The climate dividend

"Climate change is the biggest global health threat of the 21st century." So concluded a *Lancet*–UCL Commission earlier this year.[1] A systematic appraisal of available evidence showed that the risks from changing patterns of disease, food insecurity, unsafe water and sanitation, damage to human settlements, extreme events, and population growth and migration were far more severe for human health than most observers had understood. The message added an important new dimension to the political debate about how to respond to climate change. The threat was not only environmental and economic; it was directed at life itself.

The health community has now begun to mobilise itself. Academies and colleges of medicine have called on doctors to speak out about climate change.[2] Physicians have taken the case for responding to climate change directly to politicians.[3] And new organisations, such as the UK's Climate and Health Council, are working to inform, affirm, advocate, innovate, and disseminate on behalf of health professionals working to address global warming.

Despite these welcome manoeuvres to emphasise the health dimension of climate change, still the overwhelming impression among the public is that any response to global warming will be negative. Cutting carbon out of our economy will be costly. We will have to drive less, fly less, eat differently, change the way we generate energy, and alter our lifestyles in ways that will limit our freedom to do as we please. The apparent progress we have made in wealth and health since the industrial revolution will stall. Climate change, so it seems, will put human development into reverse. Not surprisingly, this political message is hard to sell to a public already struggling during a time of global financial insecurity.

But, as this latest Series of six papers on the health co-benefits of intervening on climate change shows, there is an important health dividend to be gained by mitigating the effects of greenhouse-gas emissions. These co-benefits for health are insufficiently known. They extend beyond rich nations and reach into low-income and middle-income countries. And they traverse sectors as diverse as household energy, urban transport, electricity generation, agriculture, and short-lived greenhouse pollutants.

This report owes a great deal to a remarkable collaboration between several health and medical institutions—the Wellcome Trust, Royal College of Physicians, National Institute for Environmental Health Sciences, National Institute for Health Research, London School of Hygiene and Tropical Medicine, Economic and Social Research Council, Academy of Medical Sciences, WHO, and *The Lancet*. It was prepared very much with the December Copenhagen climate conference in mind. But too much pressure and too many hopes have already been put on this single meeting. By suggesting that Copenhagen is the "last chance" for a binding international climate-change agreement, anything less will seem a failure. Copenhagen is a beginning, not the end.

The complexity of a global climate agreement is immense. Targets have to be set and agreed domestically. Verification procedures have to be devised. Financial support has to be assembled for poorer nations. Trust between countries has to be fostered. Each of these domains will take time to work out. Copenhagen is a starting pistol marking the beginning of concerted high-level political negotiations. After Copenhagen there can be no turning back. And as these negotiations proceed, health is likely to become an increasingly important concern, not only for a public anxious about the impact of climate-change mitigation policies on their lives, but

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also for politicians eager to sweeten the climate-change policy pill.

This latest report aims to accelerate political and public assent for large cuts in greenhouse-gas emissions. It indicates the contribution of science and public health to one of the greatest predicaments facing human and non-human life. That contribution now needs to be embraced fully by health professionals and medical scientists worldwide.

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Cutting carbon, improving health

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Events such as the financial crisis and climate change are not quirks of the marketplace or quirks of nature. Instead they are markers of massive failure in international systems that govern the way nations and their populations interact. The contagion of our mistakes shows no mercy and makes no exceptions on the basis of fair play. For example, countries that have contributed least to greenhouse-gas emissions will be the first and hardest hit by climate change.[1]

Several health consequences of a changing climate have been identified with a high degree of certainty. Malnutrition, and its devastating effects on child health, will increase. Worsening floods, droughts, and storms will cause more deaths and injuries. Heat waves will cause more deaths, largely among people who are elderly. Finally, climate change could alter the geographical distribution of disease vectors, including the insects that spread malaria and dengue.[2] All these health problems are already huge, largely concentrated in the developing world, and difficult to control.[3]

Sadly, policy makers have been slow to recognise that the real bottom-line of climate change is its risk to human health and quality of life. Thankfully, however, this situation is beginning to change. At the World Health Assembly, health ministers have called for intensified action to protect health from climate change,[4] including awareness raising, the development of regional and national action plans, and increased support to strengthen adaptive capacities in health systems, especially in the most vulnerable countries. The past few months have also seen statements and campaigns by major medical associations and health non-governmental organisations, speaking on behalf of tens of thousands of health professionals and other concerned citizens.[5,6]

Research findings which show how carbon-reduction strategies can be good for health have helped to drive these changes. The papers presented in a Series in *The Lancet* today, are therefore timely and profoundly important.

These papers make a strong case for linking climate and health goals. Most of the mitigation measures for climate change investigated (including cleaner household-energy sources, less dependence on automobile transport, and reduced consumption of animal products in developed countries) would bring public health benefits. In many cases, these benefits are substantial, and would help to address some of the largest and fastest growing global health challenges and the greatest drains on health-sector resources, such as acute respiratory infections, cardiovascular

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disease, obesity, cancer, and diabetes. While the climatic effects of mitigation measures are long term and dispersed throughout the world, the health benefits are immediate and local, making them more attractive to politicians and the public.

This research therefore brings a sharper focus to the role of the health community in climate policy. It provides another reason why we should speak out in favour of effective and fair mitigation measures, and brings a strong positive argument for more sustainable and healthier public policies. The papers also illustrate wide variation in the size of the health benefits that can be achieved for any given financial investment or reduction in greenhouse-gas emissions. Failing to prioritise the most health-enhancing mitigation choices would waste an important social opportunity, and give a poorer return on investments.

The issue now is not whether climate change is occurring, but how we can respond most effectively. The first steps are clear. In the short term, strengthening health systems, and widening coverage of proven and cheap public health interventions to control climate-sensitive diseases, would accelerate progress towards the health-related Millennium Development Goals and save millions of lives. In the long term, the same actions would also reduce vulnerability to climate change. Responding to climate change is not a distraction from the business of protecting health: it is part of the same agenda.

As governments convene in Copenhagen on Dec 7–18 (the COP15 conference) to reach an agreement on how to respond to climate change, there are three clear messages from the health community. First, climate change is a fundamental threat to health. Second, strengthening control of diseases of poverty is essential to protect the most vulnerable populations, and is a safe investment for adaptation resources for climate change. Third, as this Series shows, cutting greenhouse-gas emissions can represent a mutually reinforcing opportunity to reduce climate change and to improve public health. Health protection should therefore be one of the criteria by which mitigation measures are judged.

Addressing climate change is not just an issue of international agreements, or economic costs; it is a choice of what kind of world we want to live in. Climate change is a price that we are paying for short-sighted policies. The pursuit of economic wealth took precedence over protection of the planet's ecological health, and over the most vulnerable in society. Fundamentally we are all facing a choice about values: improving lives, protecting the weakest, and fairness. These are the same values that motivate public health, and the health community is a willing partner in addressing this challenge.

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Health professionals must act to tackle climate change

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Climate change already affects human health, creating problems that will increase if no action is taken. The most vulnerable are the world's poorest people, who already face poor health and premature death, and are least responsible for greenhouse-gas emissions.[1–3]

The only heartening aspect of this bleak terrain is the gathering awareness that many of the measures needed to make the necessary reductions in greenhouse-gas emissions are those needed to protect and improve global health. Overall, what is good for tackling climate change is good for health.

The Comments and Articles in *The Lancet* today provide a needed quantitative underpinning for this vitally important and optimistic health message, a message that offers a radically reshaped political space in which climate-change negotiations can take place.

Additionally, a clear implication is that policies needed to mitigate climate change will exert health effects by acting on many of the determinants of health and health inequality.[4] These determinants include the conditions in which people are born, grow, live, work, and age, and the structural drivers of those conditions: inequities in power, money, and resources. Andy Haines and colleagues[5] point out that converging to an equal per-head carbon entitlement (the fair shares framework, as exemplified by contraction and convergence[6]) will ensure that these inequities are addressed head on. They include inequities in access to female education and family planning, which are both key to population stabilisation.

Who better to spell out this message than health professionals? We have the evidence, a good story to tell that dramatically shifts the lens through which climate change is perceived, and we have public trust. Health professionals will be in the forefront of developing and delivering a low-carbon health service, and explaining to patients and populations the health benefits of low-carbon living. We will also have an important role in monitoring the effect of the changes that will have to be put in place. If the world does not adequately address climate change, we will be in the forefront of coping with the catastrophic consequences. But at present our voice is muted, and the health arguments are conspicuously absent from the minds of many of those involved in the negotiations.

UN Photo/Martine Perret

To maximise our influence, we must be much clearer than we have been to the public, to patients, and to politicians about the risks of doing nothing and the benefits to individual and global health of effective action. We should justify this message through personal example, and we should influence the organisations where we work to reduce their emissions. We should be powerful advocates for the fair-shares framework, recognised by many governments to be necessary[7] but proposed without the force of the arguments shown by the papers in today's Series. The discussions in Copenhagen this December are crucial to getting initial agreement to such a framework, but concerted pressure thereafter will be necessary to ensure that the process moves forward quickly. Our advocacy must be directed at those best placed to influence the political process, and based on tried and tested elements: being specific, brief, personal, timely, confident, and factual. Scientific rigour is vital.

Putting the necessary framework in place will take time. However, action on emission reduction and providing resources for low-carbon development must start immediately. A low-carbon development fund of at least US$150 billion is the minimum requirement of the G77 group of developing countries. This sum could be raised from a $5 dollar tax on each of the 20 billion barrels of oil used yearly by the countries of the Organisation for Economic Co-operation and Development, plus a tax on airline tickets.[8]

We must be innovative and imaginative in how we amplify the voice of health practitioners, and disseminate the message, its significance to us all, and its urgency, by using all our extensive networks.

The papers in today's Series give us the opportunity to make a step change in our endeavours. There are already several organisations that collaborate to give to the health arguments the prominence they require (eg, the UK's Climate and Health Council[9]). But to have maximum effect, we need an international equivalent to represent our views, and national equivalents to the UK's Council. The Climate and Health Council is approaching colleagues across the world who have expressed interest in this idea, and inviting doctors to put themselves forward, particularly those from the parts of the world that will suffer the most adverse effects of climate change. Let us collectively make sure that we do not fail present or future generations.

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Aligning climate change and public health policies

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On Dec 7–18, 2009, representatives from 192 countries will meet in Copenhagen to formulate a climate agreement for 2012 onwards. This conference (called COP15) represents the most important opportunity in decades to achieve international agreement on how to cut emissions of greenhouse gases deeply enough to reduce the likelihood of dangerous climate change.[1]

The case for major reductions in greenhouse-gas emissions is well established.[2] The case is based on the recognition of the multiple adverse effects of climate change not only on population health[3,4] but also on the environment (disruption of ecosystems, species loss), social integrity (population displacement, effects on livelihoods), nutrition (altered agricultural productivity), and the economy (regional and local economic shocks).[5,6]

But there are obstacles to a meaningful outcome at the conference, including: reaching agreement on the relative contributions of emerging economies, such as India, China, and Brazil, and industrialised nations; the lobbying activities of companies with vested interests in fossil fuels; and the need for upfront investment in new technologies during an economic recession. Therefore the deliberations must be informed by the best available scientific evidence on the benefits and harms of reducing greenhouse-gas emissions. In this respect health professionals have an important role.

Many policies to reduce greenhouse-gas emissions can also have a range of ancillary effects, including effects on health. Examples include reduced air-pollution, improved energy security, or increased rural employment.[7] Better quantification of the health effects of greenhouse-gas mitigation (reduction) policies will contribute to evidence-based policy making by indicating the magnitude of potential near-term health benefits (and in some cases harms) associated with a given strategy and, we hope, will provide additional motivation for action. A Series starting in *The Lancet* today provides indicative estimates of the magnitude of effects (largely positive) on health in four sectors with large global emissions of greenhouse gases: electricity generation, household energy, urban land transport, and food and agriculture.[8–11] A further article shows how reducing emissions of several short-lived greenhouse gases (and black carbon, which is not a gas but contributes to increased warming[12])—which by contrast with carbon dioxide have relatively short atmospheric lifetimes and direct health effects—could benefit health

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while reducing the rate of climate change in the next few decades.[13] The paper also points out that sulphate aerosols, which have a cooling effect, seem to have adverse health effects. Thus policies to reduce sulphate aerosols, while likely to improve health, will necessitate even greater reductions in greenhouse gases to offset the reduced atmospheric cooling.

The Series is the result of the international collaboration of scientists supported by a consortium of funding bodies coordinated by the Wellcome Trust. The initiative arose from the leadership of the Climate and Health Council, which made a compelling case for independent scientific analysis of the potential health benefits of addressing climate change. The programme focused on quantification of the effects of strategies to reduce greenhouse-gas emissions on public health, because estimates of potential co-benefits to health from such reductions provide a useful guide to policy makers in identifying the most appropriate mix of mitigation policies for different settings, and indicate how they can implement win–win policies that address public health priorities while reducing climate change. Other activities are underway, but on a longer timescale, to update the calculations of the burden of disease arising from climate change.[14]

The public health benefits of mitigation policies have not had sufficient prominence in international negotiations. This Series seeks to address that deficiency and strengthen the case for deep cuts in emissions. Additionally, the Series makes specific contributions to discussion by: illustrating a methodological approach to compare the relative effects on health of different mitigation strategies; showing the extent to which most mitigation choices lead to net health benefit compared with business as usual; and highlighting areas of uncertainty and needs for further research.

Our approach involved modelling exercises relevant to the type of mitigation changes necessary in each of the four sectors in both high-income and low-income settings.[15] We drew heavily on the evidence of Working Group III of the fourth assessment report of the Intergovernmental Panel on Climate Change,[7] and on the first report of the UK's Climate Change Committee,[16] which set necessary mitigation targets, globally and in the UK, and suggested how they might be achieved. The Committee concluded that "global emissions reductions of at least 50% in 2050 [against a baseline of 1990] are required if risks of dangerous climate change are to be kept at acceptable levels…[and that] a UK emissions reduction of 80% is an appropriate contribution to a 50% global cut".[16] We assume that the 80% reduction target by 2050 is also appropriate, although conservative, for most other high-income countries. The contribution of different countries to the achievement of this objective must in some degree reflect the very different current per-head emissions. To achieve international equity,[17] there would need to be convergence on a common annual per-head emission target for greenhouse gases of 2·1–2·6 tonnes of carbon dioxide equivalents. This target is below the year 2000 regional average for all regions of the world except parts of sub-Saharan Africa, and if achieved would result in important welfare benefits to some populations from increased access to energy, transport, and food. According to the Climate Change Committee and other sources,[18] achievement of these targets is feasible with a combination of current technology and technology under development. The cost has been projected to be much less than the cost of dealing with the effects of unrestrained climate change.[6] Even these targets are probably too high in light of recent work showing that climate change is evolving more rapidly than was thought, due to the diminishing capacity of carbon sinks to absorb additional carbon dioxide and several possible feedbacks that increase warming, such as loss of snow and ice cover that reflects heat from the earth's surface.[19]

Mitigation strategies considered in this Series for each sector, therefore, would lead to reductions of greenhouse-gas emissions broadly consistent with a trajectory to meet the 2050 target of 50% reduction in global emissions. For each of the four sectors, the complex connections between mitigation choices and health are described. Pathways for which there is sufficient evidence to quantify the health effects are identified, and we discuss pathways with insufficient evidence. Case studies are used to illustrate the health effects under different emission-reduction scenarios. Because of substantial uncertainties and the hypothetical scenarios, the aim is to be illustrative and analytical rather than to be precise.

The concluding paper in this Series[20] discusses the intersection of policies to mitigate climate change with international development and public health.[21]

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The Copenhagen conference presents an important opportunity to choose those policies that can not only achieve needed reductions in greenhouse gases, but also move toward development and health goals.

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Health and Climate Change 1

Public health benefits of strategies to reduce greenhouse-gas emissions: household energy

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Energy used in dwellings is an important target for actions to avert climate change. Properly designed and implemented, such actions could have major co-benefits for public health. To investigate, we examined the effect of hypothetical strategies to improve energy efficiency in UK housing stock and to introduce 150 million low-emission household cookstoves in India. Methods similar to those of WHO's Comparative Risk Assessment exercise were applied to assess the effect on health that changes in the indoor environment could have. For UK housing, the magnitude and even direction of the changes in health depended on details of the intervention, but interventions were generally beneficial for health. For a strategy of combined fabric, ventilation, fuel switching, and behavioural changes, we estimated 850 fewer disability-adjusted life-years (DALYs), and a saving of 0·6 megatonnes of carbon dioxide (CO_2), per million population in 1 year (on the basis of calculations comparing the health of the 2010 population with and without the specified outcome measures). The cookstove programme in India showed substantial benefits for acute lower respiratory infection in children, chronic obstructive pulmonary disease, and ischaemic heart disease. Calculated on a similar basis to the UK case study, the avoided burden of these outcomes was estimated to be 12 500 fewer DALYs and a saving of 0·1–0·2 megatonnes CO_2-equivalent per million population in 1 year, mostly in short-lived greenhouse pollutants. Household energy interventions have potential for important co-benefits in pursuit of health and climate goals.

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Introduction

Climate change presents a formidable challenge to societies throughout the world.[1–3] Targets to limit the global temperature rise to around 2°C and the risk of dangerous climate change to a low level present a very challenging abatement path, needing a worldwide peak in greenhouse-gas emissions within only a few years and a steep fall that would halve emissions by around 2050.[4] Even this target might be insufficiently ambitious. We employ the widely used term greenhouse gases, although since some anthropogenic climate-active atmospheric species are aerosols, greenhouse pollutants is a more accurate term. Most important of the climate-active aerosols produced by human activities are black carbon, sulphate, and organic carbon particles, which have important although not identical health effects, but quite different climate implications.[5]

Key messages

- Many important health and climate outcomes are related to the products of incomplete combustion that are emitted from traditional solid fuel use in developing countries, even when little carbon dioxide (CO_2) is produced overall.
- Sustained national programmes to promote modern low-emissions stove technology for burning of local biomass fuels in poor countries provide a highly cost-beneficial means to potentially avert millions of premature deaths and hundreds of millions of tonnes of CO_2-equivalent greenhouse pollutants. Such programmes could help countries to achieve Millennium Development Goals and climate targets, and offer one of the strongest climate–health links with respect to co-benefits.
- Improvements in the efficiency of UK household energy use could, if implemented correctly, have appreciable benefits for population health, mainly arising from improved indoor air quality and control of winter indoor temperatures.

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- For UK housing interventions, the magnitude and even direction of effects on health depend on how energy efficiency measures are implemented and maintained. Potential for adverse health outcomes arises from increases in indoor concentrations of pollutants, including radon and environmental tobacco smoke, in dwellings with energy efficiency measures that reduce air exchange; and increased ingress of outdoor particle pollutants with higher air exchange rates in dwellings fitted with mechanical ventilation systems unless there is effective filtering of air.
- Household energy interventions in low-income settings have greater potential to improve public health than do those in high-income countries, but household energy interventions in high-income settings have potential for greenhouse-gas reduction per dwelling and are vital for achievement of climate abatement targets worldwide.

Urgent and profound changes in power generation and energy use in all sectors are therefore necessary, especially in high-income countries, where a halving of emissions is needed by 2030.[4,6] Action to reduce energy use by households and in buildings is especially important because of the scale of their contribution to greenhouse-gas emissions and the opportunities for emissions reduction. Currently, energy use in UK residential buildings is estimated to account for around 140 megatonnes of carbon dioxide (CO_2) emissions,[4,7] or around 26% of the country's total (table 1). Substantial reductions in these emissions are achievable with present technology and through energy efficiency, behavioural change, and low-carbon power generation.[4]

In low-income countries, where per head emissions are low, global principles of equitable burden sharing imply that less contraction in greenhouse-gas emissions is necessary compared with high-income countries, and even, in some cases, an increase to a sustainable per head worldwide average. But even in such settings, efficiency and cleanliness of household energy use can be improved, with both greenhouse-pollutant reductions and direct health benefits from reduced indoor and outdoor air pollution. Improvement of combustion efficiency of solid household fuels (biomass and coal) used by poor populations of developing countries is one of the greatest opportunities for health co-benefits worldwide and was among the first to be recognised.[8] The poorest half of the world's households rely on such fuels, with the highest fraction of households in sub-Saharan Africa, followed by low-income Asia (figure 1).[9,10]

Most of this combustion is done in simple stoves with low combustion efficiency, thus producing large amounts of products of incomplete combustion,[5] with consequences for both climate and health. When biomass is harvested renewably—eg, from standing tree stocks or agricultural wastes (crop residues and animal dung)—no contribution to atmospheric CO_2 is made. Net CO_2 is produced, however, when harvesting of wood fuels leads to deforestation. In detail, such determinations are difficult and depend on local, sometimes changing, conditions. Therefore, we do not assume any CO_2 reductions. Because the products of incomplete combustion include important short-lived greenhouse pollutants, however, even sustainable harvesting does not make such fuel cycles greenhouse neutral.[5]

	Total for all sectors (megatonnes per year)	Housing sector (megatonnes per year)	
		Sector total	Total (adjusted)*
1990†	593	156	154
2010†	542	142	140
2030‡	297	78	77

*Emissions exclude non-aerosol consumer products as per National Atmospheric Emissions Inventory.[7] †Data for 1990 and 2010 total emissions are from reference 7. 2010 emissions assumed to be the same as 2007 emissions. ‡2030 emissions are estimates based on 50% reduction for all sectors from 1990.

Table 1: **UK total and housing sector carbon dioxide emissions in 1990, 2010, and 2030**

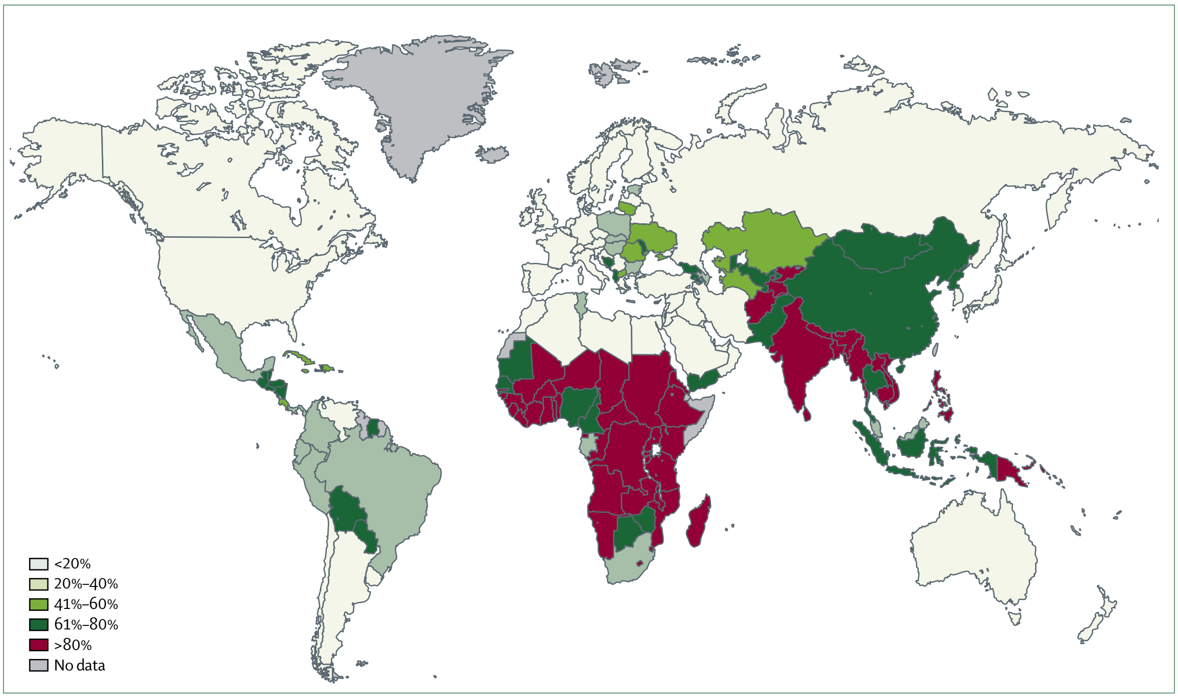

Figure 1: **National use of solid fuels for cooking in 2000**
Solid fuel is mostly in the form of biomass (wood and agricultural residues), even in China, where many households use coal. Data are from reference 10.

Case studies

We considered case studies in two countries—the UK and India—as examples of high and low per head CO_2 emissions. The International Energy Annual[11] shows that, in 2006, emissions of CO_2 from the consumption and flaring of fossil fuels were 9·66 metric tonnes per head in the UK and 1·16 tonnes per head in India. These figures rank the UK 49th highest worldwide in terms of per head emissions of 206 countries with 2006 emissions data (15th highest of 35 European countries), and India as 137th highest (25th of 42 countries in Asia, Australasia, and Pacific Islands). For each country we chose household-energy efficiency interventions of the types that are most relevant to policy needs and have a bearing on health.

For the UK, we specified interventions to improve the energy efficiency of heating of the housing stock through changes to the dwelling fabric (ie, to the thermal properties of the materials of the walls, windows, floor, and roof), ventilation control, fuel use, and occupant behaviour. At present, space heating is estimated to account for 53% of household CO_2 emissions (74 megatonnes of CO_2).[12] Panel 1 details the five specific scenarios. These scenarios explore interventions based on present technology of the type and scale needed to meet 2030 abatement targets, as described by the UK Climate Change Committee.[4] The interventions can be viewed as examples of actions that will need to be implemented in many other industrialised countries. The costs associated with these interventions are described in the webappendix p 28, but because of the complexity we did not attempt to quantify costs in detail. The broad range is a one-off cost of US$5000–50 000 per dwelling, offset by reduced yearly fuel bills of around $500 per year at estimated 2010 prices.

