012;51:397-404.

255. Costantino J, Redmond C, Bearden A. Occupationally related cancer risk among coke oven workers: 30 years of follow-up. J Occup Environ Med. 1995;37(5):597-604.

256. Li X, Feng Y, Deng H, Zhang W, Kuang D, Deng Q, et al. The dose-response decrease in heart rate variability: Any association with the metabolites of polycyclic aromatic hydrocarbons in coke oven workers? PLoS ONE. 2012;7(9):e44562.

257. Miller B, Doust E, Cherrie J, Hurley J. Lung cancer mortality and exposure to polycyclic aromatic hydrocarbons. BMC Public Health. 2013;13:962.

258. Sathaye J, Lucon O, Rahman A, Christensen J, Denton F, Fujino J, et al. Chapter 9: Renewable energy in the context of sustainable development. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, et al., editors. IPCC special report on renewable energy sources and climate change mitigation. Cambridge and New York: Cambridge University Press; 2011. p. 707-90.

259. Kovats S, Depledge M, Haines A, Fleming LE, Wilkinson P, Shonkoff SB, et al. The health implications of fracking. Lancet. 2014;383(9919):757-8.

260. Shonkoff SB, Hays J, Finkel ML. Environmental public health dimensions of shale and tight gas development. Environ Health Perspect. 2014;122(8):787-95.

261. Sumner SA, Layde PM. Expansion of renewable energy industries and implications for occupational health. Journal of the American Medical Association. 2009;302(7):787-9.

262. World Health Organization. Health in the green economy: Health co-benefits of climate change mitigaiton - occupational health (initial findings). Geneva, 2012. Available from: http://www.who.int/hia/green_economy/hgebrief_occ.pdf?ua=1

263. Mulloy KB, Sumner SA, Rose C, Conway GA, Reynolds SJ, Davidson ME, et al. Renewable energy and occupational health and safety research directions: A white paper from the Energy Summit, Denver, Colorado, April 11–13, 2011. Am J Ind Med. 2013;56(11):1359-70.

264. Ellwood P, Bradbrook S, Reynolds J, Duckworth M. Foresight of new and emerging risks to occupational safety and health associated with new technologies in green jobs by 2020: Phase 2 - key technologies. Luxembourg: European Agency for Safety and Health at Work; 2011.

265. Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants. Scientific advistory panel 2013 scientific update. Available from: http://www.unep.org/ccac/Portals/50162/HLA/norway/docs/SAP%202013%20Annual%20Science%20Update%20(Full)%20-%20EN.pdf; 2013.

266. World Health Organization. Healthy hospitals, healthy people, healthy planet: Addressing climate change in healthcare settings. Geneva; 2009.

267. Adair-Rohani H, Zukor K, Bonjour S, Wilburn S, Kuesel AC, Hebert R, et al. Limited electricity access in health facilities of sub-saharan africa: A systematic review of data on electricity access, sources, and reliability. Global Health: Science and Practice. 2013;1(2):249-61.

268. Ani VA. Feasibility analysis and simulation of a stand-alone photovoltaic energy system for electricity generation and environmental sustainability - equivalent to a 650VA fuel-powered generator. Frontiers in Energy Research. 11 September, 2015; 3 (38). doi. 10.3389/fenrg.2015.00038 Available from: http://journal.frontiersin.org/article/10.3389/fenrg.2015.00038/abstract.

269. Ani VA, Emetu AN. Simulation and optimization of photovoltaic/diesel hybrid power generation systems for health service facilities in rural environments. Electronic Journal of Energy & Environment. 2013;1(1):57-70.

270. Ani VA. Energy optimization map for off-grid health clinics in Nigeria. International Journal of Renewable Energy 2014;4(1).

271. Ani VA, Abubakar B. Feasibility analysis and simulation of integrated renewable energy system for power generation: A hypothetical study of rural health clinic. Journal of Energy 2015. Available from: http://dx.doi.org/10.1155/2015/802036.

272. World Health Organization. Access to modern energy services for health facilities in resource-constrained settings. Geneva; 2014 [cited]; Available from: http://www.who.int/hia/green_economy/modern-energy-services/en/.

273. Southeast Combined Heat and Power Technical Assistance Partnership. Project profile: Mississippi baptist medical center: US Department of Energy; 2013.