For India, we specified a 10-year programme to introduce 150 million low-emissions household cookstoves. This scenario was chosen because of the major public health burden that is associated with indoor air pollution from inefficient burning of biomass fuels in India and in many other low-income countries. It is also consistent with proposals that are being considered in India. The cost would be less than $50 every 5 years, perhaps paid partly through government subsidy and partly by the households because of fuel cost savings and time savings in harvesting of fuel.

The scenario used here draws lessons from the previous Indian national stove programme, the National Programme for Improved Chullhas,[13] which, like the major national programme in China,[14] was initiated in the early 1980s and focused mainly on increasing fuel efficiency to assist with rural welfare and, to a lesser extent, protect forests. Secondary emphasis was on reduction of smoke exposure through use of chimneys, and there was no consideration of outdoor pollution or climate. However, there have been major changes in our understanding about the value of and technology for emissions reductions and in world conditions that have modified the landscape for improved biomass stove programmes.

The changes in health related to traditional fuel use patterns are much better established than they were previously, with hundreds of reports documenting the associated health outcomes. An estimated 400 000 premature deaths per year in India are caused by biomass-fuel use in households.[9] The international price of liquified petroleum gas, which is the major alternative clean household fuel, will probably continue to increase faster than will rural incomes, making the transition to modern fuels difficult and, if subsidised by government,

Panel 1: **Exposures and associated changes in health included in models of mitigation measures applied to UK housing stock**

Baseline (2010)

Distributions of efficiency for UK housing stock (ie, fabric, ventilation) and associated greenhouse-gas emissions and health effects.

Scenario 1: fabric improvements

Overall heat loss of the fabric is reduced (from 224 J/s per °C to 98 J/s per °C) because of increased insulation, reducing exposure to wintertime cold.

Scenario 2: improved ventilation control

Air tightness and ventilation systems are improved. The present permeability of the housing stock is shifted to represent reduced air leakage in all dwellings. Those dwellings in the tightest band (3 m^3/m^2 per h), in addition to the shift, have (idealised) mechanical ventilation and heat recovery systems installed.

Scenario 3: fuel switching

All indoor household fossil fuel (eg, gas, coal, oil) combustion sources are removed and switched to electricity without change to ventilation characteristics. The effects on health are modelled, but those on carbon dioxide (CO_2) emissions are not. Currently, such a shift would increase CO_2 emissions because of the CO_2 content of electricity, but this is projected to decrease rapidly to 2030 and beyond. We make the assumption that the opportunity is taken during refurbishment to fit high capture efficiency hoods to all cookstoves.

Scenario 4: occupant behaviour

Dwellings with internal average temperatures greater than 18°C are reduced by 1°C by occupants to an upper limit of 18°C. Temperatures less than 18°C are unchanged.

Scenario 5: combination of scenarios 1–4

Fabric insulation is increased along with an overall improvement in ventilation and air tightness (ie, scenarios 1 and 2) and the internal average temperature is reduced by 1°C (scenario 4). The change in CO_2 emissions due to the switch to electricity (scenario 3) as the primary fuel source is not included (because the effect will depend on the mode of the additional electricity generation), although the health implications are.

See Online for webappendix

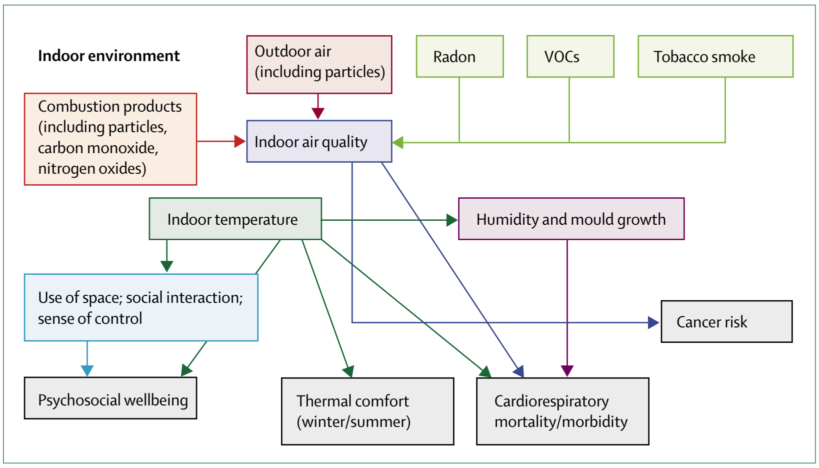

Figure 2: **Connections between the built indoor environment and health**
VOCs=volatile organic compounds.

increasingly expensive for national budgets. This situation adds to the attraction of deployment of advanced biomass stoves that provide high performance, use local renewable resources, and relieve the government of the cost of fuel subsidies. Climate change is a major threat and household fuel combustion is an important contributor, especially to black carbon, with high greenhouse effects per unit energy delivered compared with many other human uses of energy, depending on the relative weighting of the climate-active pollutants emitted (webappendix p 10).

In view of the combined goals of energy security, health protection, and minimisation of changes in climate, the best approach is to move toward advanced combustion devices with high combustion efficiency and low emissions, such as so-called gasifier stoves. Even well operated chimney stoves do not provide these benefits. To achieve reliable high performance, stoves should use either ceramics or customised metal alloys, neither of which can be effectively manufactured at village level, but have to be made in central manufacturing facilities with good quality control and other modern mass-production techniques. Truly improved stoves tend to have a narrow tolerance to fuel size and moisture and thus generally need increased fuel processing in households or, for high performance, preprocessing as pellets or briquettes. Hybrid gasifier stoves (with small electric blowers), however, effectively maintain good performance for a wide range of fuel characteristics. Microchip and personal computer developments offer cost-effective ways to monitor and assess programmes covering millions of households.

Close to two-thirds of rural Indian households now have access to electricity for at least part of the day—which is a substantial change since the 1980s. This development makes use of advanced blower stoves that are feasible in much of the country. The Rajiv Gandhi Scheme[15] to electrify all households should bring this benefit to an even greater proportion in coming years. Widespread access to radio, television, and cell phones and growing access to the internet provide new ways to market, monitor, and otherwise facilitate stove sales and dissemination. Improvements in health infrastructure in rural India could be used for dissemination of stoves, including the growth of the Anganwadi Centres Programme,[16] a network of prenatal care clinics, which by the middle of the decade was already helping to provide 77% of all pregnant women with check-ups, education, and drugs.[17]

Advanced biomass stoves sold in India today achieve some 15 times fewer particle emissions per meal than do traditional stoves,[18] thereby promising substantial reductions in air pollution exposure and health-related burdens. Prices are \$20–50, and more than half a million have been sold so far. Although no major studies have been done directly investigating the effect of such stoves on health, since they produce little smoke they arguably achieve better exposure reduction than do chimney stoves that merely divert the smoke a short distance, and could rival benefits seen with clean fuels.[19,20]

Panel 2: Core assumptions of UK model

Baseline
- 2010, with population and health status based on WHO projections (Comparative Risk Assessment exercise); building stock, external air pollution, and weather conditions as they are at present.

Mitigation scenarios*
- No projection: instantaneous implementation assumed, as though present conditions are fully replaced with 2010 scenario conditions.
- Based on existing technology (no assumption of new or improved technology).

Health estimates
- Derived from attributable burdens calculated with adaptation of Comparative Risk Assessment method—assumes changes in health for each scenario are represented by the difference in modelled exposures compared with baseline, from which attributable burdens are computed with relevant relative risks and 2010 mortality and disease rates. Changes in burdens of chronic disease and lung cancer are counted, irrespective of probable time lags.
- Years of life lost computed as difference between age at death and the theoretical optimum life expectancy at that age, which, to be normative across populations, is always calculated with reference to life tables representing the best in the world.[45]
- No time discounting or age-weighting applied in disease burdens.
- No inclusion of indirect health effects (eg, those operating through economic pathways) or of those arising from success in restricting climate change.

*Panel 1 shows descriptions of specific scenarios.

	Health effects	Relative risk used	Principal sources of evidence and comments
Particle pollutants*†	Cardiopulmonary mortality; lung cancer	1·059 per 10 μg/m³; 1·082 per 10 μg/m³	US cohort, outdoor air[46,47]
Radon	Lung cancer	1·16 per 100 Bq/m³ increase in usual radon concentrations	Collaborative analysis of data from European case control studies of radon in homes[29]
Carbon monoxide exceedance	Death from acute carbon monoxide toxicity	Rate of one death per million people assumed for dwellings with combustion appliances	Health Protection Agency data for acute carbon monoxide poisoning[48]
Second-hand tobacco smoke	Myocardial infarction; cerebrovascular accident	1·30 if in same dwelling as smoker; 1·25 if in same dwelling as smoker	Meta-analyses[49,50,51]
Mould growth	Respiratory symptoms	1·50	US Institute of Medicine report and meta-analysis on dampness/mould[32,33]
Cold‡	Cardiovascular mortality	–2·0% reduction in excess winter death per °C increase in standardised winter indoor temperature	Epidemiological analyses of cold-related mortality risk in relation to indoor cold in England[52]

*Particulate matter with aerodynamic diameter 2·5 μm or less. †Effects of exposure to nitrogen dioxide (respiratory symptoms at high concentrations) and volatile organic compounds (possible allergic or respiratory symptoms especially in children) were not quantified because the evidence was considered too uncertain.[53] ‡Standardised indoor winter temperature at 5°C outdoor temperature.

Table 2: **Exposures and health effects included in models**

Our analysis does not assume health benefits greater than those suggested by meta-analyses of previous studies reported as part of the WHO Comparative Risk Assessment comparing traditional use against a mixture of less advanced improvements and clean fuels.[21] Since the high reductions that advanced stoves are capable of producing could well be lessened in the field, where fuel and operator variability are high, extrapolation beyond present evidence is unwise.

The decade-long 150-million stove programme is certainly ambitious, but actually at the same rate and less in total than the 180 million stoves achieved in the Chinese national programme in 12 years[14] starting in 1983 with a national population then similar to that of India today. Additionally, India would have 25 years more experience to work from. The new programme should implement a range of different dissemination modes, including those aimed at the most vulnerable populations. An attractive mode would be to include dissemination as part of pre-natal examinations within the prenatal clinic system. In addition to targeting of the most vulnerable group, pregnant women and their unborn children, these women are already being identified and contacted. If targeted only at first pregnancies, this strategy would cover 7–8 million households a year, about half the requirement. The remainder could be introduced through targeted subsidies to other population groups, perhaps linked to the electrification programme, since in general these advanced stoves are too expensive for poor households to pay the full cost, even though they receive the direct benefits of fuel savings. Similar to what has happened in other countries, the international carbon market, either through the official Clean Development Mechanism[22] or the voluntary Gold Standard system,[23] can help to offset part of the cost.

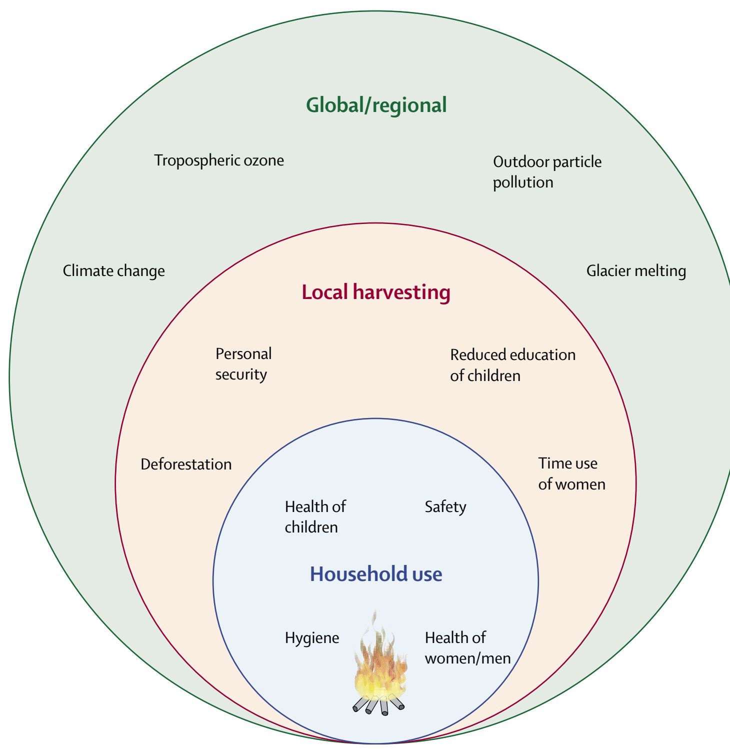

Figure 3: **Effects of traditional household fuel use**

This figure illustrates the wider effects of traditional household biomass fuel use. Here, however, we quantify only the direct effects on health and global climate.

Modelling changes in health

We began by mapping the complex connections between energy production and use as it relates to the built environment (webappendix p 2).[24] We concentrated on the part of this scheme that relates to the indoor environment (figure 2). The changes in health relating to energy supply systems for commercial energy are partly addressed in a separate report about electricity generation[25] and are not considered here. Nor did we include the role of household fuel combustion on outdoor air pollution, or the health benefits operating through climate-change mitigation, despite their evident importance.[26,27] Because of uncertainties we also did not directly address pathways relating to fuel cost, household

	Fabric improvements	Improved ventilation control	Fuel switching	Occupant behaviour	Combined
Premature deaths					
$PM_{2·5}$	0	–32	–64	0	–107
Radon	0	3	0	0	3
CO	0	0	–1	0	–1
ETS	0	24	0	0	24
Mould	0	0	0	0	0
Cold	–7	–1	0	0	–8
DALYs					
$PM_{2·5}$	0	–310	–619	0	–1026
Radon	0	43	0	0	43
CO	0	0	–25	0	–25
ETS	0	219	0	0	219
Mould	–2	12	0	5	15
Cold	–60	–12	0	0	–72
Totals					
Premature deaths	–7	–6	–65	0	–89
DALYs	–62	–48	–644	5	–847
Change in disease burdens per megatonne CO_2 saved					
Premature deaths	–12·2	–64	··	0·0	–133
DALYs	–115	–492	··	17·3	–1267

Data are change per million population compared with baseline (2010). Negative values show reductions in disease burdens. $PM_{2·5}$=particulate matter with aerodynamic diameter 2·5 μm or less. CO=carbon monoxide. ETS=environmental tobacco smoke. DALYs=disability-adjusted life-years. CO_2=carbon dioxide.

Table 3: **Health effects of the UK built stock scenarios**

budgets, and energy security, although these again might have important health implications in both developed and developing countries. We therefore defined a small range of pathways for quantitative modelling, the most important of which relates to combustion sources and ventilation characteristics, which have bearing on the concentration of pollutants[28] such as radon,[29,30] second-hand tobacco smoke,[31] and dampness and mould,[32–38] especially in low-income households.[24,39–44]

Quantitative modelling of changes in health burden for the case studies is described in the webappendix pp 3–10. The basis of the calculations differed between the two settings. For UK household energy scenarios, estimated changes in health were calculated from the difference between 2010 (present) exposures and those that would occur under mitigation, assuming that circumstances are otherwise held constant at 2010 conditions. Panel 2 summarises our core assumptions and table 2 details exposures and health effects included in the models. We assume an instantaneous implementation of the proposed mitigation measures, with no other change. This approach avoids the need for uncertain projections, and the effect of mitigation measures is clear because these are the only changes. We chose this approach in part because a substantial degree of improvements in household energy efficiency will probably be implemented with time anyway, so specification of a future counterfactual baseline is difficult. The disadvantage, however, is that this approach does not take account of potentially important trends in exposure that are unrelated to climate change mitigation policies, and it does not show a timecourse of implementation.

For the India case study, we were able to specify a 10-year staged implementation plan and adapt methods accordingly. Many health-related effects have been associated with inefficient household use of simple biomass fuel, not only within the household but also in the local community and worldwide (figure 3). In this analysis, however, we quantify the effects of improvements in terms of indoor air pollution alone (mainly health of women and children). As in the UK study, the baseline was 2010, but cumulative health effects of the 10-year staged implementation were calculated on the basis of WHO projections of baseline health status for 2020, in addition to projections for population and the slow natural transition to clean fuels, to improve estimates of underlying mortality and morbidity rates for intervening years. For more direct comparison with UK results, we also computed the beneficial effect of the cookstove programme using the same methods as for the UK study (as if fully implemented under 2010 conditions).

Outcomes

UK household energy efficiency programme

All UK energy efficiency scenarios, with important caveats, result in an overall benefit to health, but with some negative effects relating to specific forms of exposure (table 3). For the fabric improvement scenario (scenario 1) we assumed that fabric improvements did not change ventilation characteristics and that the effect on health was confined to temperature effects arising from reduced heat loss. The changes in health consisted of both direct effects on winter mortality and potentially morbidity[52,54–59] and indirect effects via changes in mould growth.[60] The modelled improvements were limited to technically plausible increases in insulation, entailing a shift in the dwelling stock distribution of thermal efficiencies.

Ventilation-system improvements (scenario 2), through changes in air exchange, had effects on indoor air quality and temperature. The most notable change was reduction of particle concentrations. Our specification for this scenario was to install mechanical ventilation systems in the most airtight 21% of dwellings (ie, those with permeability reduced to 3 m^3/m^2 per h), since this system provides potentially the most effective control of ventilation and recovery of heat (webappendix p 27). All other dwellings were assumed not to have mechanical ventilation systems, but to have improvements in air tightness only. Dwellings with mechanical ventilation benefit from high air exchange rates, and so exposures for pollutants from internal sources (tobacco smoke, etc)

	Baseline (2010)	Change compared with baseline				
		Fabric improvements (scenario 1)	Improved ventilation control (scenario 2)	Fuel switching (scenario 3)*	Occupant behaviour (scenario 4)	Combined (scenario 5)
Pollutant concentrations†						
$PM_{2.5}$ (μg/m³)‡	5·5	0·0	–0·9	–1·8	0·0	–3·0
NO_2 (% of hourly averages exceeding 400 ppb)§	0%	0%	0%	0%	0%	0%
CO (probability of poisoning)	10^{-6}	0	0	-10^{-6}	0	-10^{-6}
Radon (Bq/m³)¶	21·7	0·0	4·5	0·0	0·0	4·5
ETS (ratio of exposure compared with baseline)¶	1·0	0·0	0·1	0·0	0·0	0·1
Dampness or humidity-related						
Mould growth (% with mould index >1)	17·7%	–0·4%	2·6%	0·0%	1·0%	3·1%
Temperature						
Winter indoor temperature (cold) (°C)‖	18·1	0·3	0·1	0·0	–0·2	–0·4
Greenhouse-gas emissions**						
Reduction in CO_2 emissions versus 2010 baseline (megatonnes)††	··	33	6	0	2	41
Reduction in CO_2 versus 1990 (megatonnes)‡‡	14	47	20	14	16	55

$PM_{2.5}$=particulate matter with aerodynamic diameter 2·5 μm or less. NO_2=nitrogen dioxide. ppb=parts per billion. CO=carbon monoxide. ETS=environmental tobacco smoke. CO_2=carbon dioxide. *Scenario assumes removal of all cooking-related $PM_{2.5}$ (via removal of combustion sources and addition of high capture efficiency cookstove hoods). †Values are for indoor air, but for calculation of attributable disease burdens, we assume change in exposure applies to 85% of the time-activity of all individuals; exposure for the remaining time (ie, spent outdoors and in other buildings) is assumed to remain unchanged. ‡Weighted average values of kitchen (10%), lounge (45%), and bedroom (45%). §Data for kitchen only. ¶Data for living room only. ‖For winter indoor temperature, scenario 5 combines scenarios 1 and 2, excluding 4. **Emissions relate to CO_2 only; CO_2 equivalents are around 5% higher, but have not been separately quantified for these scenarios; energy needed to implement the retro-fit is not taken into account—only the change in operating energy use; we assume a stock average heating system efficiency of 0·75. ††We assume no change to CO_2 emissions from fuel switching because the contribution could be negative or positive dependent on form of electricity generation. ‡‡CO_2 saved between 1990 and 2010 is added to the figures for 2010 baseline to show total saving compared with 1990 level.

Table 4: **Changes in exposure† and carbon dioxide emissions in the UK built stock scenarios**

were reduced. However, dependent on external conditions, the high rate of air exchange might draw increased particle pollution into the dwelling from outside. Fortunately, air filters are readily available for mechanical ventilation systems, and in our models, for illustrative purposes, we assumed 80% effective reduction of particle influx.

In dwellings without mechanical ventilation but with increased air tightness, particle concentrations also fell because of reduced ingress from outdoor air. The assumed national average background external concentration of particulate matter with aerodynamic diameter 2·5 μm or less ($PM_{2.5}$) is 13 μg/m³ (informed by DEFRA).[61] The average baseline indoor concentration might thus seem low compared with measured data reported elsewhere (eg, Lai and colleagues[62]). The indoor/outdoor ratio is also crucially dependent on assumptions related to kitchen window opening, internal door opening, and extract fan use, for example. Additionally, the emission rate for $PM_{2.5}$ does not include any contribution from indoor activities such as smoking and (because of an absence of suitable data) cleaning and general resuspension.

The balance of ventilation change in this scenario is such that other pollutants from indoor sources (or under-house sources in the case of radon; webappendix p 27) increased. Thus, the radon-associated burden of deaths caused by lung cancer increased by around three premature deaths per million of the UK population, and those from environmental tobacco smoke by around 24 deaths per million (table 3). Although radon concentrations higher than the UK action concentration of 200 Bq/m³ can be dealt with by remediation measures, this process would need a very large number of dwellings to be monitored for increases in radon since our scenarios imply upgrades to the entire housing stock. Moreover,

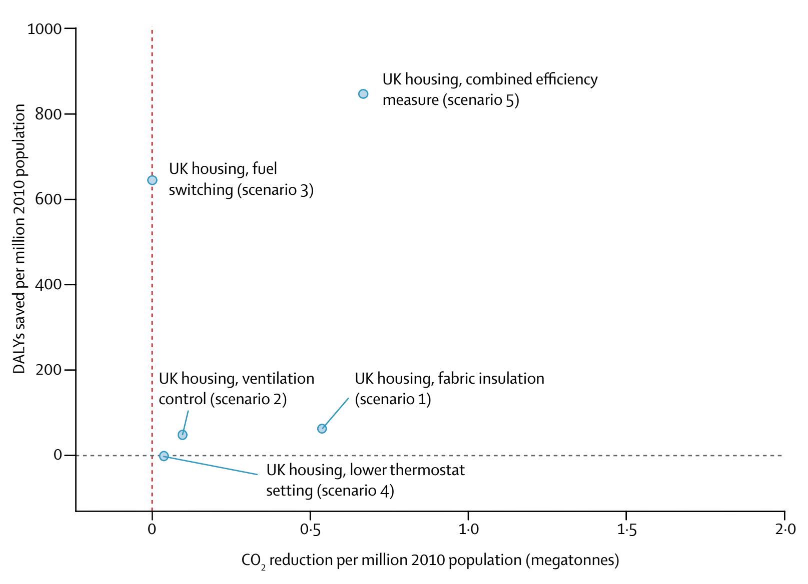

Figure 4: **Estimated effect of the UK household energy scenarios on disability-adjusted life-years saved and reduction of carbon dioxide emissions**

Calculations included the entire UK population in 2010. DALYs=disability-adjusted life-years. CO_2=carbon dioxide.

	Indian population (millions)	Average number of people per household	Baseline				Stove intervention programme			
			Number of households (millions)	Number of households with traditional stoves (millions)	Fraction of traditional stoves	Population using traditional stoves (millions)	Improved stoves distributed (millions)	Number of households with traditional stoves (millions)	Fraction of traditional stoves	Population using traditional stoves (millions)
2010	1214*	4·8	252	187·1	0·74	898·1	15	172·1	0·68	826·1
2011	1228	4·8	258	187·5	0·73	890·9	15	157·5	0·61	748·3
2012	1242	4·7	264	187·8	0·71	883·6	15	142·8	0·54	671·9
2013	1256	4·7	270	188·1	0·70	876·3	15	128·1	0·48	596·8
2014	1270	4·6	276	188·4	0·68	868·9	15	113·4	0·41	523·1
2015	1285	4·6	281	188·7	0·67	861·5	15	98·7	0·35	450·7
2016	1299	4·5	287	189·0	0·66	854·0	15	84·0	0·29	379·5
2017	1313	4·5	293	189·2	0·64	846·6	15	69·2	0·24	309·7
2018	1327	4·4	300	189·4	0·63	839·0	15	54·4	0·18	241·1
2019	1341	4·4	306	189·6	0·62	831·5	15	39·6	0·13	173·7

Percentage of households naturally converting to clean fuels (without stoves) because of economic growth are from reference 9. *Population data from WHO and National Family Health Survey (reference 17).

Table 5: **Population, number of households, and proportion of households with and without improved stoves at every year of the India cookstove intervention**

much of the adverse effect would still occur because of the large number of dwellings with increases in radon to values less than 200 Bq/m³.

Overall, in our particular scenarios, these detrimental changes were more than offset by the reduction in particle exposures, but the balance of risks and benefits varies between dwellings. One area of particular uncertainty and concern, however, is what could occur if mechanical ventilation systems were not properly installed, operated, or maintained or if they broke down. In these circumstances, affected dwellings might have very low air exchange rates, with probable substantial detrimental effects on indoor air quality. In the UK there is as yet insufficient large-scale experience with such systems in households to know how they are likely to operate in real life in the long term.

We assumed that switching to electricity (scenario 3) removes all indoor sources of combustion-related pollutants and cooking-related $PM_{2·5}$. We assumed no change in ventilation characteristics, although in reality a change could occur in some dwellings because of removal of open flues and chimneys, and we assumed that the opportunity was taken to fit high capture efficiency hoods to cookstoves. The reduced health burden came from lowered exposure to fine particles, and the small but important reduction in risk of poisoning from carbon monoxide. With no indoor combustion, there is no indoor source of carbon monoxide (tables 3 and 4). Because we did not model health effects operating through unaffordable fuel costs that cause poverty, we showed no other adverse effects. However, under present conditions, electricity generated from renewable sources is appreciably more expensive than is generation of coal or gas in the UK, although this difference will diminish as fossil-fuel costs increase. This cost is likely to have a disproportionate burden on low-income families, increasing levels of fuel poverty,[4] unless fuel switching is combined with other measures to reduce energy needs or with financial protection for poor households.

The results of the occupant behaviour scenario (scenario 4) were the most difficult to interpret, not only because of the scarce and uncertain evidence about temperature thresholds for cold effects, but also because of the uncertainty about whether and how people are likely to comply. We made the simple assumption of a resetting of thermostat temperatures in winter to result in average temperatures 1°C lower than present values in dwellings with temperatures above 18°C. We therefore made the uncertain assumption that, because the change occurred only in the warmest homes, there was no adverse effect on temperature-related mortality or morbidity. In reality, this situation would be difficult to specify, and personal choices are complex. Much variation is therefore likely—evidence suggests that indoor temperatures in UK dwellings have risen substantially since 1970, along with energy use per person, whereas energy use per unit of disposable income has fallen.[12]

The combined scenario (scenario 5) would achieve the largest benefit to health. Reductions in dwelling CO_2 emissions associated with the scenarios are substantial (table 4). Emissions in the combined scenario compared with the 2010 baseline are reduced by 0·6 megatonnes of CO_2 per million population per year. If reductions in this scenario are added to the reduction already achieved since 1990,[7] CO_2 emissions from dwellings are reduced by 36% compared with the 1990 baseline. This decrease is still short of the 50% target, but we made no allowance for a change to a lower carbon intensive energy supply, and made no specification of changes in device efficiency, including electrical equipment, and space-heating and water-heating devices.

The greatest gain in health from the individual scenarios (ie, excluding the combined scenario) was fuel switching, mainly because of reductions in particle exposure (figure 4). However, in terms of avoided disability-adjusted life-years (DALYs) per tonne of CO_2 saved the greatest gains occur in the ventilation improvement scenario (table 3). The results suggest that there are appreciable benefits of measures to improve the energy efficiency of dwellings through improvement to the fabric and ventilation, but some of the apparent benefit relates to ventilation system changes and air filtering of mechanical ventilation systems. These benefits could be substantially reduced if systems are not well fitted, operated, and maintained. Details of sensitivity analyses of changes in exposure under different assumptions of ventilation and external $PM_{2·5}$ concentrations are provided in the webappendix p 26.

Cookstove programme for India

Table 5 shows the numbers of improved cookstoves implemented in every year of the India cookstove programme, and figure 5 the premature mortality that could be prevented—ie, the avoidable burden for every outcome. At the end of the period, 87% of Indian households would have clean combustion, either through graduating on their own to clean fuels or receiving advanced biomass stoves as part of the intervention. By 2020, the total number of averted premature deaths from acute lower respiratory infections will have reached about 240 000 children aged younger than 5 years, and more than 1·8 million premature adult deaths from ischaemic heart disease and chronic obstructive pulmonary disease (COPD) will have been averted (table 6).

Figure 6 shows the total number of DALYs averted from the three diseases and the contribution of each to the total. Overall, the national burden of disease (DALYs) in 2020 from these three major diseases would be about a sixth lower than it would have been without the stove programme—which is equivalent to elimination of nearly half the entire cancer burden in India in 2020.[63] About half the total health benefit is in the form of averted COPD, with ischaemic heart disease and acute lower respiratory infections sharing the other half more-or-less equally. In reality, the health benefit for acute lower respiratory infections in children accrues almost immediately on introduction of stoves. The benefit for ischaemic heart disease, however, occurs more slowly, and for COPD slower still. Thus, by 2020, the benefits for these diseases have not yet been fully realised and the figures should be interpreted as the committed avoided ill health—ie, the total avoided ill health that would eventually be realised from operation of the improved stoves between 2010 and 2020.

The climate benefits of such a major shift in household combustion are also substantial. There would be decadal

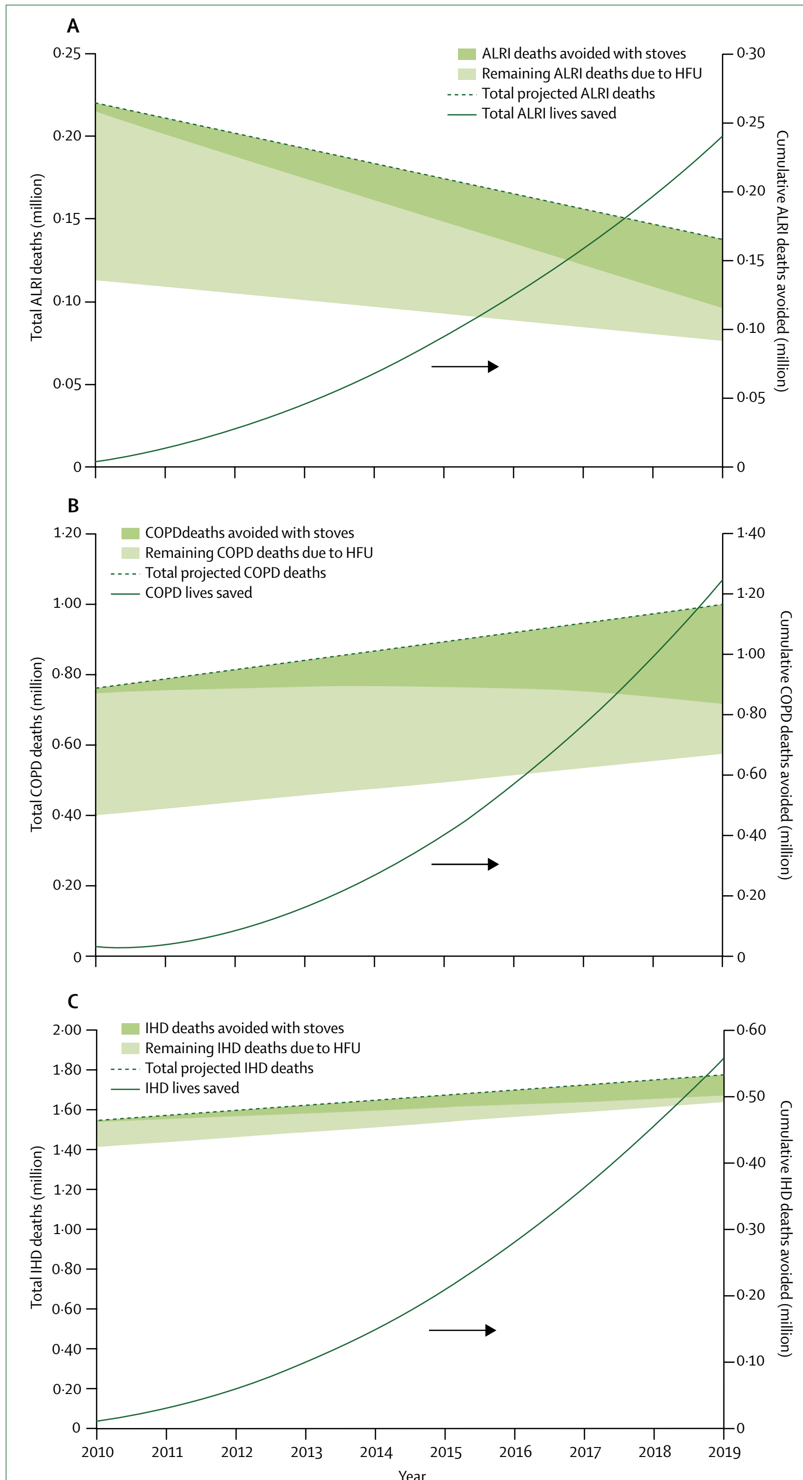

Figure 5: **Premature deaths avoided by large-scale introduction of low-emissions stoves in India**
(A) Deaths from acute lower respiratory infections (ALRI) in children aged younger than 5 years; (B) chronic obstructive pulmonary disease (COPD) in adults aged older than 30 years; and (C) ischaemic heart disease (IHD) in adults aged older than 30 years. HFU=household fuel use. Dotted lines show estimated mortality trends without intervention (from WHO estimates). Solid areas beneath dotted lines show mortality avoided by the stove programme, and dotted areas show total mortality from traditional solid fuel use without improved stoves. Right axes plot cumulative total premature deaths avoided by improved stoves.

	Deaths from ALRI	Deaths from COPD	Deaths from IHD	Total DALYs for these diseases
Avoided in 2020 (%)	30·2%	28·2%	5·8%	17·4%
Annual number in 2020 without stoves (×10⁶)	0·14	1·00	1·77	63·0
Total avoided 2010–20 (×10⁶)	0·24	1·27	0·56	55·5

ALRI=acute lower respiratory infections. COPD=chronic obstructive pulmonary disease. IHD=ischaemic heart disease. DALY=disability-adjusted life-year.

Table 6: **Health benefits of the Indian stove programme**

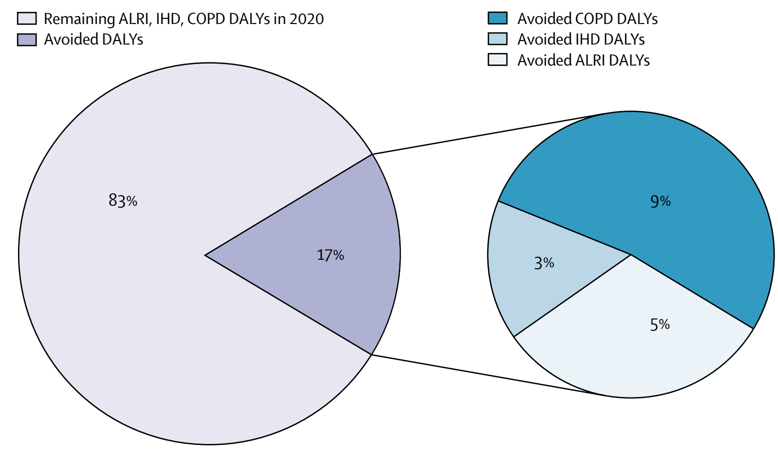

***Figure 6:* Health benefits of Indian stove programme after completion in 2020**
Estimated disability-adjusted life-years (DALYs) from acute lower respiratory infection (ARLI), chronic obstructive pulmonary disease (COPD), and ischaemic heart disease (IHD) that could be avoided in India in 2020, compared with total DALYs for these diseases.

reduction of about 14 megatonnes of methane and 0·5 megatonnes of black carbon, each representing substantial reduction in direct global warming. Additionally, there would be a reduction of nearly 100 megatonnes carbon monoxide and 40 megatonnes non-methane volatile organic compound emissions, which would otherwise contribute to ozone formation. Ozone is not only a greenhouse gas but is also damaging to health and ecosystems. Dependent on metrics applied, these emissions reductions (of methane, black carbon, carbon monoxide, and non-methane volatile organic compounds) could be equivalent to 0·5–1·0 billion tonnes CO_2 equivalent during the decade (webappendix p 10). Finally, the reduction in overall particle emissions, although partly countering the global climate benefits of reduction of black carbon (because of the cooling effects of some types of particles), would have substantial benefits for lessening of regional outdoor air pollution, climate disruption, and the solar dimming that adversely affects agriculture in south Asia.[64]

The benefit of the cookstove programme, if assessed on the same basis as for UK housing scenarios (2010 population with and without mitigation), would give rise to a saving of around 12 500 DALYs and 0·1–0·2 megatonnes CO_2 equivalent per million population in 1 year, compared with 847 DALYs and 0·6 megatonnes CO_2 per million population in 1 year for the UK combined scenario.

Discussion

The modelling we have presented should be interpreted as illustrative of the scale of health benefits that are associated with selected strategies aimed at abatement of emissions of greenhouse pollutants. The broad conclusion is clear—that in both high-income and low-income settings there is a set of abatement actions with appreciable potential overall benefits to health. In the contrasting examples we investigated, the health benefits seem especially great for the populations of India that rely on inefficient combustion of biomass fuels for household energy. Evidence from many studies shows that women, children, and men in such settings are exposed to very high concentrations of particles, gases, and other noxious pollutants that are often at least an order of magnitude higher than the health-protection values set by national and international agencies. Further, these populations might be especially vulnerable to the health consequences of breathing such pollution because of poor nutrition, poor access to health care, and other risk factors.

We should note that the models we developed are somewhat artificial constructs that, necessarily, do not provide accurate real-life representations of population health or, in the UK example at least, the timecourse during which the proposed changes might take place. The programmes that have been implemented in the UK, such as Warm Front, although probably beneficial for health,[65] are much more restricted in the type of energy efficiency upgrading than is implied by our scenarios, and are much more restricted in coverage of the built stock. Our scenarios are therefore very ambitious, but technically feasible, and are necessary to achieve the abatement goals set out by the UK Climate Change Committee. They will also need much political will and public motivation to bring about.

Our models assume that exposure-related changes in health took place without lag, and that attributable burdens equate to preventable burdens—which are both oversimplified assumptions. In reality, the world is not static but is full of rapid change in its population, health status, pollution levels, technology, and socioeconomic development, and although these and other trends can in theory be accounted for, there is substantial complexity in attempting to do so.

We were also restricted to modelling only a subset of possible pathways to health. Notable omissions are those relating to economic effects both at a macroeconomic level and in terms of household budgets, as well as those of climate change itself. For example, improvements in efficiency and cleanliness of household fuel in poor countries are highly cost-beneficial, a major contribution of which is the time saved for women.[66,67]

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The interpretation of findings assumes causality and reversibility of exposure–response links and accuracy in estimation or modelling of changes in exposures, all of which entail uncertainties. Furthermore, several of our simplifying assumptions probably lead to overestimation of the health benefits of abatement interventions; for example, by failing to account for falling outdoor particle pollution or trends of improving health status and by assuming immediate and complete reversal of exposures—even leaving aside how long implementation of the abatement changes we specified would take in reality. Conversely, for the India example, we have used a conservative assumption for particulate reductions with ischaemic heart disease and did not include several health outcomes with potentially large population effects (eg, low birthweight) for which evidence was not sufficiently robust at the time of the 2004 Comparative Risk Assessment, but additional evidence has accrued since.

The limitations of our models are important, but should not deflect from the main message. Overall, they provide important comparative evidence of the possible type and scale of local environmental health effects that can be expected from pursuit of mitigation policies. The evidence adds to the case for acceleration of mitigation because of the probable health benefits, and shows the differences in interventions in high-income and low-income settings. Housing interventions in the UK have a greater effect on reduction of CO_2 per dwelling than they do in the India case study, and are essential for that reason alone. However, the potential health benefits, although generally positive and significant, are small by comparison with those of improved cookstove technology in India, showing the large burden that is associated with inefficient burning of solid fuels. Our results are consistent with the findings of the most authoritative health risk assessment of this hazard, which suggested that in 2000, around 950 000 children worldwide died each year from acute lower respiratory infections, along with about 650 000 premature deaths of women from COPD and lung cancer (in coal-using populations).[9,68] At 2·7% of the total global burden of disease, these factors place household air pollution second after poor water and sanitation among environmental causes of ill health. In poor countries, household air pollution ranks even higher, and causes in India, for example, about 4% of all lost healthy life-years.

Replacement of inefficient cookstove technology will be a very important public health measure. Although improved stove programmes in the past have not always been successful, some have achieved remarkable penetration. The historical model used here, the Chinese national improved stove programme during the 1980s and 1990s, was able to provide stoves to 180 million rural households.[14,69,70] Typical of such programmes in the past century, however, the technology was able to lower indoor pollution somewhat through chimneys, but did not substantially reduce overall air pollution and greenhouse-gas emissions. Nowadays, however, new stove technologies have the potential to bring emission of products of incomplete combustion from biomass stoves down nearly to those of clean fuels, such as liquefied petroleum gas.

Worldwide, household-fuel combustion causes about a third of the warming due to black carbon and carbon monoxide emissions from human sources, about a sixth of ozone-forming chemicals, and a few percent of methane and CO_2 emissions.[21] When deposited in regions with vulnerable mountain glaciers, black carbon particles contribute to glacier melting.[71,72] This contribution is most crucial in the Himalayan region, where glaciers stabilise summer flow in rivers that supply water and irrigation to 1·5 billion people.

In high-income settings such as the UK, greenhouse-pollutant abatement strategies will necessarily entail major changes in the efficiency of energy use by households and in the dominant forms of energy supply. These changes will have appreciable implications for public health, and are potentially positive through changes to the indoor environment (winter temperatures, air quality) and outdoor air quality. The contrasting example of the cookstove intervention shows the very great potential for improvement of public health by interventions that also have appreciable bearing on climate change mitigation.

Early this decade, the UN Millennium Project called on countries to adopt the voluntary cooking energy target "by 2015, to reduce the number of people without effective access to modern cooking fuels by 50%, and make improved cookstoves widely available". Achievement of this target was regarded as an essential contribution to Millennium Development Goals 4 and 5, which focus on reduction of child and maternal mortality. Although progress is being made, present efforts are very unlikely to lead to achievement of these goals by the target date of 2015.[73] We suggest that the case for far bolder and emphatic action is strengthened by our evidence. Finding of ways to combine or leverage climate mitigation investments to help to accelerate achievement of Millennium Development Goals should have a high priority. Improvements in the household fuel sector offer important potential benefits for health of women and young children as well as for mitigation of climate change.

For the **UN Millennium Project** see http://www.unmillennium project.org

Contributors

All authors participated in the development of ideas for the report. The text was drafted mainly by PW, KRS, and MD, with contributions from all other authors. Data analysis was done principally by ZC, IH, IR, HA, BA, and PW.

Conflicts of interest

We declare that we have no conflicts of interest.

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Health and Climate Change 2

Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport

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We used Comparative Risk Assessment methods to estimate the health effects of alternative urban land transport scenarios for two settings—London, UK, and Delhi, India. For each setting, we compared a business-as-usual 2030 projection (without policies for reduction of greenhouse gases) with alternative scenarios—lower-carbon-emission motor vehicles, increased active travel, and a combination of the two. We developed separate models that linked transport scenarios with physical activity, air pollution, and risk of road traffic injury. In both cities, we noted that reduction in carbon dioxide emissions through an increase in active travel and less use of motor vehicles had larger health benefits per million population (7332 disability-adjusted life-years [DALYs] in London, and 12 516 in Delhi in 1 year) than from the increased use of lower-emission motor vehicles (160 DALYs in London, and 1696 in Delhi). However, combination of active travel and lower-emission motor vehicles would give the largest benefits (7439 DALYs in London, 12 995 in Delhi), notably from a reduction in the number of years of life lost from ischaemic heart disease (10–19% in London, 11–25% in Delhi). Although uncertainties remain, climate change mitigation in transport should benefit public health substantially. Policies to increase the acceptability, appeal, and safety of active urban travel, and discourage travel in private motor vehicles would provide larger health benefits than would policies that focus solely on lower-emission motor vehicles.

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Introduction

In 2004, transport accounted for almost a quarter of carbon dioxide (CO_2) emissions from global energy use.[1] Three-quarters of transport-related emissions are from road traffic.[1] Although large reductions in greenhouse-gas emissions are needed to prevent serious climate destabilisation,[2] emissions from transport are rising faster than from other energy-using sectors and are predicted to increase by 80% between 2007 and 2030.[1]

Reduction in transport-related greenhouse-gas emissions through less use of motor vehicles and increase in the distances walked and cycled could have important health benefits.[3] Reduction in the use of motor vehicles could reduce urban air pollution. Prevalence of physical inactivity and the associated burden of chronic disease could be lowered with increases in the distances walked and cycled.[4] Decrease in motor vehicle traffic also has the potential to reduce danger from road traffic, although exposure to the remaining danger might increase with the number of pedestrians and cyclists.[5] However, the extent of these effects is not known.

We modelled the effects of urban land transportation scenarios on CO_2 emissions and health. Motor vehicles are a source of several other climate-active pollutants, including black carbon, ozone (indirectly), nitrous oxide, and methane. In this Series, Smith and colleagues[6] discuss the climate and health implications of several of these pollutants. However, we have restricted our analysis to CO_2, and modelled emissions only from motor vehicle fuel combustion; full life-cycle modelling was beyond the scope of this analysis.

We focused on urban transport because more than half the world's population lives in cities and because we

Key messages

- Transport-related greenhouse-gas emissions are increasing, with a rapid growth projection in low-income and middle-income countries.
- Production of lower-emission motor vehicles (cars, motorcycles, and trucks) and reduction in travel by motor vehicles are needed to meet targets for reduction of greenhouse-gas emissions.
- Lower-emission motor vehicles would reduce the health burden from urban outdoor air pollution, but a reduction in the distance travelled by motor vehicles could have a greater effect.
- Increase in the distances walked and cycled would also lead to large health benefits. Largest health gains would be from reductions in the prevalence of ischaemic heart disease, cerebrovascular disease, depression, dementia, and diabetes.
- Although reducing motor vehicle use would decrease the injury risk for existing pedestrians and cyclists, if many more people walked and cycled there might be an increase in the number of pedestrian and cycle injuries, since more people would be exposed to the remaining risk.
- Creation of safe urban environments for mass active travel will require prioritisation of the needs of pedestrians and cyclists over those of motorists. Walking or cycling should become the most direct, convenient, and pleasant option for most urban trips.

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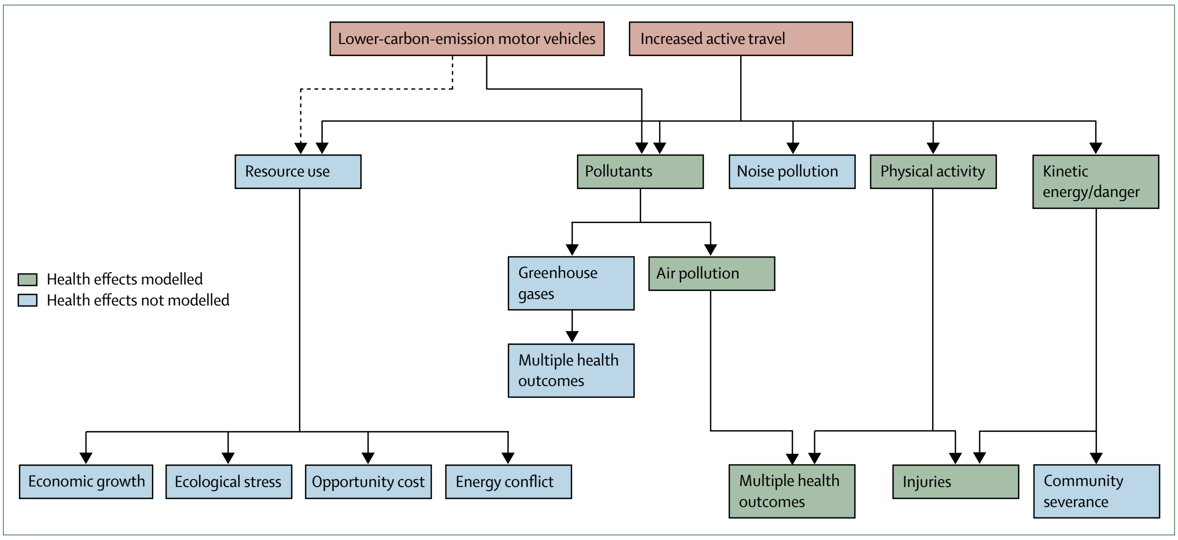

Figure 1: **Modelled and unmodelled pathways relating lower-carbon-emission motor vehicles and increased active travel scenarios with health**

expected the potential for change and health effects to be greatest in cities. In low-income and middle-income countries, urbanisation is associated with an increased health burden from non-communicable diseases.[7] In the UK, transport in urban areas accounts for 20% of distance (km) travelled by vehicles,[8] but accounts for a disproportionate share of CO_2 emissions and air pollutants as a result of the driving conditions[9] and frequent vehicle cold starts.[10]

We assessed physical activity, outdoor air pollution, and risk of road traffic injury. Although transport can affect health in other ways, including noise pollution, community severance, and the opportunity cost of transportation resource use,[3] the three exposures were selected because the evidence linking them with health outcomes is strong. Figure 1 shows the pathways that were included and excluded.

Modelling the scenarios

We designed scenarios with reference to a large city in a highly motorised country (London, UK), and a large city in a country that is becoming rapidly motorised (Delhi, India).

See Online for webappendix

For London, we developed four scenarios and compared them with a business-as-usual 2030 projection (panel 1; webappendix p 9). In the lower-carbon-emission motor vehicles scenario, we focused on reducing the emission factors from motor vehicles. The increased active travel scenario represented a large increase in cycling, a doubling in the distance walked, and a reduction in car use with a small reduction in road freight. The towards sustainable transport scenario combined the lower-emission motor vehicles from the lower-carbon-emission motor vehicles scenario, and the low car use and longer distances walked and cycled from the increased active travel scenario. The short-distance active travel scenario included the same low-car use as in the increased active travel scenario but with half the rise in distances walked and cycled because of shorter distances and reduced travel times.

The Greater London Authority has adopted a target of 60% cross-sector reduction in emissions by 2025,[11] and the mitigation scenarios draw on the work done to quantify and model this target, including the study for Visioning and Backcasting for Transport (VIBAT)[12] in London and the related Transport and Carbon Simulation model.[13] Table 1 shows the total distance travelled per person and CO_2 emitted from vehicles according to the different scenarios (webappendix pp 10–11).