274. ICF International. Combined heat and power: Enabling resilient energy infrastructure for critical facilities. Washington DC and Oak Ridge Tennessee 2013.

275. Bogner J, M. , Ahmed A, Diaz C, Faaij A, Gao Q, Hashimoto S, et al. Waste management. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L, editors. Climate change 2007: Mitigation contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2007.

276. World Health Organization Regional Office for Europe. Population health and waste management: Scientific data and policy options. Copenhagen; 2007.

277. Hoornweg D, Bhada-Tata P. What a waste: A global review of solid waste management. Washington, DC: World Bank; 2012.

278. Giusti L. A review of waste management practices and their impact on human health. Waste Manag. 2009;29(8):2227-39.

279. Mattiello A, Chiodini P, Bianco E, Forgione N, Flammia I, Gallo C, et al. Health effects associated with the disposal of solid waste in landfills and incinerators in populations living in surrounding areas: A systematic review. Int J Public Health. 2013;58:725-35.
280. Ashworth D, Elliot P, Toledano M. Waste incineration and adverse birth and neonatal outcomes: A systematic review. Environmental International. 2014;69:120-32.
281. Fischedick M, J Roy, A Abdel-Aziz, A Acquaye, JM Allwood, JP Ceron, et al. Chapter 10: Industry. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al., editors. Climate change 2014: Mitigation of climate change contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2014. p. 739-810.
282. Medina M. The informal recycling sector in developing countries. Gridlines. 2008.
283. Wilson D, Velis C, Cheeseman C. Role of informal sector recycling in waste management in developing countries. Habitat International. 2006;30(4):797-808.
284. European Commission. Towards a circular economy: A zero waste programme for Europe. Brussels; 2014.
285. WHO/UNICEF. Progress on sanitation and drinking water: 2013 update. Geneva; 2013.
286. UNEP/GEC. Water and wastewater reuse: An environmentally sound approach for sustainable urban water management. Japan; 2004.
287. Lemieux P, Lutes C, Santoianni D. Emissions of organic air toxics from open burning: A comprehensive revew. Progress in Energy and Combustion Science. 2004;30(1):1-32.
288. Zhang R, Fiedler H, Yu G, Ochoa G, Carroll Jr W, Gullett B, et al. Emissions of unintentinal persistent organic pollutants from open burning of municipal solid waste from developing countries. Chemosphere. 2011;84(7):994-1001.
289. US Environmental Protection Agency. The hidden hazards of backyard burning. Washington, DC; 2003.
290. UN Department of Economic and Social Affairs PD. World urbanization prospects: The 2009 revision. New York; 2010.
291. Seto K.C., S. Dhakal, A. Bigio, H. Blanco, G.C. Delgado, D. Dewar, et al. Chapter 12: Human settlements, infrastructure, and spatial planning. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, et al., editors. Climate change 2014: Mitigation of climate change contribution of Working Group 3 to the Fifth Assessment Report of the Inter-Governmental Panel on Climate Change. Cambridge and New York: Cambridge Unversity Press; 2014. p. 923-1000.
292. UN Human Settlements Programme. The challenge of slums - global report on human settlements 2003. London: Earthscan; 2003.
293. Satterthwaite DE. The transition to a predominantly urban world and its underpinnings. London: International Institute for Environment and Development; 2007.
294. Leon D. Cities, urbanization and health. Int J Epidemiol. 2008;37(1):4-8.
295. Dye C. Health and urban living. Science. 2008;319(5864):766-9.
296. Singh G, Saiahpush M. Widening rural-urban dispairities in life expectancy, US, 1969-2009. Am J Prev Med. 2014;46(2):e19-e29.
297. Menegat R. Participatory democracy and sustainable development: Integrated urban environmental management in Porto Alegre, Brazil. Environment and Urbanization. 2002;14(2):181-206.
298. Brownstone D, Golob T. The impact of residential density on vehicle usage and energy consumption. Journal of Urban Economics. 2009;65(1):91-8.
299. Karathodorou N, Graham D, Noland R. Estimating the effect of urban density on fuel demand. Energ Econ. 2010;32(1):86-92.
300. Kennedy C, Steinberger J, Gasson B, Hansen Y, Hillman T, Havranek M, et al. Greenhouse gas emissions from global cities. Environ Sci Technol. 2009;43(19):7297-302.
301. International Association of Public Transport Providers. Millennium cities database (1995). Brussels; 2001.