We developed four equivalent transport scenarios and a business-as-usual projection for Delhi (panel 2; webappendix p 9). Projections for Delhi are based on few data for vehicle and passenger flows. With a lower baseline than London and a rising population, the predicted scenarios focused on prevention of the rise in emissions. No specific targets for reductions have been set by the city authorities. The basis for the Delhi transportation scenarios were the VIBAT in India and Delhi scoping studies,[15,16] and the work done by Wilbur Smith Associates.[17] Table 2 shows the total distance travelled per person and CO_2 emissions for the Delhi transportation scenarios.

Modelling health effects

For all scenarios, we estimated the distributions of physical activity and exposure to air pollution. We then used the methods of Comparative Risk Assessment (webappendix pp 6–8) to estimate the change in disease burden. A modified approach was used for road traffic injury in which we calculated absolute numbers of deaths. Although we started with projected data for disease burden for 2010, we compared each mitigation

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Panel 1: London, UK, scenarios

Business-as-usual 2030

- Ground transport emissions (road and rail) of carbon dioxide (CO_2) in London are projected to increase from 9·6 megatonnes in 2006 to 10·3 megatonnes by 2030.
- 4% increase in total transport CO_2 emissions from 1990 levels.
- Per person transport CO_2 emissions are 1·17 tonnes.
- Basically a projection of present trends in the next 20 years, including some actions to reduce growth in the use of cars and increased investment in public transport. There is little change in the efficiency of the car stock and in use of alternative fuels, and no coherent strategy for change.

Lower-carbon-emission motor vehicles

- Focus is on reduction of the emission of CO_2 from motor vehicles through more efficient engines and fuel switching.
- 35% reduction in transport CO_2 emissions from 1990 levels.
- Per person CO_2 emissions are 0·73 tonnes.
- This scenario relies on an ambitious implementation of technologies, mainly lower-emission motor vehicles and other fuels, with some use of information and communication technologies to reduce the emissions from motorised travel. In this scenario, we assume an average of 95 g/km CO_2 for cars compared with 177 g/km CO_2 at the moment.
- Policy change would require government legislation for mandatory lower-emission motor vehicles and acceptance and use of alternative fuels, motor manufacturers to produce lower-emission vehicles for the mass market, and consumer behaviour change in purchasing these vehicles.

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Increased active travel

- Focus is on replacement of some car travel with active travel. Also includes a small reduction in distance (km) travelled by road freight and a large reduction in the number of motorcycles (from a low baseline).
- 38% reduction in transport CO_2 emissions from 1990 levels.
- Per person CO_2 emissions are 0·69 tonnes.
- High levels of walking and cycling are assumed, similar to the practice in some cities in continental Europe (eg, Copenhagen [Denmark], Delft [Netherlands], Amsterdam [Netherlands], Freiburg [Germany]).
- Assumptions made for this scenario are that the distance walked is more than doubled and distance cycled is increased eight-fold (but from a low baseline).
- Policy change implies a reprioritisation designed to restrict car use and ensure active travel is the most convenient, pleasant, and quickest way to reach destinations.
- Specific policies would include substantial investment in the design of infrastructure for pedestrians and cyclists to reshape the streetscape and public realm, carbon rationing, geographically expanded road pricing, traffic demand management, restrictions on car parking and access, reduced speed limits, and behavioural change approaches (eg, raised awareness, travel planning).

Towards sustainable transport

- Represents progress towards a sustainable transport system that includes complete implementation of the lower-carbon-emission motor vehicles and increased active transport scenarios.
- 60% reduction in transport CO_2 emissions from 1990 levels.
- Per person CO_2 emissions are 0·45 tonnes.
- Policy change would require high-intensity implementation and effectiveness of all measures.
- Transport emissions in London and Delhi are converging and moving towards sustainable levels. Further reduction in emissions would still be needed to achieve truly sustainable transport.
- Further reductions could occur through use of electric vehicles with energy from low-carbon sources; reduction of trip distances; and continued modal shift from car use to walking or cycling.

Short-distances active travel (sensitivity analysis)

- In this scenario, we envisaged the same motor vehicle distances as in the sustainable transport scenario but only half the increase in distances walked and cycled. This scenario represents less travel and shorter travel distances than in the other scenarios.

scenario against the 2030 business-as-usual transport scenario—ie, if 1000 individuals died in 2010, we estimated the number of deaths for 2030 business as usual and every mitigation scenario. We then calculated the difference in the number of deaths for each mitigation scenario compared with 2030 business-as-usual scenario to estimate the effect of the mitigation strategy. We used this approach because the effects of other changes on disease burdens were difficult to predict. Estimates of the effect of the relevant risk factor on health outcomes, including exposure-response associations, were obtained mostly from systematic reviews. Baseline estimates of disease burden were obtained from Mathers and Loncar[18] and from STATS19[19] and data provided by the Delhi police.[20]

We estimated the health effects of the changes in active travel that would arise with the different transportation scenarios (full details of the methods are provided in the webappendix pp 12–19). The scenarios were used to provide estimates of mean distances walked and cycled per year, which we used to estimate mean time spent walking and cycling per week. We then created travel-time distributions by fitting log-normal

Figure 2: **New bicycle facilities in Delhi, India**

	Car	Bus	Rail	HGV	Walking	Bicycle	Motorcycle	Total (km)	CO_2 emissions (tonnes)*
2010	5599	1110	2630	244	262	151	70	10 065	1·27
2030 BAU	5053	1044	2776	217	233	137	69	9528	1·17
Lower-carbon-emission motor vehicles	5053	1044	2776	217	233	137	69	9528	0·73
Increased active travel	3698	1044	2776	173	573	1239	25	9528	0·69
Towards sustainable transport	3698	1044	2776	173	573	1239	25	9528	0·45
Short-distances active travel	3698	1044	2776	173	403	688	25	8807	0·45

HGV=heavy goods vehicle. CO_2=carbon dioxide. BAU=business as usual. *London scenarios included the effects of a range of policy packages that were not included in the Delhi scenarios.

Table 1: **Distance travelled and CO_2 emissions per person per year in London, UK, for each scenario**

distributions. Because we modelled disease burdens by age and sex, we needed age-specific and sex-specific travel-time distributions. Estimates of how travel times and speeds varied by age and sex were obtained from a travel survey of London, UK.[21] Table 3 provides the walking and cycling speeds. The London travel time and speed ratios were used for Delhi because of the absence of high-quality data for Delhi. For the two scenarios with high levels of cycling, the estimated age and sex distributions were based on data from the Netherlands where levels of cycling are similar to those in these scenarios.[22] In London and Delhi, men are more likely to cycle than are women, whereas the proportions are similar in the Netherlands. Intensity of physical activity is usually measured with metabolic equivalents (METs); one MET is the typical energy expenditure of an individual at rest (1 kcal/kg/h). The distributions of the times for walking and cycling were converted into distributions of METs with tabulated data for different activities and speeds.[23] Median MET times (h) were taken as the best summary statistic of active travel for all age–sex groups. To estimate total physical activity, we added these estimates to those of non-travel-related physical activity derived from surveys[24,25] (webappendix p 13).

We did systematic searches until March, 2009, for studies of the association between moderate-intensity physical activity and the incidence (fatal and non-fatal) of prespecified conditions included in the assessment of global burden of disease (webappendix pp 13–18). We selected the most recent high-quality systematic reviews for every condition (except depression) to assess the evidence for a causal association. For depression, we did a broad search and assessed the main studies. When the association between physical activity and disease outcome is modelled, the shape of the exposure-response function is important, but this association has been assessed in only a few systematic reviews.

If the systematic review provided an exposure-response function, we used that. If not, then we used three exposure-response functions with different shapes. These were a square-root linear model (webappendix pp 18–19), a linear model, and a linear model with a threshold (with an assumption of no further benefit beyond a particular exposure). We used the relative risk from the systematic review, estimated the corresponding exposure in METs, and then applied each of the three different shapes to generate exposure-response functions between MET time (h per week) and the relevant disease outcome. When we modelled the health effects of the different scenarios, we selected the median overall change in disability-adjusted life-years (DALYs) from physical activity as our main estimate, with the range representing the uncertainty bounds (webappendix p 18).

We showed the potential effect on the population distribution of body-mass index by modelling the effect of the scenario with increased active travel on the prevalence of obesity and overweight for men aged 45–59 years in London, assuming a constant energy intake.[26]

Although traffic generates various pollutants, we modelled only the health effects of fine particulate matter (particulate matter with aerodynamic diameter 2·5 μm or less [$PM_{2·5}$]) for which the strongest evidence of health effects exists.[27] The basis for our method is WHO's Comparative Risk Assessment exercise for urban air pollution.[27] The methods are summarised here and further details are provided in the webappendix (pp 20–22).

Because few data exist about emissions and ambient concentrations of $PM_{2·5}$ in London, we modelled the PM_{10} concentrations for our transportation scenarios and then assumed that the changes in concentrations between our mitigation scenarios and 2030 business-as-

Panel 2: **Delhi, India, scenarios**

Business as usual 2030

- Projected population increase accounts for some of the projected increase in emissions.
- We estimated that ground transport emissions for Delhi, starting with a lower baseline than in London, UK, would increase from 6·1 million tonnes of carbon dioxide (CO_2) in 2004 to 19·6 million tonnes in 2030.
- 526% rise in CO_2 emissions from 1990 values.
- Per person CO_2 emissions are 0·75 tonnes.
- Projection of existing trends and no coherent strategy to reduce the increase in the use of cars, but includes an anticipated increase in rail use.
- Most vehicles in the UK are expected to achieve Euro 6 emission[14] standards by 2020. In the primary analyses, we assumed that vehicles in Delhi will have achieved this standard, which is considerably lower than present levels, by 2030. If emission factors remained unchanged, CO_2 and particulate-matter emissions would be much higher than 0·75 tonnes per person.

Lower-carbon-emission motor vehicles

- 447% rise in transport CO_2 emissions from 1990.
- Per person CO_2 emissions are 0·66 tonnes.
- This scenario relies on an ambitious implementation of vehicle technologies, and represents an anticipated increase in rail use.
- The policy trajectory would require government legislation on mandatory lower-emission motor vehicles and acceptance and use of alternative fuels, motor manufacturers to produce lower-emission motor vehicles for the mass market, and consumer behaviour change in purchasing such vehicles.

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Increased active travel

- 235% rise in transport CO_2 emissions from 1990.
- Per person CO_2 emissions are 0·40 tonnes.
- In this scenario, a reversal of present trends is assumed with a small increase in the distance walked and more than double increase in distance cycled. It represents a large increase in rail use and small increase in bus use. Other assumptions made are a slower increase in distance (km) travelled in freight vehicles than in the business-as-usual scenario, substantial reductions in motorcycle use, and similar car use to 2010.
- Policy change would require prioritisation for people who walk and cycle, and restriction of car travel to ensure active travel is the safest and most convenient, pleasant, and quickest way to reach destinations. The reallocation of space to provide a high-quality streetscape that is designed to meet the needs of pedestrians and cyclists is of particular importance. Rather than active travel being the mode of necessity for those unable to afford motor vehicles it would become the mode of choice.
- Specific policies would perhaps include substantial investment in infrastructure designed for pedestrians and cyclists rather than for cars, carbon rationing, road pricing, traffic demand management, restrictions for car parking and access, reduced speed limits, and behavioural change approaches (eg, raised awareness, travel planning).

Towards sustainable transport

- This scenario represents progress towards a sustainable transport system that includes complete implementation of the lower-carbon-emission motor vehicles and increased active transport scenarios.
- 199% increase in CO_2 emissions from 1990.
- Per person CO_2 emissions are 0·36 tonnes.
- Emissions per person are higher than in 1990 but lower than in 2010.
- Policy change would require high-intensity implementation and effectiveness of all measures.
- Transport emissions in Delhi and London are converging and moving towards sustainable levels. Further reduction in emissions would still be needed to achieve truly sustainable transport.
- Further reduction could occur through use of electric vehicles with energy from low-carbon sources; shorter-distance trips; and continued shift from car use to walking or cycling.

Short-distance active travel (sensitivity analysis)

- In this scenario, we envisaged the same motor vehicle distances travelled as in the sustainable transport scenario but only half the increase in distances walked and cycled. This scenario represents less travel and shorter travel distances than in the other scenarios.

usual scenario were in the $PM_{2\cdot5}$ size range. This assumption seems reasonable since the transportation scenarios would mainly affect the $PM_{2\cdot5}$ subset of PM_{10}. For London, population-weighted yearly average PM_{10} concentrations for every scenario were estimated with an emission-dispersion model (webappendix pp 20–21).[28] To account for changes in the contribution of traffic outside London to the concentrations of PM in London because of the long-range transport of pollutants, we assumed that the same changes occurred in other European cities. We assumed that the non-traffic sources of PM did not change. For Delhi we used a simpler model because of few available data. $PM_{2\cdot5}$ concentrations were estimated for each scenario from source-specific emissions data with the simple interactive models for better air quality (SIM-AIR, version 1.3).[29]

Further information about the model inputs and assumptions are provided in the webappendix (p 22). We considered the effects of PM on mortality from cardiorespiratory disease and lung cancer in adults, and

	Car	Bus	Rail	HGV	Walking	Bicycle	Two-wheel motorcycle	Three-wheel motorcycle	Total (km)	CO_2 emissions (tonnes)*
2010	1118	2860	582	36	536	650	1716	312	9820	0·47
2030 BAU	2995	2860	1456	104	463	390	2860	260	11388	0·75
Lower-carbon-emission motor vehicles	2995	2860	1456	104	463	390	2860	260	11388	0·66
Increased active travel	1186	3245	1950	68	616	1716	1258	260	10299	0·40
Towards sustainable transport	1186	3245	1950	68	616	1716	1258	260	10299	0·36
Short-distance active	1186	3245	1950	68	540	1053	1258	260	9559	0·36

HGV=heavy goods vehicle. CO_2=carbon dioxide. BAU=business as usual. *London, UK, scenarios included the effects of a range of policy packages that were not included in the Delhi scenarios.

Table 2: **Distance travelled and CO_2 emissions per person per year in Delhi, India, for each scenario**

	Walking		Cycling	
	Men	Women	Men	Women
15–29 years	4·6	4·0	14·8	12·0
30–44 years	4·3	3·7	17·7	14·4
45–59 years	4·0	3·4	14·0	11·3
60–69 years	3·4	2·9	10·6	8·6
70–79 years	2·8	2·4	9·8	7·9
≥80 years	2·4	2·1	8·9	7·2

Table 3: **Walking and cycling speeds (km/h) by age group**

	2010	BAU	Lower-carbon-emission vehicles	Increased active travel	Towards sustainable transport
London, UK	10·1	8·2	7·8	7·7	7·4
Delhi, India	88·7	90·4	79·0	75·5	72·3
Sensitivity analysis					
Delhi (high)*	88·7	134·0	108·4	82·7	78·4

BAU=business as usual. *Fewer improvements in vehicle emission factors than in the main Delhi analysis.

Table 4: **Estimates of air pollution (particulate matter with aerodynamic diameter of 2·5 μm or less) concentrations (μg/m³)**

from acute respiratory infections in children. In the main analysis, we used a linear model for London where present and projected yearly average $PM_{2·5}$ concentrations are much lower than 40 μg/m³, and a log-linear model for Delhi where the concentrations are greater than 40 μg/m³. Table 4 shows the concentrations for each of the scenarios. In the sensitivity analysis, we also estimated health effects using a log-linear model for London and a linear model for Delhi.

Changes in the amount of motor vehicle traffic and in the numbers of pedestrians and cyclists in the transportation scenarios could affect the numbers of individuals injured as a result of road traffic. We used a different approach for injury from that used for physical activity and air pollution. We developed a model to generate absolute numbers, rather than relative risks, of deaths from road traffic collisions. Therefore, we used these data in preference to those available at the national level from the global burden of disease project.

We constructed an injury matrix for road traffic that described the injury risk per unit of travel for each type of road user. For London, numerator data were obtained from STATS19,[19] and for Delhi, they were obtained from the Delhi police.[20] Denominator data for the number of vehicles and average distance (km) travelled were based on the scenarios with additional data from Transport for London (webappendix p 23).

Because injury risk for each group of road users also depends on the distance travelled by other road users, we estimated the injury risk per unit of travel from the vehicles that could cause injury. For example, the risk of a pedestrian being injured by a car was expressed as a linear function of both the distance walked and the distance travelled by cars. This method is an elaboration of the injury model described by Bhalla and colleagues (webappendix pp 23–26).[30] For London, we adapted this method to take into account variations in injury risks over different parts of the road network; data for Delhi were insufficient. For all scenarios we estimated the expected number of deaths and serious injuries after changes to the distance travelled by all the included road users. These were then used to estimate the changes in years of life lost (YLL) and years of healthy life lost as a result of disability (YLD). To calculate YLLs and YLDs, we assumed that their ratios to deaths were the same as those from the global burden of disease national data for road traffic injuries in both countries.

Sensitivity analyses were done to take into account possible reductions in injury risk for pedestrians and cyclists from measures to increase their safety. Such measures (eg, reduced speed limits, increased enforcement of driving rules, and improved infrastructure) could be expected as part of the scenarios for increased active travel. We therefore used the injury rates per 100 million km walked and cycled for the Netherlands, a country in which people do a lot of walking and cycling with low injury rates.

Findings

Evidence from systematic reviews showed that increased physical activity reduced the risk of cardiovascular disease, depression, dementia, diabetes, breast cancer, and colon cancer. Table 5 shows the results of our overview, strength of the association between the

	Systematic review/ study, year	Studies included	RR (95% CI) and corresponding exposure	Age group (years)	RR reduction from 2·5 h per week of moderate intensity physical activity		Maximum exposure per week for linear threshold
					Square-root model	Linear model	
Dementia (U087)	Hamer et al, 2009 (search year 2007)[31]	16 cohort studies (163 797 people, 3219 cases)	0·72 (0·60–0·86); 33 METs per week (>1657 kcal per week)[32]	≥45	–0·18	–0·11	21 METs (>2 miles walked per day)[33]
Cardiovascular diseases (ischaemic heart disease [U106], hypertensive heart disease [U107], cerebrovascular disease [U108])	Hamer et al, 2008 (search year 2007)[34]	18 cohort studies (459 833 people, 192 49 cases)	0·84 (0·79–0·90); 7·5 METs per week (3 h walking per week)	≥30	–0·19	–0·23	52·5 METs (>10·5 MET h per day from walking)[35]
Diabetes (U079)	Jeon et al, 2006 (search year 2006)[36]	10 cohort studies (301 211 people, 9367 cases)	0·83 (0·75–0·91); 10 METs per week	≥30	–0·18	–0·19	22·5 METs (>4 h per week moderate activity)[37]
Breast cancer (U069)	Monninkhof et al, 2007 (search year 2006)[38]	19 cohort studies, 29 case control studies	0·94 (0·92–0·97) for each additional h per week	≥15 (women only)	Not used	–0·13	57·8 METs[39]
Colon cancer (U064)	Harriss et al, 2009 (search year 2007)[40]	15 cohorts (7873 cases)	Men 0·80 (0·67–0·96); women 0·86 (0·76 to 0·98); METs per week: 30·1 for men and 30·9 for women	≥15	–0·13 for men, –0·09 for women	–0·08 for men, –0·05 for women	47 METs[41]
Depression (U082)	Paffenbarger et al, 1994[42]	Cohort study (10 201 men, 387 first episodes of physician-diagnosed depression)	1·0*, 6·9 METs per week (<1000 kcal per week); 0·83*, 24·2 METs per week (1000–2499 kcal per week); 0·72*, 63·7 METs per week (≥2500 kcal per week)	≥30 (15–29: smaller effect assumed)	–0·14 (–0·07†)	–0·07 (–0·03†)	34·6 METs (>2511 kcal per week)[42]

RR=relative risk. METs=metabolic equivalents. *95% CIs not available. †Effect used in age group 15–29 years.

Table 5: **Studies used to generate exposure-response functions by condition (global burden of disease code)**

	2010		Business as usual		Increased active travel		Short-distance active travel	
	Men	Women	Men	Women	Men	Women	Men	Women
15–29 years	95 (51–174)	107 (58 –196)	84 (45–154)	95 (51–174)	329 (179–604)	371 (202–680)	198 (107–363)	223 (121–409)
30–44 years	86 (47–158)	97 (53–178	77 (17–140)	86 (47–158)	299 (163–549)	337 (183–613)	180 (98–330)	203 (110–372)
45–59 years	70 (38–128)	79 (42–144)	62 (33–113)	70 (38–128)	243 (132–445)	273 (148–501)	146 (79–267)	164 (89–301)
60–69 years	77 (42–141)	87 (47–159)	68 (37–125)	77 (42–141)	267 (145–490)	301 (164–552)	161 (87–295)	181 (98–332)
70–79 years	69 (37–125)	77 (41–141)	61 (33–111)	69 (37–125)	214 (116–392)	241 (131–442)	143 (77–261)	161 (87–294)
≥80 years	50 (27–92)	57 (30–104)	45 (24–82)	50 (27–92)	155 (84–284)	174 (95–320)	105 (57–192)	118 (64–216)

Table 6: **Median active travel times per week (min; 25th to 75th percentiles) by age group in London, UK**

exposure and outcome, and estimates used in the modelling (webappendix pp 27–31).

All these conditions, except for depression and dementia, were included in the earlier Comparative Risk Assessment study of physical activity (search date 2001).[43] Physical activity seems to reduce the duration and severity of existing depression, and also the incidence.[44–46] Of particular relevance to this project were longitudinal studies in which new episodes of doctor-diagnosed depression arose less frequently in individuals who undertook regular physical activity, including walking and cycling, than in those who did not.[42] Evidence from randomised trials of individuals with memory loss and decline in cognitive function lend support to the observational epidemiological evidence for physical activity and dementia.[47,48] The changes in the distances walked and cycled in the scenarios were converted into changes in the time spent in active travel and MET time (h) for all age groups in London and Delhi. Table 6 and table 7 show the median times spent in active travel, and median MET times for travel and other activities are presented in the webappendix (pp 32–33). Figure 3 shows the distributions of the active travel times for men in one age group for the mitigation scenarios.

Table 8 shows the estimated changes in health burden with the different transport scenarios. For London, with the lower-carbon-emission motor vehicles scenario, the total number of premature deaths and DALYs were reduced through reductions in the rate of mortality caused by air pollution. For the increased active travel and sustainable transport scenarios, substantial reductions were noted in premature deaths and DALYs as a result of increased physical activity and reductions in the rates of mortality caused by air pollution. These

	2010		Business as usual		Increased active travel		Short-distance active travel	
	Men	Women	Men	Women	Men	Women	Men	Women
15–29 years	203 (92–446)	229 (104–502)	153 (69–335)	172 (78–377)	410 (186–900)	462 (210–1014)	269 (122–590)	303 (137–665)
30–44 years	185 (84–405)	208 (94–457)	139 (63–304)	156 (71–343)	373 (169–818)	420 (191–922)	245 (111–537)	275 (125–604)
45–59 years	150 (68–328)	169 (76–370)	112 (51–246)	127 (57–278)	302 (137–663)	340 (154–747)	198 (90–434)	223 (101–490)
60–69 years	165 (75–362)	186 (84–408)	124 (56–272)	140 (63–306)	333 (151–731)	375 (170–823)	218 (99–479)	246 (112–540)
70–79 years	147 (66–321)	165 (75–362)	110 (50–241)	124 (56–272)	246 (112–540)	277 (126–608)	161 (73–354)	182 (82–399)
≥80 years	108 (49–236)	122 (55–267)	81 (36–175)	91 (42–200)	164 (74–360)	185 (84–405)	108 (49–236)	121 (55–266)

***Table 7:* Median active travel times per week (min; 25th to 75th percentiles) by age group in Delhi, India**

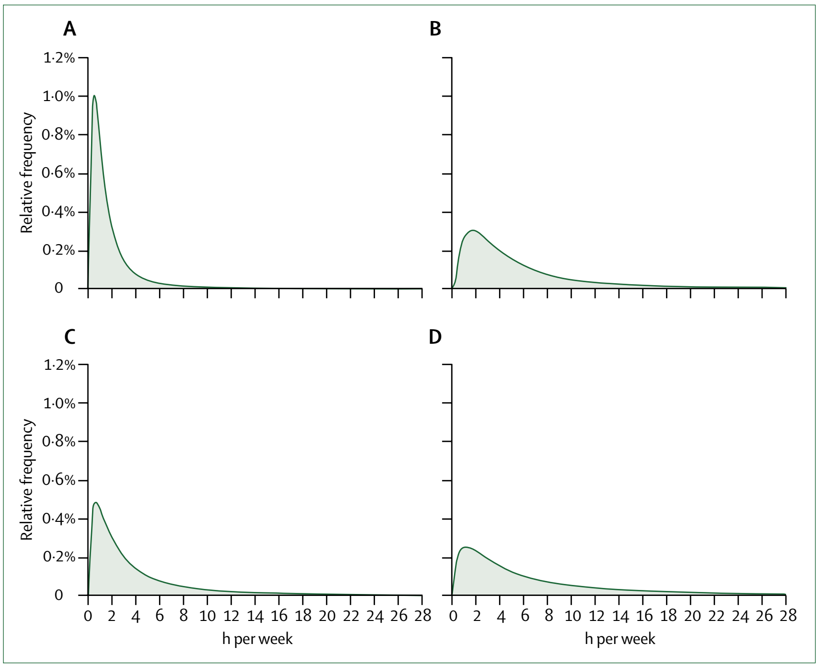

***Figure 3:* Distribution of active travel times for men aged 45–59 years in London, UK, and Delhi, India**
(A) London 2010. (B) London: increased active travel. (C) Delhi 2010. (D) Delhi: increased active travel.

gains more than compensated for the increase in the burden from road traffic injuries. In 1 year, compared with business as usual, the lower-carbon-emission motor vehicles scenario saved 160 DALYs and 17 premature deaths per million population, increased active travel saved 7332 DALYs and 530 premature deaths per million population, and the towards sustainable transport scenario saved 7439 DALYs and 541 premature deaths per million population. Disease-specific estimates for each of the different exposure-response functions are provided in the webappendix (pp 34–36). For London, the largest gains were from reductions in ischaemic heart disease (10–19% of total ischaemic heart disease burden), cerebrovascular disease (10–18% of cerebrovascular disease burden), dementia (7–8% of dementia disease burden), depression (4–6% of total depression disease burden), and breast cancer (12–13% of total breast cancer disease burden). Although walking and cycling became safer per km travelled the large increase in the total distance walked and cycled led to the road traffic injury disease burden rising by 39%.

For Delhi, the lower-carbon-emission motor vehicles and increased active travel scenarios resulted in a greater health gain from reduced air pollution than for London. Unlike for London, we noted that in Delhi the increased active travel scenario substantially reduced the burden of road traffic injury compared with business as usual. However, the estimated burden of road traffic injury with increased active travel was still higher than for 2010. For 1 year, compared with business as usual, the lower-carbon-emission motor vehicles scenario saved a total of 1696 DALYs and 74 premature deaths per million population, increased active travel scenario saved 12 516 DALYs and 511 premature deaths per million population, and the towards sustainable transport scenario saved 12 995 DALYs and 532 premature deaths per million population. The largest health gains were from reductions in ischaemic heart disease (11–25% of total ischaemic heart disease burden), cerebrovascular disease (11–25% of total cerebrovascular disease burden), and diabetes (6–17% of total diabetes disease burden); the reduction in road traffic injuries was 27%.

In both cities, we noted that the risk to pedestrians, and especially cyclists, was higher from heavy goods vehicles (HGVs) than from cars. On A-type roads (ie, main roads but not motorways or freeways) in London, the risk of an injury for a cyclist was 23 times higher per km from HGVs than from cars. For pedestrians, the risk from HGVs was four-fold greater than that from cars. For cyclists in Delhi, risk of injury from HGVs was 30 times greater than that from cars, whereas for pedestrians the difference was 15-fold. Indicating the effect on obesity, the proportion of men (aged 45–59 years) who were obese decreased by about 5% when compared with the increased active travel scenario against the 2010 baseline for London (table 9).

Although there were many sources of uncertainty in the development and modelling of the scenarios, we assessed the effect of a few sources of uncertainty one at a time. We focused on the exposure-response relation for air pollution and physical activity, PM emissions from vehicles in Delhi for 2030 business as usual, achievement of best safety practice for pedestrians and cyclists to avoid

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injuries, and uptake of active travel for physical activity and risk of injury (webappendix pp 37–38 for full results of the sensitivity analyses).

When we applied a linear model for air pollution in Delhi and a log-linear model for London we noted greater health benefits than in the main analysis. We also noted increased health effects in the mitigation scenarios when we assumed a less optimistic 2030 business as usual for Delhi, in which PM emissions per km from vehicles stayed at present levels rather than achieving Euro 6 standards (webappendix p 37).[14] In this analysis, 7590 DALYS as a result of reduced air pollution were saved with the towards sustainable transport scenario compared with 2749 DALYs in the main analysis.

When we applied injury rates per km walked and cycled from the Netherlands to our respective distances in the increased active travel scenarios, the injury rates were reduced by 14% in London and by 58% in Delhi (webappendix p 38).

In the short-distances active travel scenario, we noted smaller benefits from increased physical activity combined with a smaller increase in road traffic injuries for London, and a substantial reduction in injuries in Delhi compared with the increased active travel scenarios. In both cities, this led to smaller overall health gains per million population (4817 DALYs in London and 11 704 DALYs in Delhi).

For London and Delhi, the increased active travel scenarios saved more DALYs than did the lower-carbon-emission motor vehicle scenarios. For London, the effects from physical activity were greater than were those from air pollution or injuries in the towards sustainable transport scenario for all sensitivity analyses. For Delhi, ranking of the effects was sensitive to the model used.

	Delhi			London		
	Lower-carbon-emission motor vehicles	Increased active travel	Towards sustainable transport	Lower-carbon-emission motor vehicles	Increased active travel	Towards sustainable transport
Physical activity						
Premature deaths	0	–352	–352	0	–528	–528
YLL	0	–6040	–6040	0	–5496	–5496
YLD	0	–816	–816	0	–2245	–2245
DALYs	0	–6857	–6857	0	–7742	–7742
Air pollution						
Premature deaths	–74	–99	–122	–17	–21	–33
YLL	–1696	–2240	–2749	–160	–200	–319
YLD	0	0	0	0	0	0
DALYs	–1696	–2240	–2749	–160	–200	–319
Road traffic crashes*						
Premature deaths	0	–67	–67	0	11	11
YLL	0	–2809	–2809	0	418	418
YLD	0	–730	–730	0	101	101
DALYs	0	–3540	–3540	0	519	519
Total†						
Premature deaths	–74	–511	–532	–17	–530	–541
YLL	–1696	–10 969	–11 448	–160	–5188	–5295
YLD	0	–1547	–1547	0	–2144	–2144
DALYs	–1696	–12 516	–12 995	–160	–7332	–7439

Negative numbers indicate reduction in disease burden. YLL=years of life lost. YLD=years of healthy life lost as a result of disability. DALYs=disability-adjusted life-years. *Injuries were calculated directly and then transformed into YLLs and YLDs rather than with a Comparative Risk Assessment approach. †Data were adjusted for double counting for the effect on cardiovascular disease.

Table 8: **Health effects (per million population) in 1 year in Delhi, India, and London, UK, compared with business as usual**

	2010	2030 more active travel
Walking (min per day)	7·5	22
Cycling (min per day)	2·5	14
Driving (min per day)	50	25
Energy intake (MJ per day)	11·06	11·06
Obesity (%)	25·7	20·6
Overweight (%)	77·1	71·7

Table 9: **Prevalence of obesity and overweight in men (aged 45–59 years) in London, UK**

Strengths and weaknesses

We noted that a scenario that represented a move towards sustainable transport could provide substantial reductions in chronic diseases, including ischaemic heart disease, stroke, depression, and dementia. The health gains were larger from increases in active travel and reductions in use of motor vehicles than from use of lower-carbon-emission motor vehicles.

Panel 3 shows the key assumptions used to model the scenarios. Our estimates of health effects depend crucially on the structure and parameters of the model. With respect to structure, several important transport-related exposure-outcome associations were not included—eg, the effect of traffic noise on health or effect of biofuels for transport on food availability. Additionally, we did not assess the wide economic or social effects.

To avoid double counting, we did not consider the health effect of the reductions in body-mass index that we might expect with increased active travel in our physical activity model. We also did not include the effect of physical activity on nicotine cravings and on smoking cessation. Moderate exercise, such as walking and cycling, reduces cigarette cravings.[49] In a Cochrane review[49] of physical activity interventions for smoking cessation, the odds of success of smoking cessation were 1·24-times higher than in control groups. With the small sample sizes of studies, this difference was not significant but if the point estimate is accurate, then applying this to the UK the increase in distances walked and cycled in the population as a whole could lead to an increase in tens of thousands of smokers stopping every year.

We used projected disease burden data for 2010. Changes with time in health status other than those directly linked to transport were not included. Thus we

Panel 3: Key assumptions

Baseline

- Population and health status based on WHO projections (global burden of disease and Comparative Risk Assessment) for 2010, and present emissions sources and air pollution levels.
- Our use of data from the whole of India to estimate disease burden in Delhi might have resulted in an underestimation of the incidence of coronary heart disease and related risk factors.

Business as usual (2030)

London, UK

- Population assumed to increase by 13% compared with 2010, and vehicle-km (excluding walking and cycling) to increase by 2%.
- Vehicle technology (emissions per vehicle-km) based on model of change achieved by 2025.
- Non-road transport sources of pollution as for 2010.

Delhi, India

- Population assumed to increase by 49% compared with 2010, vehicle-km (excluding walking and cycling) to increase by 187%.
- Main analysis assumes achievement of Euro 6 emission standards by 2030 entailing substantial improvements in carbon dioxide (CO_2) and particulate matter emissions per vehicle-km, compared with 2010 and phasing out of two-stroke two-wheeled vehicles. In the sensitivity analysis, no change in vehicle technology (CO_2 or particulate matter emissions per vehicle-km) from 2010 except for phasing out of two-stroke two-wheeled vehicles.
- Decrease in sulphur content of fuel from 350 parts per million to 50 parts per million; industrial emissions at 2010 values.

Mitigation scenarios

- Main comparison: 2030 scenarios with 2030 business as usual. The effect per million population in 2010 based on such comparisons is not affected by differences in population size (except by affecting local pollutant emissions) or changes with time in exposures (except by affecting the 2030 baseline for business as usual).
- For London, the assumption was that reduction in emissions from transport in London was matched elsewhere in Europe (effect on regional air masses).
- We modelled the health effects of the different transport scenarios as if they had been implemented instantaneously. In reality, background changes and other changes that might accompany the scenarios would affect the health effects.

(Continues in next column)

(Continued from previous column)

Health effects

- Derived from attributable burdens calculated with adaptation of the method for Comparative Risk Assessment: assumes health effects of a scenario are represented by the difference in modelled exposures compared with the baseline, from which attributable burdens are computed with relevant relative risks and 2010 mortality and disease rates. Ignores time lags even for chronic disease and lung cancer, and any irreversibility of the effect of past exposures.
- Years of life lost (YLL) computed as a difference between age at death and the theoretical optimum life expectancy at that age which, to be normative across populations, is always calculated with reference to Japanese life tables.
- No time discounting or age-weighting of health effects.
- No inclusion of indirect health effects (eg, operating through economic pathways) or those that arise from success in restricting climate change.
- Model used for direct calculation of death from road traffic crashes and, for London, injury rates. Data converted to YLLs and years of healthy life lost as a result of disability using ratios from the 2010 global burden of disease study.
- Use of population median as best representative of physical activity. Assumption of no changes in non-travel physical activity.

did not consider other changes in road safety, emissions of PM from other sources, changes in background physical activity, or population age structure.

We noted that there was greater uncertainty for the variables for Delhi than for London—in particular, for estimates of the level and distribution of non-travel physical activity for Delhi. Confidence in future estimates for Delhi could be improved if primary data are gathered.

Our estimates of the health effects of physical activity are susceptible to measurement error and confounding. In a systematic review,[50] physical activity, when measured objectively, had a stronger association with mortality than did self-reported physical activity, which might suggest that we underestimated the effect. However, the effect of residual confounding is not as clear. With the large contribution of changes in ischaemic heart disease to the overall effect, the exposure-response function that we selected is especially important. Evidence for a large effect of walking on cardiovascular disease accords with data from a systematic review done after our search, in which the association between weekly walking METs and coronary heart disease was near linear.[51]

The plausibility of our scenarios can be questioned. In the increased active travel and the sustainable transport scenarios, we envisage large increases in the distances walked and cycled, and a 37% reduction in car use in London (after exclusion of light-goods vehicles). In the dataset from the London area travel survey,[21] 55% of distance travelled in cars was accounted for by trips shorter than 8 km (ie, within cycling distance), including

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11% by trips shorter than 2 km (ie, within walking distance), suggesting that large reductions in car use are possible. Another assumption is that changes to total distances walked and cycled lead to changes in the respective median times, and that there is no change in the amount of other physical activity.

The main uncertainties in modelling the health effects of PM exposure are the functional form of the PM exposure response at low and high concentrations and modelled concentrations of PM in Delhi.

For London, our emission-dispersion air pollution model was well suited for modelling the effects of modal shifts and changes in the vehicle fleet on air pollution. We could not use the same model for Delhi because of insufficient data. For Delhi, several factors contribute to uncertainty in the changes in $PM_{2\cdot5}$ concentration between the scenarios. These include uncertainties in the increase of motor vehicle use, composition of and emission factors for the projected 2030 vehicle numbers, and the extent of paved roads that affect the resuspension of PM. If PM emissions per km in Delhi do not improve in accordance with Euro 6 emission standards, the health burden from PM exposure in 2030 under the business-as-usual scenario will be much greater than we estimate (webappendix p 37).

Achievement of reductions in particulate and CO_2 emissions through technology is associated with more uncertainties than through reductions in distances travelled in motor vehicles. For example, diesel engines generally emit less CO_2 than do petrol engines, but currently emit more particles, including black carbon, which also causes climate warming.[6,52] Similarly, diesel particle traps, although effective at reducing particle emissions, increase emissions of CO_2 and nitrogen dioxide.[52,53] Although further improvements could be achieved with vehicles that use batteries powered from renewable sources, PM emissions could persist from brake and tyre wear and resuspension of road dust.

Our injury model, an elaboration of the model described by Bhalla and colleagues,[30] is also based on assumptions—in particular, a linear association between distance travelled and risk of injury from road traffic. In other words, we assumed that if the distance walked is doubled then the risk of injury to the pedestrian is also doubled; and if the distance driven in motor vehicles is halved then the risk of injury to the pedestrian is also halved. Although the direction of these associations is supported by empirical evidence,[54,55] the quantitative association is uncertain. Research has shown that increased levels of walking or cycling are associated with safer walking or cycling.[56] Although this outcome might be due to the lower motor vehicle volumes, it could indicate a non-linear safety-in-numbers effect. Furthermore, finding different directions of effect on injuries from the increased active travel scenarios for London and Delhi suggest greater uncertainty than with those for physical activity or air pollution.

We did not model changes in vehicle speeds, which could arise in at least four ways in our scenarios. First, with a reduction in the number of vehicles, congestion might fall with consequent increases in speeds. Second, policies that reallocate space from motor vehicles to other road users could reduce speeds. Third, legislation and enforcement might reduce vehicle speeds. Fourth, changes to the traffic mix—eg, bicycles and cars, could also affect speeds.

With our assumptions about model structure and the uncertainties in the model variables, the results of this study should be regarded as provisional and should be revised when more accurate estimates become available. One real-world indication that decarbonisation can produce positive health effects, even under difficult circumstances, is provided by Cuba. In the early 1990s after the collapse of the Soviet Union and with the US embargo, transport and agriculture were largely decarbonised, with substantial reductions in calorie intake and increases in the distance cycled and overall physical activity. In this period the average body-mass index fell by 1·5 units from 24·83 kg/m² in 1991 to 23·34 kg/m² in 1995, with the prevalence of obesity halved (from 14% to 7%). Results from epidemiological studies show that during this period the numbers of deaths from diabetes decreased by 51%, from heart disease by 35%, and from stroke by 20%.[57]

The extent to which our results can be generalised to other cities is open to question. For example, London and Delhi are megacities with high levels of public transport use, which suggests that they are likely to have more walking and lower carbon emissions per person than cities with lower levels of public transport use. In cities with higher car use, the emission cuts needed would be increased but the health benefits could be even greater.

We did not consider the socioeconomic distribution of effect although evidence suggests inequalities in the adverse health effects of motorised transport.[58,59] Since traffic-related air pollution is unevenly distributed within cities, reduction in the amount of traffic is likely to have large health benefits in some areas. For example, from the results of a study of the socioeconomic distribution of mortality benefits from reduced air pollution as a result of the London congestion charge, health benefits were estimated to be the largest in the most deprived areas of London.[60] In this city, differences between high-income and low-income groups in distances walked are small, but high-income groups are more likely to cycle and participate in recreational physical activity than are those in low-income groups. In Delhi, individuals living in low-income groups walk and cycle more than do those in high-income groups (39·0% *vs* 3·6% and 20% *vs* 5%, respectively).[61] Therefore, high-income groups in Delhi could be expected to increase their activity more than would the low-income groups, whereas the low-income groups might benefit more from the reduced risk of road injury than would high-income groups.

Because we have estimated the health effects of scenarios rather than specific interventions we cannot assess cost effectiveness. However, the infrastructure for individuals to walk or cycle might be less resource-intensive than that for cars. Additionally there are likely to be direct and indirect economic and social effects that cannot be adequately addressed here. A key consideration is whether such cities could, with low resource use, achieve social goals.

Implications for policy

Effective policies to increase the distances walked and cycled and reduce use of motor vehicles are needed to achieve the health benefits we have discussed. Policies that encourage people to walk and cycle would be expected to increase the safety of active travel, as shown in our sensitivity analysis of injury risks in the Netherlands.[22] Substantial increases in the distances cycled in cities, including Copenhagen (Denmark), London, and New York (USA), are associated with a decrease in the numbers of cyclists killed or seriously injured (webappendix p 38).[19,62–66] Without strong policies to increase the acceptability, appeal, and safety of walking and cycling, the vicious circle of increased motorisation and road danger will continue in Delhi, and the large potential health and environmental gains will not be achieved.

Creation of safe urban environments for mass active travel will mean prioritisation of the needs of pedestrians and cyclists compared with those of motorists. Walking or cycling should be the most direct, convenient, and pleasant options for most urban trips. Policy makers should divert investment from roads for motorists towards provision of infrastructure for pedestrians and cyclists.[67] Compared with cars and trucks, pedestrians and cyclists should have direct routes with priority at junctions. Strict controls for HGVs in urban areas are key safety prerequisites for cyclists. Properly enforced reductions in speed limits or zones can reduce injuries.[5,68] With such policies, achievement of low levels of risk from road injury for active travel, at least as low as the best practice in the Netherlands, should be possible. Enhanced streetscape design can make active travel pleasant.[69] With short distances, active travel becomes convenient; planned mixed-use developments would reduce distances to employment, education, services, and retail. Urban form matters since the incidence of road traffic injuries and urban crime are related to street design and land-use patterns.[70,71] Hence effective urban design can enable high modes shares for walking and cycling.

For **the slides** see http://www.lshtm.ac.uk/nphiru/research/transportandhealthgroup/

Conclusions

Important health gains and reductions in CO_2 emissions can be achieved through replacement of urban trips in private motor vehicles with active travel in high-income and middle-income countries. Technological measures to reduce vehicle pollutants might reduce emissions, but the health effect would be smaller. The combination of reduced reliance on motorised travel and substantial increases in active travel with vigorous implementation of low-emission technology offers the best outcomes in terms of climate change mitigation and public health. In many cities, the increase in use of cars, motorcycles, and HGVs, with the resulting increase in road danger has meant that many individuals who can afford to are changing to private motorised transport. An increase in the safety, convenience, and comfort of walking and cycling, and a reduction in the attractiveness of private motor vehicle use (speed, convenience, and cost) are essential to achieve the modal shifts envisaged here. Although the model assumptions can be questioned and further research will undoubtedly provide more robust estimates, large health benefits associated with active travel are highly likely and these benefits should be taken into account in the development and implementation of policy.

Contributors

IR, JW, AH, BGA, PE, CT, and ZCha led the conceptual development of the report. RH, JW, DM, OA, GT, and DB led the development of the scenarios. CT, BGA, SB, ZCho, and AC led the air pollution and health impact modelling. JW, PE, ZCha, OHF, AW, and GL led the physical activity and health impact modelling, and literature reviews. JW, PE, and IM led the injury modelling with contribution from ZCha and IR.
The text was mainly drafted by JW, CT, PE, IR, and AH with contribution from all authors.

Conflicts of interest

We declare that we have no conflicts of interest.

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Health and Climate Change 3

Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation

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In this report, the third in this Series on health and climate change, we assess the changes in particle air pollution emissions and consequent effects on health that are likely to result from greenhouse-gas mitigation measures in the electricity generation sector in the European Union (EU), China, and India. We model the effect in 2030 of policies that aim to reduce total carbon dioxide (CO_2) emissions by 50% by 2050 globally compared with the effect of emissions in 1990. We use three models: the POLES model, which identifies the distribution of production modes that give the desired CO_2 reductions and associated costs; the GAINS model, which estimates fine particulate matter with aerodynamic diameter 2·5 µm or less ($PM_{2·5}$) concentrations; and a model to estimate the effect of $PM_{2·5}$ on mortality on the basis of the WHO's Comparative Risk Assessment methods. Changes in modes of production of electricity to reduce CO_2 emissions would, in all regions, reduce $PM_{2·5}$ and deaths caused by it, with the greatest effect in India and the smallest in the EU. Health benefits greatly offset costs of greenhouse-gas mitigation, especially in India where pollution is high and costs of mitigation are low. Our estimates are approximations but suggest clear health gains (co-benefits) through decarbonising electricity production, and provide additional information about the extent of such gains.

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Introduction

We assess the effect on health of low-carbon electricity generation as part of a broad climate change mitigation strategy. Similar to the other reports in this Series,[1–3] we assume the greenhouse pollutant abatement trajectories discussed in the UK Climate Change Committee's first report,[4] and the evidence of Working Group III of the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC).[5] The abatement trajectories in these reports are based on the idea that global emissions need to decrease soon and halve by 2050 compared with emissions in 1990, with an especially great reduction in high-income countries.

We focus on the changes that can be implemented with potentially available technology to reduce carbon dioxide (CO_2) emissions by 50% in high-income countries by 2030 and less in low-income and middle-income countries. These reductions in emissions by 2030 are consistent with an approach that will reduce emissions worldwide by 50% by 2050. We consider three case studies: the EU (27 countries), China, and India.

Models

We developed models to estimate health effects of electricity generation in 2010 and three scenarios for 2030—business as usual and two mitigation scenarios. Electricity generation is associated with almost every aspect of modern life and affects health in many ways (figure).[6,7] To quantify the effects of electricity generation on health, we focused in this study on pathways related to environmental emissions of particle air pollution, and did not take into account those arising from other environmental wastes or the risk of deaths related to the production cycle. We recognise that a full life-cycle approach, which looks at health effects of extraction, transport, generation, and disposal of waste, would have been preferable; however, data for all countries and technologies on a life-cycle basis are not available.

As for the other reports of this Series,[1–3] we did not include health benefits of climate change abatement because our focus was on direct and short-term health effects before much of the projected effects of climate

Key messages

- In the European Union (EU), China, and India, changes of modes of electricity generation would reduce not only carbon dioxide (CO_2) emissions but also particulate air pollution and consequently mortality. The greatest effect would be in India, where electricity generation is associated with the greatest level of particulate pollution, and the smallest in the EU, where electricity production from fossil fuels is quite clean.
- Between now and 2030, the time by which such changes in electricity generation might be implemented, pollution from electricity production and its adverse effects will rise if no climate change mitigation is implemented under a business-as-usual scenario in India because of increasing production. The increased production is offset in China and the EU to a point that pollution concentrations are expected to drop over time to 2030. Even in India and China, however, scenarios in which CO_2 emissions are reduced show decreased levels of pollution and associated adverse health effects compared with business-as-usual scenarios in 2030.
- If effects on mortality are expressed in monetary units, costs of changing electricity production to modes that emit less CO_2 would be substantially offset by reduced pollution-related mortality, especially in China and India.

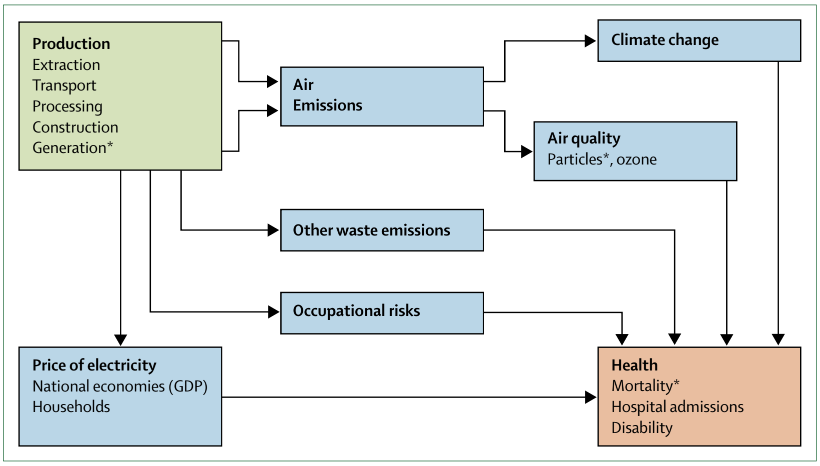

Figure: **Pathways in which electricity production affects health**
GDP=gross domestic product. *Indicate pathways modelled in this report.

change will have occurred. We also did not take into consideration economic pathways (ie, economic development patterns, market price trends, and socio-economic behaviour), although these are important both in terms of national economic performance and, more importantly, fuel costs and use by households. Finally, we did not quantify health effects that relate to energy security, geopolitical risks, or lifestyle because we regarded them as too complex.

Quantification of exposures entailed two models. First, implementation of an economic model, POLES—Prospective Outlook on Long-term Energy Systems—that specifies future growth paths under different greenhouse-gas emission constraints and estimates how these can be met in the context of global energy markets. This model was developed by the University of Grenoble (Grenoble, France) as part of a wide effort of the European Community to understand associations between economic, energy, and climate systems in a global framework.[8] It provides estimated energy use up to 2050 under different scenarios for all developed countries and for India, China, and some other developing regions (panel 1).

Second, we applied air pollution emissions—dispersion models to estimate population exposure to air pollutants from fossil-fuel combustion and associated health consequences under different forms of electricity generation. Specifically, we used the GAINS model—Greenhouse Gas and Air Pollution Interactions and Synergies (panel 2).

Models were developed for three scenarios to compare health burdens caused by electricity generation in the EU as a whole, India, and China. The first scenario was business as usual, in which no additional measures are taken to reduce greenhouse gases other than what is already in place. The second was a limited-trade scenario, in which developed countries aim for an 80% reduction in greenhouse gases by 2050 relative to that in 1990, with the rest of the world making whatever further reduction is necessary to achieve a 50% global reduction by that date. This scenario assumes that developed countries can trade emission rights in pursuit of the 80% objective, whereas developing countries are not fully engaged in this trade (sale of some certified emission reductions from developing to developed countries might be possible, as is the case of the Clean Development Mechanism). Because of time constraints, we analysed this scenario only for India and China because analysis for the 27 member states of the EU would have meant estimating the effects for all 27 states. The third setting was a full-trade scenario, in which only the 50% target is imposed on the system and cuts are made wherever it is most cost effective to make them. All countries can in this scenario participate in a global emissions trading system. Because developing countries have more low-cost options, greater reductions are made in those countries than in developed ones. In this scenario, developed countries make cuts of about 65–75% of their levels in 1990 by 2050, and developing countries make correspondingly bigger cuts.