302. City of Cape Town. Myciti. 2014 [cited 25 July 2014]; Available from: myciti.org.za/en/home.

303. Greenwood G, Bulman A, Kingma R. Myciti integrated rapid transit system: It is not just about the bus. Civil Engineering. 2013:31-9.

304. City of Cape Town. Integrated rapid transit: Phase overview. 2014 [cited 25 July 2014]; Available from: www.capetown.gov.za/en/irt/Pages/Phaseoverview.aspx.

305. Ewing R, Rong F. The impact of urban form on us residential energy use. Housing Policy Debate. 2008;19(1):1-30.

306. Wilson A, Boehland J. Small is beautiful: US house size, resource use and the environment. Journal of Industrial Ecology. 2005;9(1-2):277-87.

307. Susca T, Gaffin SR, Dell'Osso GR. Positive effects of vegetation: Urban heat island and green roofs. Environ Pollut. 2011;159(8-9):2119-26.

308. Oberndorfer E, Lundholm J, Bass B, Coffman R, Doshi H, Dunnett N, et al. Green roofs as urban ecosystems: Ecological structures, functions and services. Bioscience. 2007;57(10):823-33.

309. Agency UEP. Cooling summertime temperatures: Strategies to reduce urban heat islands. Washington DC; 2003.

310. Akbari H, Pomerantz M, Taha H. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. Solar Energy. 2001;70(3):295-310.

311. Susca T. Multiscale approach to life-cycle assessment: Evaluation of the effect of an increase in New York City's rooftop albedo on human health. Journal of Industrial Ecology. 2012;16(6):951-62.

312. Taha H. Modeling the impacts of increased urban vegetation on ozone air quailty in the south coast air baisn. Atmos Environ. 1996;30(20):3423-30.

313. Taha H. Modeling the impacts of large-scale albedo changes on ozone air quality in the south coast air basin. Atmos Environ. 1997;31(11):1667-76.

314. Sullivan E, Ward PM. Sustainable housing applications and policies for low-income self-build and housing rehab. Habitat International. 2012;36(2):312-23.

315. Hartwig T, Mitchell R, de Vries S, Frumkin H. Nature and health. Annu Rev Public Health. 2014;35:207-28.

316. Roe JJ, Thompson CW, Aspinall PA, Brewer MJ, Duff EI, Miller D, et al. Green space and stress: Evidence from cortisol measures in deprived urban communities. Int J Environ Res Public Health. 2013;10(9):4086-103.

317. Aspinall P, Mavros P, Coyne R, Roe J. The urban brain: Analysing outdoor physical activity with mobile eeg. Br J Sports Med. 2013;49(4):272-6.

318. Ward Thompson C, Roe J, Aspinall P, Mitchell R, Clow A, Miller D. More green space is linked to less stress in deprived communities: Evidence from salivary cortisol patterns. Landscape and Urban Planning. 2012;105(3):221-9.

319. Maas J, Van Dillen SM, Verheij RA, Groenewegen PP. Social contacts as a possible mechanism behind the relation between green space and health. Health Place. 2009;15(2):586-95.

320. Kuo FE, Sullivan WC. Environment and crime in the inner city: Does vegetation reduce crime? Environment and Behavior. 2001;33(3):343-67.

321. Garvin EC, Cannuscio CC, Branas CC. Greening vacant lots to reduce violent crime: A randomised controlled trial. Inj Prev. 2013;19(3):198-203.

322. Beyer KM, Kaltenbach A, Szabo A, Bogar S, Nieto FJ, Malecki KM. Exposure to neighborhood green space and mental health: Evidence from the survey of the health of Wisconsin. Int J Environ Res Public Health. 2014;11(3):3453-72.

323. Maher B, Ahmed I, Davison B, Karloukovski V, Clarke R. Impact of roadside tree lines on indoor concentrations of traffic-derived particulate matter. Environ Sci Technol. 2013;47(23):13737-44.

324. Brantley H, Hagler G, Deshmukh P, Baldauf R. Field assessment of the effects of roadside vegetation on near-road black carbon and particulate matter. Sci Total Environ. 2014;468-49:120-9.

325. Wania A, Bruse M, Blond N, Weber C. Analysing the influence of different street vegetation on traffic-induced particle dispersion using microscale simulations. J Environ Manage. 2012;94(1):91-101.