The second and third scenarios (limited trade and full trade) are both consistent with stabilisation at 550 CO_2 parts per million by volume. Further details of these scenarios, including the variety of production modes identified for each region, are provided in table 1.

These reduction targets apply to total emissions, not only to those from the power sector. Here, the percentage reduction in each sector is not assumed to be the same as the overall target (other reports in this Series[1–3] make different assumptions). The percentage reductions are greater than for most other sectors for electricity, because there are more low-cost options in this sector. For example, in the limited-trade scenario, emissions for the EU from the electricity sector are reduced by 56% in 2030 compared with those in 2000, whereas total emissions in the region are only reduced by 34%. Similar differences can be seen for all regions. Table 2 shows emissions of CO_2 in each region in 2000 and 2010, and for the scenarios for 2030. Emissions for 1990 are not included in this table because data for the POLES model were not available for that year.

Table 1 shows a detailed breakdown of the different technologies adopted and the effect of a carbon constraint on the electricity sector. The adoption of the carbon target slightly reduces generation of electricity by 2030 compared with what it would have been in the absence of a target: about 6% in the 27 member states of the EU, 16% in India, and 12% in China. The remaining reduction comes from a shift in technologies and fuels. Most reduction is the result of: a decrease in coal, which declines from 37% of all generation in business-as-usual scenarios to around 25% with the carbon constraint in the EU, from 75% to 50% in India, and from 68% to 49% in China; the use of carbon capture and storage, which captures around three-quarters of CO_2 emissions

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from coal; an increase in nuclear energy; and an increase in the share of renewable energy of around 10% in China and India, but not in the 27 member states of the EU. Although there is no increase in the share of

Panel 1: The POLES model

POLES (Prospective Outlook on Long-term Energy Systems) is an econometric, partial-equilibrium world model for analysis of long-term energy, technology, and climate change effects, with a special focus on the electricity sector. It takes long-term projections for economic output and population growth as given, along with data for supplies, costs of extraction, and location of the main sources of energy. The model analyses demand and supply for energy in interconnected markets, with prices being the main determinant of the choice of energy and of technology.

The current version of the model works with 47 national or regional submodels, which allows identification of the key parties in the international negotiation, whether industrialised or emerging. These regions are Canada, the USA, 20 regions of enlarged Europe, Russia, and Ukraine, and five key developing countries (Mexico, Brazil, India, South Korea, and China). In each region, energy options change over time at different rates as some technologies become more efficient and as prices of fuels change at different rates. Among the factors that determine the cost of different fuels and technologies is the price of carbon. The model can be run under different carbon reduction targets, which in turn imply different paths for the prices of carbon (where a carbon constraint is imposed, it calculates a price of carbon implied by the constraint). These prices can be regarded as taxes per tonne emitted, or as the cost of a certificate that is tradable and that allows the holder to emit a tonne of carbon. As carbon prices rise, they induce reduction of the use of fuels that emit carbon, while also providing incentives for the development of technologies that are carbon efficient or even carbon neutral.

The model aims to address four main objectives. The first is to reduce the uncertainties in future developments of world energy consumption and greenhouse-gas emissions with baseline scenarios constructed on a common consistent framework of market and price dynamics. The second is to provide a global analysis of emission reduction policies worldwide. The third is to provide information about the strategic areas for development of energy–environment policies, taking into account costs and intensity of diffusion of technologies. The fourth is to assess the marginal abatement costs for carbon dioxide emissions. Finally, it also addresses the effect of emission reduction policies on international energy markets and prices.

The model uses data produced by ENERDATA (Grenoble, France) available from 1971, together with techno-economic data obtained and structured at Laboratoire d'Economie de la Production et de l'Intégration Internationale (LEPII, CNRS-UPMF, Grenoble, France). The model has been used to produce energy and climate scenarios in different research projects of European Union's DG Research Framework Programmes, the latest being the ADAM project.

Panel 2: The GAINS model

GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) can be used to estimate the potential effect of changes in energy policies on carbon dioxide emissions, air pollution concentrations, and resulting effects on health. Air pollution emissions were calculated from estimates of the quantities of fuels (eg, coal, gas) burnt for about 300 sources and 530 emission control options.[9]

Air pollution estimates—combined with population distribution data—provided the exposure estimates used in subsequent calculations for our study. In the GAINS model, associations between emissions of air pollutants in a particular (source) region and resulting concentrations in other (receptor) regions are based on atmospheric chemistry transport models. Pollutants taken into account in these models were anthropogenic primary particulate matter with aerodynamic diameter 2·5 μm or less ($PM_{2·5}$), and secondary particles derived from sulphur dioxide, nitrogen oxide, and ammonia.

Calculations were done for every source region (country in Europe, province in China, or state in India). For all the pollutants, GAINS estimates emissions based on activity data, uncontrolled emission factors, the removal efficiency of emission control measures, and the extent to which such measures are applied.[9] We allowed activity data to vary according to POLES output, but kept changes in emission control measures constant across the scenarios analysed. We did not attempt to model the effect of carbon capture and storage on emissions of air pollutants. Emission calculations were done for all scenarios at 5-year intervals from 2000 to 2030.

National study regions were nested within a global grid resolution. Source–receptor associations were derived from model calculations in which anthropogenic emissions in each source region were reduced by 20%. For Asia, results from the TM5 chemical transport model[10] were used to create simplified (reduced-form) source–receptor associations. For primary $PM_{2·5}$, an almost linear relation between changes in emissions and atmospheric concentrations existed. For secondary inorganic aerosols, the relation was approximated with piecewise linear functions.

At local scales, emission sources (and therefore, to some extent, air pollution concentrations) are correlated with population density. This correlation means that the average air pollution concentration over 1° by 1° cells is unlikely to be representative of population exposure. GAINS adjusts for subgrid differences in particulate matter concentrations as a function of local emission densities and spatial extent of urban areas within grid cells.[4]

For **input data and results of the GAINS model** see http://gains.iiasa.ac.at

For more on **ENERDATA** see http://www.enerdata.fr/enerdatafr/

For more on **Laboratoire d'Economie de la Production et de l'Intégration Internationale** see http://webu2.upmf-grenoble.fr/LEPII/spip/

For more on **the ADAM project** see http://www.adamproject.eu renewable energy in the EU, the business-as-usual scenario already has considerable renewable electricity generation built in. Some minor differences exist between the limited-trade scenario and the full-trade scenario in China and India, where under full trade there is more carbon capture and storage undertaken and more nuclear energy (in India). In no case does the share of renewable energy respond to the change in trade options.

The GAINS model was used to estimate population exposure to outdoor particulate matter from electricity generation for each of the scenarios specified by the three POLES scenarios and for the 2010 baseline. Results of the air pollution model allowed for changes over time in emissions of pollutants arising from the use of gas, oil, coal, and biomass as better technologies are introduced. Particulate matter concentrations were population-weighted and included only the anthropogenic component of particulate matter. The model also includes projected changes in emissions from 2010 to 2030 for sectors other than electricity generation. However, although we adjusted emissions for electricity generation to account for the scenarios, we left all other sector emissions unchanged from business as usual. Changes in particulate matter concentrations between 2010 and 2030 thus indicate projected changes in all sectors (eg, transport). Difference between 2030 business-as-usual and the mitigation scenarios are, however, entirely caused by differences in electricity generation.

For consistency with WHO's Comparative Risk Assessment[11] and other modelling exercises presented in this Series (household energy,[1] transport[2]), we focused on fine particulate matter with aerodynamic diameter 2·5 μm or less ($PM_{2·5}$), for which the strongest evidence of adverse effects on health exists and for which methods for quantification of health effects are well established.

	EU	India	China
BAU			
Coal total	37%	74%	68%
Coal with CCS	0%	0%	0%
Gas	15%	5%	5%
Biomass	3%	0%	2%
Nuclear	14%	5%	3%
Renewable	26%	14%	19%
Other	5%	2%	3%
Total	100%	100%	100%
Total terawatt-hours	4473	3044	8972
Limited trade			
Coal total	25%	50%	49%
Coal with CCS	19%	36%	34%
Gas	19%	6%	9%
Biomass	4%	0%	2%
Nuclear	21%	16%	7%
Renewable	26%	23%	29%
Other	5%	5%	4%
Total	100%	100%	100%
Total terawatt-hours	4218	2572	7903
Full trade			
Coal total	26%	49%	48%
Coal with CCS	18%	38%	36%
Gas	19%	6%	9%
Biomass	4%	0%	3%
Nuclear	20%	17%	7%
Renewable	26%	23%	29%
Other	5%	5%	4%
Total	100%	100%	100%
Total terawatt-hours	4242	2550	7819

Source: authors' calculations based on the POLES model. Renewable energy includes wind, solar, hydrolic, and geothermal energy. Around a quarter to a third of gas generation also uses carbon capture and storage (CCS) in limited-trade and full-trade scenarios. BAU=business as usual. EU=European Union.

Table 1: **Distributions of electricity production mode (fuel) for the three scenarios for 2030**

Estimation of health burdens

See Online for webappendix

Methods for estimation of health burdens are described in detail in the webappendix pp 1–2. Briefly, we used an adaptation of the 2000 Comparative Risk Assessment exercise for the global burden of disease to estimate premature mortality, and hence years of life lost, in 2010 as a result of particulate air pollution, and how that would change under various counterfactual exposure concentrations estimated by the GAINS model. Years of life lost were not discounted or age-weighted, as is standard in published reports in the climate change field, although discounted years of life lost were calculated in sensitivity analyses. We specifically regarded effects of $PM_{2·5}$ on deaths from cardiorespiratory disease and lung cancer in adults, and acute respiratory infections in children, which were the associations considered in the Comparative Risk Assessment to be well established for quantification. Thus, following the practice of the Comparative Risk Assessment for outdoor air pollution we do not make estimates of disability caused by air pollution or years lost from disability. We used models and coefficients developed for the Comparative Risk Assessment. We focus mainly on differences between the 2030 business-as-usual and the two mitigation scenarios, but for context we also show total burden attributable to $PM_{2·5}$ in 2010 and 2030, estimated with a counterfactual $PM_{2·5}$ concentration of 4 μg/m³.

For an **example of a cost–benefit analysis** see http://www.cafe-cba.org

We also translated health burdens into monetary terms. Since this has now been done extensively as part of various EU and US projects on health effects, this exercise is not as controversial as it once was, and it allows comparison of the benefits with the costs of carbon mitigation (summarised in the price of CO_2 that the POLES model estimates).

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We did additional sensitivity analyses to test several assumptions using baseline years of life lost that were time-discounted and age-weighted, projected changes in demographics and health status in 2030, and different forms of associations between particulate matter and mortality risk. We also estimated occupational health effects, but, because preliminary estimates showed these to be much smaller than those of air pollution, we do not present results here.

Effects of mitigation policies on health

Table 3 shows particle pollution exposures and health burdens for 2010, business-as-usual scenario for 2030, and the two mitigation scenarios for 2030 compared with the business-as-usual exposures for 2030. Air pollution exposure has a serious effect on health in the EU. Years of life lost in 2010 would be 2002 per million people, which, with no climate change mitigation policies, would fall to 1185 per million people with emissions predicted from changes projected anyway by 2030 (caused by better technologies and less use of coal). However, in the full-trade scenario the decline is increased by a further 104 per million people. Therefore, by pursuing a climate target we would, if other changes did not modify this, save 104 life-years per million people every year in the EU (48 000 in total). For China, the loss of life-years in 2010 is estimated at 19 205 per million people. Under emissions changes projected anyway by 2030, this would drop to 18 488 life-years per million people because of a shift to cleaner coal and other changes. With a climate target, however, as given in the full-trade scenario, there is a further fall of 542 life-years per million people in 1 year. Therefore, the climate target saves about 542 life-years per million people.

For India, the loss of life-years in 2010 is estimated at 19 489 per million people, which increases to 28 408 with increasing levels of emission expected under the business-as-usual scenario by 2030. With the climate target, however, life-years lost falls by 1492 per million people compared with the business-as-usual scenario in 2030. A similar pattern to that of loss of life-years is seen for premature deaths (table 3). Comparison of the results from the limited-trade scenario with those from the full-trade scenario shows a smaller saving in life-years lost from the climate policy in China (148 000 fewer life-years are saved) but no difference in the case of India.

Table 4 compares the contribution to loss of life-years for each type of health burden modelled. The greatest contribution to mortality is from cardiorespiratory disease followed by lung cancer. Results also show the large burdens associated with childhood acute respiratory infection in China and India, although these remain small compared with adult cardiorespiratory burden.

Table 5 shows the additional cost of the mitigation scenarios relative to the business-as-usual scenario in 2030 in all regions and the additional health benefit of the same scenarios. Costs and benefits are given per tonne of CO_2 not emitted. Health benefits are valued at the current €40 000 per loss of life years, used by the EU to decide on policies to control local air pollution. This value is converted into US$ at the rate of US$1·4 per €1 (exchange rate in June, 2009). Values of loss of life-years would differ at the present time across countries, but we should remember that by 2030 considerable convergence is expected in incomes per person between the 27 member states of the EU, China, and India. For example, by 2030, income per person in China and India are expected to be 69% and 30%, respectively, that

	Total emissions of CO_2			Emission of CO_2 from electricity		
	EU	China	India	EU	China	India
2000	3876	3001	1007	1235	1232	528
2010	3912	6991	1571	1305	3298	825
2030						
BAU	4444	11 358	3825	1726	5539	1990
Limited trade	2504	5404	1918	543	1679	511
Full trade	2867	4862	1738	669	1422	413

Data are expressed per million tonne. Source: authors' calculations based on the POLES model. BAU=business as usual.

Table 2: **Estimated emissions of carbon dioxide (CO_2) under different scenarios**

	2010*	2030 BAU*	Changes relative to 2030 BAU†	
			Limited trade‡	Full trade
EU				
$PM_{2·5}$ (μg/m³)	8·8	6·9	..	−0·3
YLL (per million population)	2002	1185	..	−104
YLL (total in thousands)	924	547	..	−48
US$ of YLL (in billions)	52	31	..	−3
Premature deaths from $PM_{2·5}$ (per million population)	200	118	..	−10
China				
$PM_{2·5}$ (μg/m³)	88	81	−4	−5
YLL (per million population)	19 205	18 488	−432	−542
YLL (total in thousands)	25 751	24 789	−578	−726
US$ of YLL (in billions)	1442	1388	−32	−41
Premature deaths from $PM_{2·5}$ (per million population)	1483	1429	−32	−40
India				
$PM_{2·5}$ (μg/m³)	55	108	−10	−10
YLL (per million population)	19 489	28 408	−1492	−1492
YLL (total in thousands)	23 652	34 476	−1811	−1811
US$ of YLL (in billions)	1325	1931	−101	−101
Premature deaths from $PM_{2·5}$ (per million population)	1041	1435	−62	−62

BAU=business as usual. EU=European Union. YLL=years of life lost. $PM_{2·5}$=particulate matter with aerodynamic diameter 2·5 μm or less. *Approximate total burden based on 4 μg/m³ $PM_{2·5}$ comparison concentration. †Reductions in exposure or mortality burden are negative. ‡Results for the limited-trade scenario are not given for the EU.

Table 3: **Particulate pollution effects on mortality in 2010, and business-as-usual and mitigation scenarios in 2030**

	YLL in 2010* (per million population)	YLL in 2030 BAU* (per million population)	YLL: changes relative to 2030 BAU†	
			Limited trade‡	Full trade
EU				
Total	2002	1185	..	−104
Cardiorespiratory	1502	890	..	−78
Lung cancer	500	295	..	−26
ARI§	1	1	..	0
China				
Total	19 205	18 488	−432	−542
Cardiorespiratory	15 801	15 242	−338	−424
Lung cancer	2996	2876	−72	−91
ARI§	408	369	−21	−27
India				
Total	19 489	28 408	−1492	−1492
Cardiorespiratory	16 579	22 416	−881	−881
Lung cancer	620	873	−39	−39
ARI§	2291	5120	−572	−572

BAU=business as usual. YLL=years of life lost. EU=European Union. ARI=acute respiratory infection. *Approximate total burden based on 4 μg/m³ $PM_{2.5}$ comparison concentration. †Reductions in exposure or mortality burden are negative. ‡Results for the limited-trade scenario are not given for the EU. §For children younger than 5 years.

Table 4: Effects on mortality by cause of death

	Limited trade	Full trade
Costs of reduction relative to BAU		
EU	169·9	137·2
China	67·6	68·3
India	42·6	41·9
Health benefits relative to BAU		
EU	..	1·82
China	5·99	7·05
India	48·98	45·94
Net costs of reduction relative to BAU		
EU	..	135·4
China	61·6	61·2
India	−6·4	−4·1

BAU=business as usual. EU=European Union. *In US$ per tonne of CO_2 not emitted.

Table 5: Costs of carbon reduction targets and value of health benefits*

of the EU. Since (mainly for reasons of equity) a single value is applied across all the 27 member states of the EU and since the ratio of the highest to the lowest income per person is more than three, it seems reasonable to apply the same value across all countries in the study. Direct costs per tonne of CO_2 not emitted in the full-trade scenario range from $42 to $137, with the highest value in the EU, the lowest in India, and China in between. Health benefits, however, are in the range of $2 per tonne of CO_2 not emitted in the EU, $7 in China, and $46 in India. If we subtract health benefits from direct costs, we get only small reductions in the EU, but appreciable reductions in China and India. Indeed, for India health benefit exceeds the direct costs of reducing CO_2, leaving a negative net cost of $4 per tonne of CO_2 not emitted.

We also did several sensitivity analyses. Use of loss of life-years discounted by 3% per year beyond the year of death and age-weighting (following the standard Comparative Risk Assessment practice) reduced loss of life-years and hence benefits by about 50% in all scenarios. Comparisons between scenarios were thus not affected. Use of baseline mortality and loss of life-years projected by WHO for 2030[12] to account for expected changes in demographics and baseline health, changed business-as-usual for 2030 and mitigation scenarios, increasing the benefits of mitigation about 20% in China and reducing them about 10% in India. Effects of acute respiratory infections were considerably less because of the lower baseline acute respiratory infections rates expected. In the EU, where demographics and baseline rates of disease are projected to change less than elsewhere, estimates changed little.

Change in assumptions on the shape of the particulate matter and mortality exposure–response relation had a greater effect on the results. When a linear rather than our default log linear exposure–response relation was assumed across the exposure range, health effect of mitigation in China and especially in India increased considerably. Relative risk for a given change in particulate matter was much greater with the linear relation at these high concentrations. Health effects of mitigation were perhaps surprisingly enhanced when a log linear rather than the default linear exposure–response relation was assumed for the EU because of the increased relative risk of this model at low concentrations. Detailed results from the sensitivity analyses are provided in the webappendix pp 3–6.

Conclusions

This study indicates that some health benefits will result from changes in the means of electricity generation in response to a 50% CO_2 reduction target by 2050. Estimates indicate savings in years of life that will be greatest in India, followed by China. If in 2030 changes were made that were consistent with the 2050 reduction targets, gains in India and China would be about 1500 and 500 life-years per million people, respectively. In the EU, the benefits are expected to be more modest, at around 100 life-years per million people in 2030.

The modest improvement in Europe expected in a carbon-mitigated future compared with that in a business-as-usual future is mainly the result of the existence of already clean methods of electricity production from fossil fuels. These methods are projected to become cleaner in the business-as-usual setting. This is also the case, but to a lesser extent, in China.

Estimates for health benefits per tonne of carbon saved from electricity are within the wide range

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Panel 3: Co-benefits of measures to reduce carbon-based power generation

Reduction of the generation of power from fossil-fuel-based sources such as coal, oil, and gas will yield health benefits in terms of reductions in local air pollutants, notably small particles. These gains are referred to as co-benefits of a climate policy that reduces emissions of greenhouse gases. When deciding on which carbon reduction policy to implement and where to implement it, such co-benefits are clearly an important consideration.

The studies reviewed in the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report[5] show that moderate carbon dioxide (CO_2) reductions (10–20%) in the next 10–20 years also reduce sulphur oxide emissions by 10–20%, and nitrogen oxide and particulate matter emissions by 5–10%. Dependent on the population exposed in the targeted sectors and its vulnerability, this reduction can lead to a few thousand premature deaths avoided in Europe and North America (and Korea), and to several tens of thousands in Asian and Latin American countries. In both cases, inclusion of the effects of air pollution on mortality caused by chronic diseases greatly increases the size of the co-benefits.

Most previous research on co-benefits records them in monetary terms per tonne of CO_2 abated. This measure involves assessment of CO_2 reduction in premature mortality and morbidity. Although controversial, reporting of benefits in monetary terms (eg, euros, US dollars, or British pounds) per tonne of CO_2 abated has the advantage of allowing these benefits to be compared with the costs of making the abatement.

Some studies cited in the third assessment report of the IPCC[13] and in a review of the Organisation of Economic Co-operation and Development (OECD)[14] indicated a wide range of health co-benefits, dependent on country, assumptions of baselines, pollutants included, dose–response functions used, and the assessment attached to different health endpoints, especially premature mortality. The range (expressed in monetary terms for 2000) was from US\$0·6 to \$145 per tonne of CO_2, with most less than \$30. Because marginal abatement costs (ie, the costs of the most expensive abatement options to meet the proposed target of a 50% reduction by 2050) from the power sector are estimated to be in the range of \$20–40, such benefits could make a big difference in the decision of which options to select for reducing greenhouse gases.

The reviewed studies included in the IPCC fourth assessment report and some other recent publications[15–25] that value the health effects in monetary terms produced a range between \$2 and \$133 per tonne of CO_2 (expressed in monetary terms for 2000), with those for OECD countries between \$2 and \$38. Values for developing countries are between \$20 and \$133 per tonne of CO_2 reduced, although a few lower values exist for this group as well.

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An important feature of published reports is the observation that the co-benefits increase over time since CO_2 reductions are assumed to get larger. A report[19] on co-benefits for 25 state members of the EU estimated reduction of nitric oxide emissions by 4·6% in 2020 between baseline and the climate action scenario, and by 9·8% in 2030. For sulphur oxide, the estimated reduction was by 12% in 2020 and almost 17% in 2030. Reductions for particulate matter with aerodynamic diameter 10 μm or less (PM_{10}) and 2·5 μm or less ($PM_{2·5}$) are 5% and 4% in 2020, and 10% and 8% in 2030, respectively.

The studies indicate that co-benefits in developing countries are higher than are those in developed countries because of higher levels of pollution and spatial distribution of population and economic activities in these countries. This finding is mainly based on studies from Asian and some Latin American countries. No studies seem to be available for Africa. For India and China, one study indicated a median value of 70 avoided deaths from acute diseases alone per million tonnes of CO_2 reduced. Moreover, the benefits are greater from policies that reduce emissions from sources such as domestic stoves than they are from centralised power stations with high stacks. The former also generate much higher benefits relative to costs compared with the latter.

Comparison of the results of this study with those from earlier ones shows that differences can mostly be explained by levels of reductions in CO_2 analysed, sectors of the economy covered, pollutants assessed, and year at which the evaluation is made and the year against which the comparison is made.

For example, an early study[26] estimated in China a reduction in 2020 of 4400–5200 lives from a 15% reduction in emissions in 2020 relative to business as usual. We estimate a saving of around 57 440 lives in 2030 from a reduction of 57% relative to business as usual. The most comprehensive estimate is that from an OECD study[14] that indicated a saving of around half a million lives in 2030, which is much bigger than our estimate. However, the OECD study looked at all sectors, whereas we took into account only the electricity sector. Another study[17] estimated that electricity accounts for about 17% of the health problems in China. Therefore, if we scale down the OECD estimate about 6%, we get about 83 000 lives saved, which is still a bit more than our estimate. The remaining difference might be the result of effects other than particulate matter and secondary particles, which they have included and we have not (ie, sulphur oxide, nitric oxide, ammonia).

For health benefits relative to the costs of mitigation, studies are not in agreement. For China, some estimated the direct costs of the reduction as negative,[17] which indicates a gain from reduction of emissions using a carbon tax, even when no account is taken of the health benefits. Others, such as the Netherlands Environmental Assessment Agency (NEAA),[24] estimated the costs of achieving the

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target reduction at about $36 per tonne of CO_2. Our estimate is $68 per tonne of CO_2, which might indicate that health benefits per tonne reduction from electricity are less than are those from other sectors (eg, transport) and that the NEAA study works with CO_2 equivalents, whereas we only took into account CO_2.

For India, our results are similar to those in other studies. We estimate savings in lives at 93 000, which is less than the 400 000 in the OECD study, but we cover only the electricity sector. If 17% reduction for this sector is true for India, then our estimates would in fact be slightly higher than that of the OECD study. We estimate 20 lives saved per tonne of CO_2 compared with 91 from another study,[16] but the difference is related to difference in amount of reduction aimed for. As bigger reductions in CO_2 are achieved, savings in lives per million tonnes drop. We can compare direct costs of reduction only with those of the OECD study: we estimated $42 per tonne of CO_2 removed, whereas the OECD study estimated $46 per tonne of CO_2.

For the EU, our results in terms of lives saved (5000) is in line with previous studies. It is lower than one previous estimate[25] (9000 lives saved in 2020) or that of the European Environment Agency (EEA) study[19] (23 000 lives saved in 2030), but these studies cover all sectors. Health benefits in monetary terms are low in our study ($2 per tonne of CO_2) compared with those in other studies that cover more sectors ($11–37). This difference might be due to the fact that health benefits in this sector per tonne of CO_2 reduced are lower than the average across all sectors.

estimated by other researchers (panel 3).[15–22] Our estimates indicate much higher benefits for developing countries than for developed countries, which is also a finding of some other studies.[5]

The very high concentrations of $PM_{2.5}$ projected in India, and to a lesser extent in China, under a business-as-usual scenario indicate a projected increase in demand for electricity, partly caused by population growth. These concentrations can be decreased without reducing CO_2 emissions, as the EU and other developed countries show. However, such air quality controls are expensive, and these costs would be offset by decarbonising electricity production. Furthermore, the high concentration of particulate matter, even in the mitigation scenarios, suggests that air quality management would be necessary together with decarbonising electricity generation to reduce adverse health effects to acceptable levels.

Because of the high availability of coal and the fact that it is a cheap fuel for generation of electricity, especially in India and China, imposition of a major carbon target results in both countries adopting substantial carbon capture and storage (table 1). Although carbon capture and storage helps to meet the carbon target, we have assumed that coal plants adopting this method do not change emissions of other pollutants relative to the technology adopted for the generation. The effect of carbon capture and storage on emissions other than CO_2 is currently an active area of research. The 2005 IPCC special report on carbon capture and storage shows that air pollution co-benefits associated with this method have not yet been analysed.[27] Preliminary analysis shows that some plants operating with carbon capture and storage could reduce emissions of sulphur dioxide, but in all cases emissions of nitrogen oxide and ammonia increase. The issue has been studied further, supporting some of these results[28] and indicating that particulate matter emissions fall with some forms of carbon capture and storage, but presently too much uncertainty exists for these factors to be modelled with any confidence. Hence, we have not treated particulate matter emissions from coal plants with carbon capture and storage differently from other coal plants. Because of this assumption, less reliance on carbon capture and storage and more on renewable or nuclear generation would lead to greater estimated reductions of health burden caused by air pollution.

Our calculations are approximations and have limitations. Estimates of air pollution and health effects are based on current knowledge on adverse health effects of electricity production, but inevitably have substantial uncertainties. The air pollution modelling approach is done at a coarse spatial scale because of limitations of computational power. We have more confidence in the estimated relative changes in exposure between 2010 and the scenarios than in the absolute changes. Adjustment of estimates for subgrid scale variations in population exposure improves the accuracy of model predictions compared with that of observations of air pollution concentrations at urban monitoring stations, but the true association between emissions and biologically effective exposure is not known. Health effects of air pollution are also uncertain in terms of the specific pollutants responsible for adverse effects and magnitude and functional form of the exposure response. For example, alternative models considered by the Comparative Risk Assessment change the estimated 1-year reduction in years of life lost in the EU from the 2030 business-as-usual baseline to the 2030 mitigation scenario from about 100 to 230 per million people, and in India from about 1500 to 8300 (webappendix pp 1–6). Also, by considering only effects of particle pollution and mortality, we might have underestimated the total health burden. Research has emphasised that ozone has important effects on mortality, and particulate matter is associated with non-mortality outcomes.[29,30] Nevertheless, we believe that this model indicates broad health effects of electricity production, resulting from plausible climate change mitigation policies.

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Interpretation of these results should also take into account that we consider only one pathway (albeit an important one), linking electricity production to health, from many (figure). In particular, if mitigation changes lead to changes in affordability of electricity, one might expect adverse health effects through this pathway. However, such effects depend on social policies, which could moderate adverse effects of lowering affordability on disadvantaged groups. Furthermore, we did not take into account health effects of generation technologies through waste products other than air emissions—a much discussed issue for nuclear generation and an emerging one for carbon capture and storage.[31,32]

We did not take into account greenhouse pollutants other than CO_2. Sulphate aerosols, formed from oxidation of sulphur dioxide, have a cooling effect that offsets, to some extent, the warming effect of CO_2. They are also an important component of $PM_{2\cdot5}$ and might be implicated in adverse health effects. This issue is considered in greater detail in the fifth paper in this Series.[33]

Finally, we should acknowledge that the comparisons we made were partly artificial. We estimated effects of various changes in electricity production projected as possibilities for 2030, but in estimating health effects we used the population in 2010. The logic was that the 2010 population suddenly experienced changes in exposure not envisaged until 2030, or the age and disease baseline were unchanged from 2010 to 2030. We used this approach because projections of such changes in population age structure and disease burdens, which depend on several factors including economic growth between now and 2030, are complex and uncertain. However, sensitivity analyses with WHO's projected changes in demographics by 2030 confirmed that comparisons within the 2030 scenarios were insensitive to specifics of baseline population. Similarly, we did not distinguish between health effects that might be immediate (acute effects on mortality) and those that might have a latent period (lung cancer), preferring to report an effect that would be apparent in the long term. These timing issues are described further in the webappendix.

Despite these limitations, we believe that we have shown clear health gains through decarbonising electricity production, and added information about the extent of such gains and how they are likely to compare, under the scenarios considered, in three regions of the world. We have also illustrated how those gains could be expressed in monetary terms to inform economic analyses. Health benefits are not usually taken into account when deciding between policies affecting electricity production, whether or not that policy considers climate change. Here, we make a case for doing so.

Contributors

AM, BGA, SH, CT, and PW contributed to the data analysis, interpretation, and writing of the report. PQ designed the energy scenarios and contributed to the analysis. AM and AC contributed to the economic analysis and the review of previous studies. SM did the simulations with the model POLES.

Conflicts of interest

We declare that we have no conflicts of interest.

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Health and Climate Change 4

Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture

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Agricultural food production and agriculturally-related change in land use substantially contribute to greenhouse-gas emissions worldwide. Four-fifths of agricultural emissions arise from the livestock sector. Although livestock products are a source of some essential nutrients, they provide large amounts of saturated fat, which is a known risk factor for cardiovascular disease. We considered potential strategies for the agricultural sector to meet the target recommended by the UK Committee on Climate Change to reduce UK emissions from the concentrations recorded in 1990 by 80% by 2050, which would require a 50% reduction by 2030. With use of the UK as a case study, we identified that a combination of agricultural technological improvements and a 30% reduction in livestock production would be needed to meet this target; in the absence of good emissions data from Brazil, we assumed for illustrative purposes that the required reductions would be the same for our second case study in São Paulo city. We then used these data to model the potential benefits of reduced consumption of livestock products on the burden of ischaemic heart disease: disease burden would decrease by about 15% in the UK (equivalent to 2850 disability-adjusted life-years [DALYs] per million population in 1 year) and 16% in São Paulo city (equivalent to 2180 DALYs per million population in 1 year). Although likely to yield benefits to health, such a strategy will probably encounter cultural, political, and commercial resistance, and face technical challenges. Coordinated intersectoral action is needed across agricultural, nutritional, public health, and climate change communities worldwide to provide affordable, healthy, low-emission diets for all societies.

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Introduction

The food system is a major contributor to global greenhouse-gas emissions. Greenhouse gases are produced at all stages in the system, from farming and its inputs through to food distribution, consumption, and the disposal of waste.[1] The latest Intergovernmental Panel on Climate Change report estimated that agriculture alone accounts for about 10–12% of global greenhouse-gas emissions, and emissions from this sector are expected to rise by up to half again by 2030.[2] Agriculturally-induced change in land use—such as deforestation, overgrazing, and conversion of pasture to arable land—presently accounts for a further 6–17% of global greenhouse-gas emissions.[3]

About half of all food-related greenhouse-gas emissions are generated during farming. Farm-stage emissions include nitrous oxide and methane from livestock, and carbon dioxide from agriculturally-induced change in land use, especially deforestation.[4,5] Nitrous oxide (from pasture land and arable land used to grow feed crops) and methane (from the digestive processes of ruminant animals such as cows and sheep) account for 80% of all agricultural greenhouse-gas emissions.[4] The emissions per unit of livestock product vary by animal type and seem to be higher in beef, sheep, and dairy farming than in pig and poultry farming (figure 1).[6] However, the ability of cattle and sheep to graze on land unsuited to other forms of farming, and the emissions associated with the production of feeds for pigs and poultry complicate the interpretation of this difference (panel 1). By 2030, rising demand for meat, especially in countries with transition economies,[8–10] is expected to drive up livestock production by 85% from that in 2000, which will substantially affect emissions.[11] Once foodstuffs leave the farm, the bulk of food-related emissions arise from use of fossil fuels.

The food system contributes to health benefits and harms through the availability, quality, and affordability of food. Animal foods are important sources of protein,

Key messages

- The agriculture sector contributes 10–12% of total greenhouse-gas emissions worldwide. Deforestation and other changes in land use contribute an additional 6–17% of global emissions. Production of foods from animal sources is the major contributor to emissions from the agricultural sector.
- Global demand for animal-source foods is projected to increase substantially over the next 30 years, especially in transition economies.
- Technological strategies within the food and agriculture sector, such as improved efficiency of livestock farming, increased carbon capture through management of land use, improved manure management, and decreased dependence on fossil-fuel inputs, are necessary but not sufficient to meet targets to reduce emissions.
- A combination of agricultural technological improvements and reduction in production of foods from animal sources could provide an effective contribution to meet national and global targets to reduce emissions.
- Concomitant reductions in consumption of livestock products in high-consumption populations could substantially benefit public health, for example via reductions in ischaemic heart disease.
- Policies to reduce emissions in the agricultural sector must ensure that the nutritional requirements of populations that might benefit from consumption of some foods from animal sources are not compromised.

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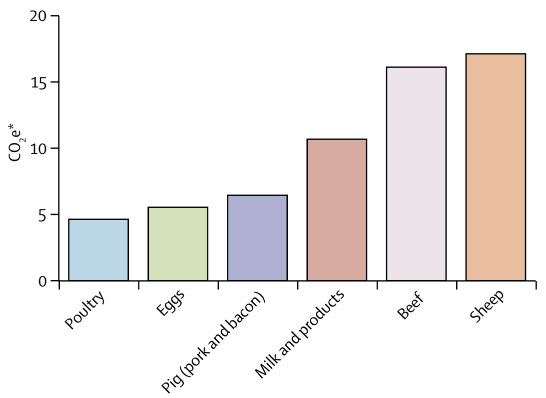

Figure 1: **Estimates of total greenhouse-gas emissions for livestock products in the UK[6]†**
CO_2e=carbon dioxide equivalents. *Tonnes of CO_2e per tonne of carcass weight, 20 000 eggs (about 1 tonne), or 10 m^3 milk (about 1 tonne dry matter equivalent). †These estimates do not include additional emissions resulting from global change in land use that is associated with livestock production in the UK.

energy, and nutrients—such as iron, calcium, vitamin B12, and zinc[12]—especially for children and for undernourished populations in low-income countries,[13] but are also major sources of saturated fats in the human diet.[14] In all but the poorest countries, diets are becoming high in saturated fat and sugar, and low in fruit and vegetables.[15] In addition to other behaviours such as physical inactivity and tobacco use, such diets are a leading cause of non-communicable diseases, including cardiovascular disease, some cancers, and type 2 diabetes.[16]

We aim to describe strategies that could substantially reduce farm-stage greenhouse-gas emissions in the food and agriculture sector by 2030, to meet targets recommended by the UK Committee on Climate Change, and to show and quantify the major effects on public health.

Potential strategies to reduce emissions

From expert reports we identified four strategies to reduce greenhouse-gas emissions in the food and agriculture sector, with a focus on the livestock sector in view of the dominant contribution of processes in livestock production to agricultural emissions:[4] improved efficiency of livestock farming; increased carbon capture through management of land use; improved manure management; and decreased dependence on fossil-fuel inputs.[3,17,18] Reduced production and consumption of foods from animal sources in high-consumption populations[2,4,7,19–22] has also been proposed as a strategy. We did not consider other potentially important strategies including reduction of emissions from food transport, processing, and retailing since these are tackled best through measures to lower the carbon emissions from energy supplies and improve efficiencies. Nor did we assess the potential effect of decreasing food waste,[23] although we acknowledge that this strategy could contribute to reduced emissions.

Panel 1: Greenhouse-gas emissions from ruminant and monogastric animal production

A shift from the production and consumption of livestock products of ruminant origin (beef, lamb, mutton, milk) to those of monogastric origin (pork, chicken, eggs) has been suggested as a measure to reduce greenhouse-gas emissions.[7] Indeed, emissions per kilogram of livestock product seem to be lower for monogastric than for ruminant animals (figure 1), at least partly because pigs and poultry have better feed-conversion efficiency than do ruminants, and because they do not emit enteric methane while digesting their feed. However, production of monogastric animals is inherently dependent on cereals and soy which could be more efficiently consumed by human beings directly, whereas cattle and sheep can subsist on marginal land that could not be used for arable production (often supplemented with food and agricultural byproducts). In so doing, cattle and sheep can make use of land that is unsuited to other forms of food production, thereby helping to avoid change in land use and reducing the competition between animals and human beings for cereals. Cattle and sheep grazing at the right stocking density on unploughed pasture can also help to maintain and even sequester carbon in the soil. Such resource efficiency by ruminants is not shared by pigs and poultry, except for cottage-scale pigs and poultry which are fed on kitchen scraps.

However, the global situation is complicated. Although ruminants can subsist on grassland, industrialised beef and dairy production relies on large inputs of cereals and oilseeds with accompanying methane emissions, thereby combining the disadvantages of monogastric and ruminant livestock production. Increasing demand for beef has led to the growth of cattle ranching and consequent deforestation in the Amazonian region and elsewhere. Furthermore, in developing countries, extensive grazing systems can lead to land degradation and the loss of soil carbon in regions where population pressures are high for human beings and livestock. Therefore, the merits of different livestock types to reduce emissions largely depend on the scale of demand and the system in which the animals are reared.

Pathways to health

We mapped the pathways from our selected strategies to reduce emissions to the most plausible nutrition-related health outcomes (figure 2). Technological strategies are necessary components of efforts to reduce emissions, but they will have little effect on health. By contrast, change in dietary intake of saturated fat from animal sources is a major pathway to population health. Consistent experimental and epidemiological evidence has linked intake of saturated fat with cardiovascular disease, largely because of the effect on serum cholesterol concentrations.[16,24] Cardiovascular disease is the world's leading cause of death, with the largest burden in countries of middle and low income.[25] Moreover, consumption of high-fat energy-dense diets is associated with increased risk of obesity,[16]

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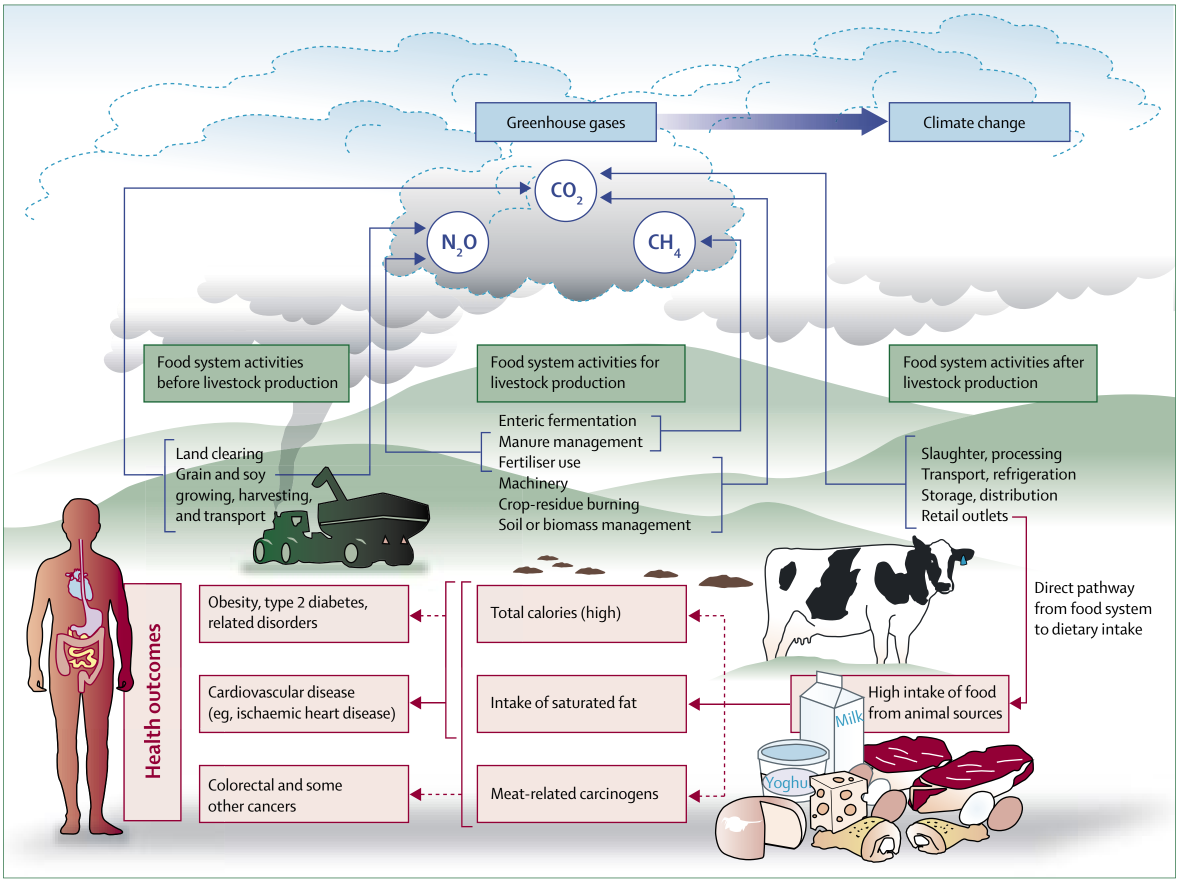

Figure 2: **Processes in the food and agriculture system that lead to greenhouse-gas emissions and population health outcomes**
Dotted lines indicate health outcomes that were not modelled in this study. CO_2=carbon dioxide. N_2O=nitrous oxide. CH_4=methane.

and, in the case of red meat, increased risk of colorectal cancer[26] and total mortality.[27]

Estimation of the effect on population health

To analyse the effect of reduced consumption of foods from animal sources on population health, we focused on changes in livestock production, the estimated shifts in intake of saturated fat and cholesterol at a population level, and the burden of cardiovascular disease, specifically ischaemic heart disease and stroke. We used Comparative Risk Assessment for modelling, as described in the first paper in this Series,[28] and briefly outlined in webappendix pp 1–2. We used case studies from the UK and São Paulo city, Brazil, to quantify the relation between the strategy to reduce emissions and the burden of ischaemic heart disease and stroke that would be attributable to decreased consumption of saturated fat and cholesterol. Both populations consume similar amounts of saturated fat; the UK is a high-income country that emits large quantities of greenhouse gases, and Brazil is an emerging economy with increasing greenhouse-gas emissions.

The UK has good data available for both dietary intake and greenhouse-gas emissions. Estimates of average consumption of saturated fat and cholesterol in the UK, stratified by age and sex, are available from published data gathered for the nationally representative National Diet and Nutrition Surveys.[29–31] The surveys used 4-day[29] or 7-day[30,31] weighed dietary intake methods, and the data are separated into the source of dietary saturated fats by broad food category, enabling estimates of the proportion of total intake of saturated fat of animal origin. The source of saturated fat for some food categories (eg, cereal products such as cakes that might contain saturated fats from both animal and vegetable sources) was not known and was assumed to be of vegetable origin. Our estimates of intake of saturated fat from animal sources in the UK are therefore probably conservative.

See Online for webappendix

Brazil, a country with a rapidly growing economy, is a mass producer and exporter of livestock products. The Brazilian population consumes substantial quantities of foods from animal sources and is undergoing a transition in its overall pattern of dietary intake.[32] Few data about greenhouse-gas emissions are available from the Brazilian agricultural sector, which restricted the scope of our modelling. Cattle ranching in combination with soy cultivation (at least partly for animal feed) are key causes of Amazonian deforestation, which substantially contributes to global emissions of greenhouse gases.[5,33] In

Panel 2: **Strategies to reduce greenhouse-gas emissions from the UK food and agriculture sector**

The supply of food to UK consumers produces about 160 megatonnes of carbon dioxide equivalents ($MtCO_2e$), or 19% of the UK's total greenhouse-gas emissions.[1,35] These estimates include the embedded emissions from imported foods for human consumption and feedstuffs for UK livestock production, and exclude emissions from exported foods. In 1990, total emissions from the UK domestic agriculture sector were 55 $MtCO_2e$, a figure which by 2007 had reduced to 44 $MtCO_2e$, of which 36 $MtCO_2e$—about 80%—were due to the rearing of livestock.[36] About two-thirds of nitrous oxide emissions are attributable to livestock because of high nitrous oxide emissions from grasslands, which account for a high proportion of the UK's total agricultural land area.

In 2008, the UK Government agreed that by 2050, it would achieve an 80% reduction in total UK greenhouse-gas emissions from concentrations recorded in 1990, and has further committed to achievement of a 34% reduction by 2020.[37] These targets relate to emissions generated within UK borders only, and do not apply to the embedded emissions in the totality of goods and services consumed. To achieve the target for 2050, emissions from food and agriculture will need to decrease from concentrations recorded in 1990 by 50% by 2030, based on a proportionate decline in emissions between 2020 and 2050.

We have calculated the reductions in emissions that could be achieved by technological changes in livestock farming, and estimated the additional reductions in livestock production that would be needed to bridge the gap with the emissions target. We have assumed that agriculture contributes a proportional share to emissions reductions that is the same as for all other sectors. The potential reduction in emissions from the strategies is summarised in table 1.

(Continues in next column)

(Continued from previous column)

Strategy one: technological change

Technological change to reduce emissions in the UK agricultural sector includes increased efficiency, new technologies, and improved farm management, but estimates of its contribution to achievement of the target for 2020 vary widely: 3–13 $MtCO_2e$.[1,23,37,38] The mid-range ADAS estimate of 5 $MtCO_2e$ is used as the basis for our analyses.[38] In the absence of robust estimates of the UK potential to reduce emissions from agriculture by 2030, we made several assumptions. The potential to reduce emissions from technological means was taken at a starting point of 5 $MtCO_2e$ for agriculture in 2020, with 80% attributed to livestock (4 $MtCO_2e$).[4] We assumed that the greenhouse-gas mitigation achievable for 2020–30 would be equal to the estimated percentage improvement for 2007–20. For the livestock sector, the reduction for 2007–20 is expected to be 11·1% in $MtCO_2e$ (reduction of 4 $MtCO_2e$ from 36 $MtCO_2e$). A further 11·1% reduction for 2020–30 lowers livestock emissions to about 28 $MtCO_2e$. However, to reach the target of reduction from concentrations in 1990 by 50% by 2030, emissions from the livestock sector would need to be 22 $MtCO_2e$.

Strategy two: technological change and reduced livestock production

There is a gap of 6 $MtCO_2e$ between the reduction in emissions that can be achieved via technological strategies and the UK's target for 2030. To accommodate the projected UK population increase of 10% for 2010–30,[39] we have added 10% onto projected emissions in 2030 (assuming a proportionate increase in the amount of livestock products needed as projected from present UK consumption), resulting in emissions of 31 $MtCO_2e$ and an increase in the emissions gap to 9 $MtCO_2e$ (table 1). With the assumption that the emissions gap can be met by reduction of livestock production above that achieved by technological improvements in productivity, a reduction in livestock production of about 30% is needed by 2030. These reductions would be additional to technological changes. The lower the feasibility of technological and managerial changes, the greater the additional reductions in production that will be needed. Our burden of disease analysis assumes that this 30% reduction in livestock production will be matched by an equal reduction in the consumption of foods from animal sources.

the absence of nationally representative data about dietary intake for the Brazilian population, we obtained estimates of saturated-fat and cholesterol consumption for adults aged 20 years and older from the Household Health Survey,[34] which was undertaken in the largest city in Brazil, São Paulo. The Household Health Survey used a 24-h dietary recall method,[34] and unpublished data were provided on the intake of saturated fat and cholesterol from animal sources.

We used available data from the UK to estimate the potential of two strategies for the UK food and agriculture sector to attain a 50% reduction in greenhouse-gas emissions by 2030 (panel 2 and table 1). Strategy one assessed agricultural technological changes alone, and strategy two assessed decreased livestock production in addition to technological changes. Agricultural technological changes seem to be insufficient to meet reduction targets for emissions by 2030, and to meet the remaining emissions gap with strategy two, we estimated that an additional 30% reduction in all UK livestock production would be needed. In the absence of sufficient data about greenhouse-gas emissions from Brazil, we assumed for illustrative purposes that the same reduction in the proportion of livestock production would be needed for our case study in São Paulo city. Notably, if the food and agriculture sector in Brazil had to reduce emissions in proportion to its share of national emissions, the importance of change in land use in Brazil as a source of emissions suggests that our proposal could be quite

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	$MtCO_2e$
In 1990[36]*	44
In 2007[36]	36
In 2020 after technological change[38]	32
In 2030†	
After technological change	28
After technological change and accounting for a 10% increase in UK population for 2010–30	31
Target for 2030 (50% of 1990 emissions)	22
Shortfall between target for 2030 and estimated emissions in 2030 (% of estimated emissions)	9 (~30%)

$MtCO_2e$=megatonnes of carbon dioxide equivalents. *Estimated as 80% of total agricultural greenhouse-gas emissions for 1990.[4,36] †Calculated with the assumption that the percentage reduction for 2020–30 will be the same as for 2007–20. ‡For simplicity, we make the assumption that the emission reductions achievable by overseas producers rearing livestock for UK consumption are similar to that achievable by technological changes in the UK. This assumption is realistic since most meat and dairy imports come from within the European Union and other developed countries in which management practices are similar. Strategies to reduce emissions focus on percentage reductions achievable through technological and consumption changes, rather than the achievement of an absolute figure in itself, and therefore the use of UK production-related reductions serve as a proxy for overall reductions achievable through technological change. We do not include the reductions in emissions from overseas producers in our calculations because of the complexities and scarcity of available data.