326. Shan Y, Jingping C, Liping C, Zhemin S, Xiaodong Z, Dan W, et al. Effects of vegetation status in urban green spaces on particle removal in a street canyon atmosphere. Acta Ecologica Sinica. 2007;27(11):4590-5.

327. Drewniak BA, Snyder PK, Steiner AL, Twine TE, Wuebbles DJ. Simulated changes in biogenic voc emissions and ozone formation from habitat expansion of acer rubrum (red maple). Environ Res Lett. 2014;9(1):014006.

328. Akbari, H. Shade trees reduce building energy use and CO2 emissions from power plants. Environmental Pollution. 2002;116(1):119–126.

329. Milieu Ltd. Assessment of the effectiveness of european air quality policies and measures. Brussels; 2004.

330. World Health Organization. Ambient (outdoor) air pollution in cities database 2014. 2014 [cited 16 October 2014]; Available from: http://www.who.int/phe/health_topics/outdoorair/databases/cities/en/.

331. Miller G, Spoolman S. Enviromental science. Belmont, CA: Brooks/Cole; 2010.

332. Suzuki H, Dastur A, Moffatt S, Yabuki N, Mauyama H. Ecocities: Ecological cities as economic cities. Washington D.C.: World Bank; 2010.

333. Atlas do desenvovimento humano no brasil 2013 [cited 25 July 2014]; Available from: http://www.atlasbrasil.org.br/2013.

334. International Council on Clean Transportation. European vehicle market statistics: Pocketbook 2014. Berlin; 2014.

335. Bressi M, Sciare J, Ghersi V, Mihalopoulos N, Petit J-E, Nicolas J, et al. Sources and geographical origins of fine aerosols in Paris, France. Atmospheric Chemistry and Physics. 2014;14(16):8813-39.

336. Medina S. Summary report of the APHEKOM project 2008-2011. Paris; 2011.

337. Paris mayor's office. Mayor Hidalgo announces a series of actions for Paris in 2015. 2015 [cited September 11 2015]; Available from: http://next.paris.fr/english/english/mayor-idalgo-announces-a-series-of-actions-for-paris-in-2015/rub_8118_actu_152414_port_19237.

338. Mairie de Paris. Lutte contre la pollution de l'air : Priorité absolue de la ville de paris. 2015 [cited September 18 2015]; Available from: http://www.paris.fr/actualites/lutte-contre-la-pollution-de-l-air-priorite-absolue-de-la-ville-de-paris-2111#favoriser-la-circulation-des-vehicules-propres-et-limiter-les-plus-polluants_2.

339. Edenhofer O, R Pichs-Madruga, Y Sokona, S Kadner, JC Minx, S Brunner, et al. Technical summary. In: Edenhofer O, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, et al., editors. Climate change 2014: Mitigation of climate change contribution of Working Group 3 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York: Cambridge University Press; 2014. p. 33-107.

340. Scarborough P, Appleby PN, Mizdrak A, Briggs AD, Travis RC, Bradbury KE, et al. Dietary greenhouse gas emissions of meat-eaters, fish-eaters, vegetarians and vegans in the UK. Clim Change. 2014;125(2):179-92.

341. Boucher O, Reddy M. Climate trade-off between black carbon and carbon dioxide emissions. Energ Policy. 2008;36(1):193-200.

342. Wang H, Zhou P, Zhou D. An empirical study of direct rebound effect for passenger transport in urban China. Energ Econ. 2012;34(2):452-60.

343. Ajanovic A, Schipper L, Haas R. The impact of more efficient but larger new passenger cars on energy consumption in EU-15 countries. Energy. 2012;48(1):346-55.

344. Small KA, Van Dender K. Fuel efficiency and motor vehicle travel: The declining rebound effect. Energy J. 2007;28(1):25-51.

345. Hanna R, Duflo E, Greenstone M. Up in smoke: The influence of household behavior on the long-run impact of improved cooking stoves: National Bureau of Economic Research; 2012.

346. European Environment Agency. Emissions of ozone precursors. Copenhagen; 2014 [cited 10 November 2014]; Available from: http://www.eea.europa.eu/data-and-maps/indicators/emissions-of-ozone-precursors-version-2/assessment-4.

347. McJeon H, Edmonds J, Bauer N, Clarke L, Fisher B, Flannery BP, et al. Limited impact on decadal-scale climate change from increased use of natural gas. Nature. 2014;514(7523):482-5.

348. Howarth RW. A bridge to nowhere: Methane emissions and the greenhouse gas footprint of natural gas. Energy Science & Engineering. 2014;2(2):47-60.

349. Murray CJ, Vos T, Lozano R, Naghavi M, Flaxman AD, Michaud C, et al. Disability-adjusted life years (dalys) for 291 diseases and injuries in 21 regions, 1990–2010: A systematic analysis for the global burden of disease study 2010. Lancet. 2013;380(9859):2197-223.

350. Lozano R, Naghavi M, Foreman K, Lim S, Shibuya K, Aboyans V, et al. Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: A systematic analysis for the global burden of disease study 2010. Lancet. 2013;380(9859):2095-128.

351. Campbell G, Hills S, Fischer M, Jacobson J, Hoke C, Hombach J, et al. Estimated global incidence of Japanese encephalitis: A systematic review. Bull World Health Organ. 2011;89:766-74E.

352a. World Health Organization. Health statistics and information systems: Estimates for 2000-2012. 2014 [cited 18 September 2015]; Available from: http://www.who.int/healthinfo/global_burden_disease/estimates/en/index1.html

352. Sinha R, Cross A, Graubard B, Leitzmann M, Schatzkin A. Meat intake and mortality: A prospective study of over half a million people. JAMA Intern Med. 2009;169(6):562-71.

353. Feskens EJ, Sluik D, van Woudenbergh GJ. Meat consumption, diabetes, and its complications. Curr Diab Rep. 2013;13(2):298-306.

354. Scarborough P, Nnoaham KE, Clarke D, Capewell S, Rayner M. Modelling the impact of a healthy diet on cardiovascular disease and cancer mortality. J Epidemiol Community Health. 2012;66(5):420-6.

355. Johnston F, Bailie R, Pilotto L, Hanigan I. Ambient biomass smoke and cardio-respiratory hospital admissions in Darwin, Australia. BMC Public Health. 2007;7:240.

356. Long W, Tate RB, Neuman M, Manfreda J, Becker AB, Anthonisen NR. Respiratory symptoms in a susceptible population due to burning of agricultural residue. CHEST Journal. 1998;113(2):351-7.

357. Johnston FH, Henderson SB, Chen Y, Randerson JT, Marlier M, DeFries RS, et al. Estimated global mortality attributable to smoke from landscape fires. Environ Health Perspect. 2012;120(5):695-701.

358. van der Werf GR, Randerson JT, Giglio L, Collatz G, Mu M, Kasibhatla PS, et al. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). Atmospheric Chemistry and Physics. 2010;10(23):11707-35.

359. Black R, Caulfield L, Allen L, Bhutta Z, De Onis M, Mathers C, et al. Maternal and child undernutrition: Global and regional exposures and health consequences. Lancet. 2008;371(9608):243-60.

360. Olofin I, McDonald CM, Ezzati M, Flaxman S, Black RE, Fawzi WW, et al. Associations of suboptimal growth with all-cause and cause-specific mortality in children under five years: A pooled analysis of ten prospective studies. PLoS ONE. 2013;8(5):e64636.

361. Victora CG, Adair L, Fall C, Hallal PC, Martorell R, Richter L, et al. Maternal and child undernutrition: Consequences for adult health and human capital. Lancet. 2008;371(9609):340-57.

362. Warburton DE, Nicol CW, Bredin SS. Health benefits of physical activity: The evidence. Can Med Assoc J. 2006;174(6):801-9.

363. Bauman AE. Updating the evidence that physical activity is good for health: An epidemiological review 2000–2003. J Sci Med Sport. 2004;7(1):6-19.

364. Pate RR, Pratt M, Blair SN, Haskell WL, Macera CA, Bouchard C, et al. Physical activity and public health: A recommendation from the Centers for Disease Control and Prevention and the American College of Sports Medicine. JAMA. 1995;273(5):402-7.

365. Stansfeld SA, Berglund B, Clark C, Lopez-Barrio I, Fischer P, Öhrström E, et al. Aircraft and road traffic noise and children's cognition and health: A cross-national study. Lancet. 2005;365(9475):1942-9.

366. Ndrepepa A, Twardella D. Relationship between noise annoyance from road traffic noise and cardiovascular diseases: A meta-analysis. Noise Health. 2011;13(52):251-9.

367. Jarrett J, Woodcock J, Griffiths UK, Chalabi Z, Edwards P, Roberts I, et al. Effect of increasing active travel in urban England and Wales on costs to the national health service. Lancet. 2012;379(9832):2198-205.

368. Roebbel N. Health in the green economy: Health co-benefits of climate change mitigation – housing sector. Geneva; World Health Organization 2011.

369. Scovronick N, Armstrong B. The impact of housing type on temperature-related mortality in South Africa, 1996–2015. Environ Res. 2012;113:46-51.

370. Abt Associates Inc.. Power plant emissions: Particulate matter-related health damages and the benefits of alternative emission reduction scenarios. Boston, MA: Clean Air Task Force; 2004.

371. Epstein PR, Buonocore JJ, Eckerle K, Hendryx M, Stout III BM, Heinberg R, et al. Full cost accounting for the life cycle of coal. Ann N Y Acad Sci. 2011;1219(1):73-98.

372. Al-Karaghouli A, Kazmerski L. Optimization and life-cycle cost of health clinic pv system for a rural area in Southern Iraq using homer software. Solar Energy. 2010;84(4):710-4.

373. Eshel G, Shepon A, Makov T, Milo R. Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States. Proc Natl Acad Sci USA. 2014;111(33):11996-2001.

374. Greene D, Plotkin S. Reducing greenhouse gas emissions from US Transportation. Arlington: Pew Center on Global Climate Change; 2011.

375. Chandler K, Vertin K, Alleman T, Clark N. Ralphs grocery ec-diesel truck fleet: Final results. Golden, CO; 2003.

376. Karplus V, Kishimoto P, Paltsev S. The global energy, CO_2 emissions, and economic impact of vehicle fuel economy standards. 15th Annual Conference on Global Economic Analysis; 2012; Geneva.

377. Heltberg R. Fuel switching: Evidence from eight developing countries. Energ Econ. 2004;26(5):869-87.

378. Ürge-Vorsatz D, Danny Harvey L, Mirasgedis S, Levine MD. Mitigating CO_2 emissions from energy use in the world's buildings. Build Res Inf. 2007;35(4):379-98.

379. Ramesh T, Prakash R, Shukla K. Life cycle energy analysis of buildings: An overview. Energ Buildings. 2010;42(10):1592-600.

380. Sims R, Schock R, Adegbululgbe A, Fenhann J, Konstrantinaviciute I, Moomaw W, et al. Energy supply. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L, editors. Climate change 2007: Mitigation contribution of Working Group 3 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York; 2007.

REDUCING GLOBAL HEALTH RISKS

Through mitigation of short-lived climate pollutants. Scoping report for policymakers.

Short-lived climate pollutants (SLCPs), including black carbon, methane, and ozone, are responsible for a substantial fraction of climate change as well as for a significant proportion of air-pollution related deaths and diseases that kill some 7 million people per year.

Reducing emissions of short-lived climate pollutants (SLCPs), which produce strong warming effects but only persist in the atmosphere for periods ranging from days to decades, can provide health benefits in three key ways: directly from reduced air pollution and related ill-health; indirectly from reduced ozone and black carbon effects on extreme weather and agricultural production (affecting food security); and from other types of health benefits that are not associated with air pollution but may accrue as a result of certain SLCP mitigation actions, such as improved diets or increased physical activity.

This report reviews a range of strategies and policies for action that can benefit health, as well as reducing air pollution and short-lived climate emissions. This review covers sectors such as urban planning, transport, household energy and building design, food production and consumption, power generation, industry, and waste management. Strategies rely upon cost-effective technologies and policy measures.

Reducing SLCP emissions can yield large near-term benefits to health, making measures particularly attractive to policy-makers. Global action to reduce SLCPs and other air pollutants can save lives as well as slowing near-term climate change.

Public Health and Environment Department (PHE)
Health Security & Environment Cluster (HSE)
World Health Organization (WHO)
20 Avenue Appia, 1211 Geneva 27, Switzerland
www.WHO.int/phe/en

Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants
Hosted by the United Nations Environment Programme
15 Rue de Milan, 75441 Paris Cedex 09, France
www.ccacoalition.org

9 789241 565080