Table 1: **Potential reduction in greenhouse-gas emissions from technological changes in the UK livestock sector‡**

	Hazard ratio (95% CI)
Dietary intake of saturated fat*[41]	
Disability from ischaemic heart disease at >35 years	0·87 (0·77–0·97)
Death from ischaemic heart disease at >35 years	0·74 (0·61–0·89)
Serum cholesterol concentration†[42]	
Death from ischaemic heart disease	
40–49 years	0·45 (0·42–0·47)
50–59 years	0·57 (0·55–0·58)
60–69 years	0·68 (0·66–0·69)
70–79 years	0·79 (0·78–0·81)
80–89 years	0·85 (0·82–0·89)

*Per 5% reduced energy intake from saturated fatty acids and a concomitant increased intake of polyunsaturated fatty acids. †Per 1 mmol/L reduction in total serum cholesterol.

Table 2: **Risk of health outcomes from exposure to dietary saturated fat or from serum cholesterol concentration for use in burden of disease models for the food and agriculture sector**

conservative.[40] We acknowledge that Brazil is not committed to the same reductions in emissions as Annex 1 (industrialised) countries. There are uncertainties in estimation of the potential to reduce emissions in a complex living system, and in separation of livestock emissions from those generated by the agriculture sector as a whole.

We estimated the effect of a 30% decrease in livestock production on dietary intake of saturated fat and cholesterol from animal sources and on serum cholesterol concentration (webappendix p 3). We assumed that reductions in livestock production would result in declines of equal size in consumption of foods from animal sources, and specifically in dietary intake of saturated fat and cholesterol. This assumption is necessarily simplistic since various interconnected factors affect dietary intake, including international trade, waste, food prices, and sociocultural practices.

Hazard ratios from published meta-analyses[41,42] enabled quantification of the relation of intake of saturated fat and cholesterol with death or disability from ischaemic heart disease (table 2). We assumed isocaloric replacement of saturated fats with polyunsaturated fats. The Keys equation[43] was used to quantify the effect of changes in dietary intake of saturated fat and cholesterol on serum cholesterol concentration; consequently, we were also able to model the relation between the change in serum cholesterol concentration and death from ischaemic heart disease and stroke.[42] In both case studies, the analyses were based on average dietary intakes, and did not allow for individual, socioeconomic, or geographical variations that are known to exist in diets, or for underlying temporal changes in consumption that might take place by 2030.

We modelled the effect of a 30% reduction in intake of saturated fat and cholesterol from animal sources on the burden of ischaemic heart disease in the UK and São Paulo city (table 3). For the UK population, a 30% decrease in intake of saturated fats from animal sources could reduce the total burden from ischaemic heart disease by 15% in disability-adjusted life-years (DALYs), by 16% in years of life lost, and by 17% in number of premature deaths. From the model of disease burden associated with change in serum cholesterol concentration, reductions in ischaemic heart disease in the UK seemed to be lower than with the model of intake of saturated fats (5% in years of life lost, 4% in number of premature deaths).

In São Paulo city, a 30% reduction in intake of saturated fat from animal sources could reduce the total burden from ischaemic heart disease by 16% in DALYs, by 17% in years of life lost, and by 17% in number of premature deaths. Similar to results for the UK, reductions in the burden of disease in São Paulo city were lower with the model of change in serum cholesterol concentration than with the model of intake of saturated fat (7% in years of life lost, 6% in number of premature deaths). Last, we modelled the effect of change in serum cholesterol concentration on burden of disease due to stroke (cerebrovascular disease);[42] the prevalence of stroke is low in both the UK and São Paulo city, and the effect on burden of disease from stroke is small, but beneficial (webappendix p 4). Our estimates necessarily contain some uncertainty, and we have attempted to quantify the aspect of uncertainty that is associated with the health outcome from exposure to dietary saturated fat or change in serum cholesterol concentration (panel 3 and table 4).

	UK		São Paulo city, Brazil	
	Baseline (2010)	Change in disease burden and death (2030)	Baseline (2010)	Change in disease burden and death (2030)
Population				
Total in thousands*	61367	NA	10435	NA
Dietary intake of saturated fat[41]				
DALYs				
Total in thousands*	1183	–175	147	–23
Per million population†	19270	–2850	14090	–2180
Years of life lost				
Total in thousands*	1052	–165	127	–21
Per million population†	17140	–2690	12130	–2030
Premature deaths				
Total in thousands*	107	–18	8	–1
Per million population†	1750	–290	750	–130
Serum cholesterol concentration‡[42]				
Years of life lost				
Total in thousands*	1052	–55	127	–9
Per million population†	17140	–900	12130	–870
Premature deaths				
Total in thousands*	107	–4	8	–0·4
Per million population†	1750	–70	750	–40

Negative values show reductions in disease burdens. NA=not applicable. DALYs=disability-adjusted life-years. *Rounded to the nearest thousand; percentage reductions cannot be calculated accurately from rounded figures. †Rounded to the nearest ten; percentage reductions cannot be calculated accurately from rounded figures. ‡DALYs are not presented because the meta-analysis that we selected for our analysis did not provide information about the association between exposure and morbidity, and, therefore, years of life lost due to disability could not be calculated.

Table 3: **Change in burden of ischaemic heart disease in 1 year from either a 30% reduction in dietary intake of saturated fat and cholesterol from animal sources, or the estimated effects of these dietary changes on serum cholesterol concentration**

Discussion

Urgent and substantial actions are needed to reduce greenhouse-gas emissions and thus stabilise the world's climate before the extent of climate change becomes obviously dangerous. Our combined strategy of agricultural technological change and decreased livestock production would reduce emissions in the agriculture sector. Moreover, our model indicated that the commensurate reductions in consumption of saturated fat and cholesterol from animal sources would substantially decrease deaths and disability caused by ischaemic heart disease. Association of exposure—saturated-fat intake and change in serum cholesterol concentration—with health outcome could have been responsible for the uncertainty in our estimates of the effect of the strategy to reduce emissions on disease burden. The estimated health benefits from decreased serum cholesterol concentration were smaller than were those from saturated-fat intake, and use of more nuanced data from cholesterol subclasses might have increased the estimated benefits. Whichever approach was used, overall the strategy improved public health.

We acknowledge that our analyses contain several limitations and assumptions, some of which could have resulted in underestimation of the effect of reduced emissions on public health. For example, health modelling was limited to pathways leading from consumption of livestock products to ischaemic heart disease, and we did not model the possible implications for other health outcomes, such as obesity and diet-related cancers.[26,44] Since we selected this specific health outcome, our modelling was undertaken for adults only. The case studies on which we based our model were set in countries where consumption of foods from animal sources is quite high; consequently, our results are not generalisable to countries with lower consumption of animal products. Our estimate of the potential reductions in emissions is subject to uncertainties and is likely to be an underestimate, since it is based on data from the UK only, and we did not include the potential savings in greenhouse-gas emissions that would accrue from livestock produced overseas for UK consumption. In other countries, especially developing countries, we expect that the potential for managerial approaches to reduce emissions might be greater than that recorded in our case studies.

Other limitations might have resulted in overestimation of health effects. First, we assumed that the reduction in national production of livestock would directly result in commensurate reductions in the intake of saturated fat and cholesterol from animal sources. This assumption is an oversimplification since livestock products are globally traded commodities, and reduced production in the UK and Brazil could only reduce national demand for consumption if such a change was not undermined by increased consumption of cheaply imported livestock products. Global actions are needed to achieve maximum benefits to public health in high-consumption populations. Second, we made no allowance for the different dietary proportions or total saturated-fat content of foods from animal sources, or for the contribution of different livestock to emissions. For example, since ruminant animals are an important source of methane, which has highly potent near-term warming potential (up to two orders of magnitude more potent than carbon dioxide in the first decade after release), reduction of products from such animals could be argued to be especially necessary.[7,45]

Third, we used data from two meta-analyses but in their investigation of the relation between saturated-fat consumption and ischaemic heart disease, Jakobsen and colleagues[41] recorded no modifying effect of age, probably because the statistical power was low, whereas the Prospective Studies Collaboration[42] reported age to be a strong modifier in their study of serum cholesterol concentration and ischaemic heart disease. Fourth, we modelled the effect of immediate and full implementation of our strategies, but in reality, the effects on public health will only become evident over time (ie, these are committed reductions that could take many years to be realised). Furthermore, the size of these effects might be modified in subsequent years because of changes in

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Panel 3: Uncertainty in burden of disease estimates

We recognise the substantial uncertainty in our estimates of the health effects of strategies to reduce greenhouse-gas emissions. Therefore, we have attempted to quantify one aspect of this uncertainty: assessment of health outcome from exposure to intake of saturated fat or change in serum cholesterol concentration. The two models gave substantially differing results. To assess the relative contribution of structural uncertainty (ie, whether the pathway to health effects from direct intake of saturated fat is different from the effect of change in serum cholesterol concentration) and parameter uncertainty (ie, the accuracy of the mean estimate of exposure to health outcome compared with the true value) to these recorded differences, we repeated calculations with our models using the upper and lower 95% CIs of the published hazard ratios (table 2).

The upper and lower uncertainty bounds (table 4) suggest that although the mean reductions in years of life lost and number of premature deaths differed between the two models, the lower uncertainty bound from the model of saturated-fat intake was similar to the upper uncertainty bound of the model of change in serum cholesterol concentration for the UK. Furthermore, in São Paulo city the lower and upper uncertainty bounds of the two models overlapped. We conclude that the difference between the estimates provided by the two models is largely compatible with parameter uncertainty in the hazard ratios, but does not exclude structural uncertainty. The wide 95% CI for the model of dietary saturated-fat intake probably indicates the difficulty in accurate estimation of fat consumption in free living populations.

	UK	São Paulo city, Brazil
Years of life lost (total in thousands*)		
Dietary intake of saturated fat	165 (67–257)	21 (9–33)
Serum cholesterol concentration	55 (50–60)	9 (9–10)
Premature deaths averted (total in thousands*)		
Dietary intake of saturated fat	18 (7–28)	1 (0·5–2)
Serum cholesterol concentration	4 (4–5)	0·4 (0·4–0·5)

Data are mean (lower–upper uncertainty bounds). *Rounded to the nearest thousand.

***Table 4:* Analysis of variability in mean estimates of reduction in burden of ischaemic heart disease from a 30% reduction in dietary intake of saturated fat and cholesterol from animal sources, and the estimated effects of these dietary changes on serum cholesterol concentration**

population structure and the background frequency of cardiovascular disease, which is declining in the UK[46] and Brazil[47] because of several factors including other public health and health-care interventions. However, for much of the world, occurrence of cardiovascular disease is rising,[25] and so strategies to reduce emissions might have even greater benefit for population health in such countries. Last, we did not account for the emissions of substitute foods in our calculation of reduced emissions from reduced consumption of livestock products. Our model is based on replacement of saturated fat with polyunsaturated fats. Generally, plant-based diets are high in polyunsaturated fats and have a lower greenhouse-gas burden than do foods from animal sources,[48,49] but some plants are also important sources of saturated fats (eg, palmitic acid in palm oil). Our analysis also made no allowance for the varying amounts of different saturated fatty acids in meat and dairy products. Whereas saturated fats raise overall serum cholesterol concentration, individual saturated fatty acids have contrasting effects.[50]

Despite these limitations, we have shown that a strategy to reduce production and consumption of foods from animal sources would help to prevent dangerous climate change from greenhouse-gas emissions and benefit the health of adults in countries consuming high amounts of animal products. This strategy has several policy implications for trade, agriculture, and health. An important challenge in public health is to balance the need for adequate population intake of animal-source protein and essential nutrients with reduced consumption of saturated fat. Almost a billion people have protein-energy undernutrition, most of whom are also undernourished in micronutrients, especially iron and zinc. Adequate protein, energy, iron, and zinc can be obtained from a plant-based diet.[51,52] However, the consumption of a small amount of animal-source foods per day in low-consumption populations could help to alleviate the burden of undernutrition.[53] At present, agricultural production is mismatched with the provision of a diet that is balanced in terms of foods from plant and animal sources. Globally, production per head of energy, fats, proteins, and micronutrients has increased and is sufficient to meet global population needs,[54] but the benefits have not been distributed evenly across countries and regions.[55] A wide range of factors affect the supply and demand for animal-source foods; some policy levers offer potential approaches to change consumption patterns in populations (panel 4).

A 30% reduction in adult consumption of livestock products in high-consumption countries results in intake of saturated fat that falls well within existing distributions of population intake[73] and is therefore realistic from a dietary perspective. Our findings have important implications for agriculture. Although reduced livestock production and consumption will have social, health, and environmental advantages, these benefits are affected by geographical, social, and economic contexts. For example, ruminant livestock in upland and marginal areas can help to maintain and build the carbon-sequestering properties of soil. Where grazing cattle are reared without use of feed inputs or additional fertiliser, and at low stocking densities, carbon sequestering can outweigh methane and nitrous oxide emissions.[74] Intensive agricultural methods have

Panel 4: Potential policy levers to reduce consumption of foods from animal sources

The food production system is a complex interaction of global, national, and local factors that can affect supply and demand with respect to foods from animal sources. Various policy levers can affect food supply: direct investment by transnational food corporations; trade arrangements affecting food imports, exports, and domestic production; agricultural policy; food processing and procurement; and retail systems.[56–59]

Food pricing, food marketing and labelling, and community-level interventions affect dietary demands of consumers.[60–63] Evidence from several countries suggests that a comprehensive range of intersectoral policies that combine such interventions with nutritional education can change the type of dietary fats consumed. In Finland, such an approach may have changed patterns of consumption, including the type of dietary fats, and reduced mortality due to ischaemic heart disease by 65%.[64] Regulatory policies in Canada, Denmark, and Mauritius, including those on food labelling and composition, have improved the fat content of foods, with benefits to health.[65–67] Preliminary work in the UK suggests that taxation of unhealthy foods could produce modest changes in diet,[63,68] and the Danish Academy of Technical Sciences has recommended that healthy foods be subsidised by 20% and unhealthy foods be taxed by 30%.[69]

New policy initiatives are emerging with a focus on the environmental benefits of dietary change. Sweden produced dietary guidelines in 2009 recommending that citizens eat meat less often and in reduced quantities, to decrease greenhouse-gas emissions,[70] and the city council of Ghent in Belgium has proclaimed a meat-free day each week.[71] Although inclusion of environmental concerns in dietary guidelines and social marketing will probably have little effect on behavioural change, as part of a comprehensive policy approach to sustainable and healthy dietary behaviours, they could be a useful advance to link health and climate-change agendas.[72]

resulted in increased atmospheric ammonia release, which has boosted forest growth in temperate and tropical regions (carbon sinks). However, curbing ammonia emissions from agriculture, even radically, would have little effect on the global carbon sink.[75] Changes in land use that disrupt the soil, such as ploughing for arable production, cause release of stored carbon into the atmosphere, and livestock production can therefore prevent land from being used for other potentially carbon-releasing purposes.[76] Further, in many geographical regions (including the uplands in the UK) no form of food production other than livestock rearing is feasible at present. Livestock rearing also has a key cultural and economic role in many parts of the world and is estimated to create livelihoods for a billion of the world's poor people.[12,13]

By contrast, excessive livestock production to meet growing demand has created problems of soil degradation, biological impoverishment, and, through overgrazing and intensive feed production, a loss in the soil's ability to sequester carbon.[13] The cultivation of crops for biofuel production is an emerging issue of relevance to livestock production. Biofuel production places additional pressure on land, but conversely, the refining of oil or starch grains to produce biodiesel or ethanol can generate protein rich byproducts that can be used to feed animals.[77–79] Furthermore, climate change generally affects livestock production and agriculture via water and heat stress, and change in the spread of pests, disease, and infections.[80]

Reduction of greenhouse-gas emissions in the food and agricultural sector could help to prevent climate change and reduce the burden of ischaemic heart disease. Formulation of appropriate national and international policies that recognise both the benefits of reduced livestock production in high-consumption countries and the need for more equitable distribution of these products remains an important global challenge. Such policies will need intersectoral actions and good global governance to succeed.

Contributors
ADD, SF, TG, AH, IR, and JW led, and CDB and AJM contributed to, the conceptual development of the report. TG developed the greenhouse-gas mitigation scenarios. ADD led, and KL contributed to, the nutrition and health analysis. ZC did the modelling. SF wrote the first draft of the report. All authors contributed to the intellectual guidance, analysis, and subsequent drafts of the report.

Conflicts of interest
We declare that we have no conflicts of interest.

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Health and Climate Change 5

Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants

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In this report we review the health effects of three short-lived greenhouse pollutants—black carbon, ozone, and sulphates. We undertook new meta-analyses of existing time-series studies and an analysis of a cohort of 352 000 people in 66 US cities during 18 years of follow-up. This cohort study provides estimates of mortality effects from long-term exposure to elemental carbon, an indicator of black carbon mass, and evidence that ozone exerts an independent risk of mortality. Associations among these pollutants make drawing conclusions about their individual health effects difficult at present, but sulphate seems to have the most robust effects in multiple-pollutant models. Generally, the toxicology of the pure compounds and their epidemiology diverge because atmospheric black carbon, ozone, and sulphate are associated and could interact with related toxic species. Although sulphate is a cooling agent, black carbon and ozone could together exert nearly half as much global warming as carbon dioxide. The complexity of these health and climate effects needs to be recognised in mitigation policies.

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Introduction

Short-lived greenhouse pollutants emitted largely from fuel combustion account directly or indirectly for a large proportion of present global warming. They also account for most of the direct damage to human health from energy use worldwide. These pollutants include two important health-damaging agents—sulphates and organic-carbon aerosols—which generally have global-cooling characteristics. Another aerosol, black carbon, is also health damaging, but is a warming agent. Other short-lived greenhouse pollutants include warming agents in the form of health-damaging gases such as ozone, a secondary pollutant formed after complex photochemical reactions, and other gases that

Key messages

- Short-lived greenhouse pollutants need to be controlled in addition to regulating carbon dioxide emissions because they collectively create a substantial proportion of all human-contributed global warming and directly damage health. Importantly, control of some short-lived greenhouse pollutants may lead to quick reductions in global warming.
- Short-lived greenhouse pollutants include gases such as the directly health-damaging carbon monoxide and non-methane volatile organic compounds, and others responsible for ozone creation in the lower atmosphere such as methane. Aerosols of short-lived greenhouse pollutants include sulphate, organic carbon, and black carbon particles, which have differing climate implications: the first two cooling, but the third strongly warming.
- The toxicology of sulphate and black carbon in pure form does not adequately indicate their health effects in ambient conditions where they are closely associated with other pollutants. The epidemiological effects of atmospheric sulphate and black carbon therefore should be interpreted as representing mixtures.

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- Meta-analyses of time-series studies of short-term exposure suggest larger mortality effects per unit mass of sulphate than of black smoke, an optical measure correlated with black carbon. Although measurements of black smoke correlate well with estimates of black carbon in some studies, black smoke measurements do not provide a reliable quantitative indicator of black carbon concentrations because of large variations by site, season, and year.
- Our analysis of a 66-city, 18-year nationwide US cohort provides estimates of the mortality effects of long-term exposure to elemental carbon, the best available measure of black carbon. This analysis shows stronger effects for elemental carbon than for undifferentiated fine particles ($PM_{2·5}$), but the model estimates are unstable with respect to inclusion of other pollutants.
- Differential mortality effects between various components of $PM_{2·5}$ are difficult to assess. Our analysis, however, does not lend support to the view that sulphate has smaller mortality effects than does undifferentiated $PM_{2·5}$ and provides new evidence that long-term exposures to sulphates and ozone exert adverse effects on mortality that are independent of other constituents.

contribute to ozone formation such as carbon monoxide, non-methane volatile organic compounds, methane, and nitrogen oxides. Most of these precursors to ozone also exert direct effects on human health.

Conversely, carbon dioxide, the most important greenhouse gas, and nitrous oxide and halocarbons, the other long-lived greenhouse gases, have little direct effect on health. Nitrous oxide and halocarbons arise mainly from sources outside the energy supply system.

All short-lived greenhouse pollutants, whether warming or cooling, have effects on health when people are exposed to them or, in the case of methane, their atmospheric byproduct, ozone. Patterns of emissions and exposures vary greatly, and because the pollutants are short-lived, their health effects depend on the location of sources in relation to local and regional factors such as weather patterns, geography, and population distribution. Localised concentrations of ozone and black carbon have been identified as agents increasing the urban heat island effect by trapping heat and interacting with urban carbon dioxide concentrations.[1] In turn, these short-lived greenhouse pollutants might increase health burdens from heat waves in urban cores.[1]

Several of the short-lived greenhouse pollutants have substantial effects on the human-managed and natural biosphere through acid precipitation (sulphate and nitrate),[2] eutrophication (nitrate), direct damage to organisms (ozone), and in the case of black carbon deposition, accelerated melting of ice and snow. Increased forest growth through eutrophication could lead to interactions with the global carbon cycle through, for example, enhanced growth and carbon dioxide uptake, suggesting a cooling effect on climate,[3] which might in turn be partly offset by ozone's negative effect on carbon uptake in ecosystems.[4]

Many important sources emit more than one short-lived greenhouse pollutant, and in some cases, control of one and not another is difficult—eg, black carbon and organic carbon from combustion of biomass, coal, and diesel fuel. Additionally, ozone and sulphate are not emitted directly, but are secondary products from transformations of precursor emissions in the atmosphere. The net effect of control measures on climate warming can thus be difficult to estimate because of simultaneous changes in both warming and cooling agents. This challenge is amplified by the scientific and policy complexities related to the widely different temporal patterns that characterise the burden of such pollutants compared with carbon dioxide control, which is usually the major consideration in climate negotiations and discussions.

Aggressive policies directed towards carbon dioxide reduction, although necessary for the long term, are by themselves insufficient to reduce the rate of warming in the next few decades because of the long atmospheric lifetime of this gas.[5] Thus, governments will need to reduce warming from short-lived greenhouse gas pollutants when considering climate change mitigation policies.[6,7] Choice of policies with positive health and ecosystem effects provides the opportunity for substantial co-benefits (eg, reductions in ozone concentrations will diminish warming while also providing substantial health benefits to human populations and ecosystems) and climate protection. Alternatively, poor choices could result in major net additional risks to human health and ecosystems.

The short-lived greenhouse pollutants climate primer (panel) summarises the issues related to these pollutants. We examine the present state of health evidence for three important short-lived greenhouse pollutants: black carbon, sulphate, and ozone. The figure shows the relative importance of different sectors that are thought to cause most anthropogenic emissions for black carbon and the precursor of sulphate, sulphur dioxide. The relative emissions differ greatly by sector, which has important policy implications for control measures. We focus on the health effects of ambient pollution and not on exposures from indoor sources, such as household fuels, which also substantially affect health worldwide.[12]

We discuss the present state of knowledge of health effects on the basis of toxicological evidence in controlled settings and from observational epidemiological studies. This review includes new meta-analyses of time-series studies and new evidence for relative mortality effects of long-term exposures to sulphates, elemental carbon, and ozone from a national US cohort study. We conclude by discussing cross-cutting issues such as the benefits of removing remaining uncertainties and the need for analyses that incorporate both climate and health implications of control policies.

Review of health effects

Sulphates

Respirable ambient particles have been associated with increased mortality and a wide range of morbidity effects.[13] Most evidence relates to undifferentiated particulate matter with aerodynamic diameter 10 μm or less (PM_{10}) and 2·5 μm or less ($PM_{2·5}$), and these metrics of particle size are the basis of most health-based standards and impact assessments for particles. Although many scientists believe that particle toxicity is also affected by particle number and chemical composition and not just particle size, these differences are difficult to quantify.[14]

Sulphur emissions from human activities are dominated by fossil-fuel combustion (figure). Although emitted as sulphur dioxide, much is converted to sulphate, depending on local conditions.[15,16] Human emissions are falling in most parts of the world because of air pollution regulations.[10] The potential role of sulphate in driving the hazard of air pollution has been addressed in several long-term and short-term animal exposure experiments, especially in relation to effects on the pulmonary system. In 1992, the UK Advisory

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Group on the Medical Aspects of Air Pollution Episodes concluded that even fairly high concentrations of inhaled sulphur dioxide, sulphate, and aerosols of sulphuric acid are well tolerated by many animal

Panel: Climate primer for energy-related short-lived greenhouse pollutants

In this panel we present a short summary of the climate issues surrounding each short-lived greenhouse pollutant, and carbon dioxide for comparison. Although only the health effects of sulphates, black carbon, and ozone are discussed in the main text, all the other short-lived greenhouse pollutants also have direct or indirect health effects, or both. The figure in the webappendix p 1, which is taken directly from the most recent authoritative international scientific assessment,[8] shows the estimated pattern across these agents of global warming in 2005 due to all human emissions since 1750. The greenhouse pollutants are compared by radiative forcing (RF), which is a metric used for the quantitative comparisons of the strength of different human and natural agents in causing climate change.

To distinguish between direct and indirect RF is important. Direct RF results when the emitted substance is a greenhouse pollutant itself, such as carbon dioxide. Indirect RF results when the emitted pollutant is not a greenhouse pollutant but takes part in chemical reactions within the atmosphere to form a greenhouse pollutant or to change the global distribution of a greenhouse pollutant. Sulphur dioxide is an example because it is transformed in the atmosphere to form aerosol sulphates that act to produce a negative RF. Nitrogen oxide emissions act to increase the oxidising capacity of the troposphere, reducing methane (negative RF), but adding to tropospheric ozone (positive RF), whereas methane, carbon monoxide, and non-methane volatile organic carbons contribute to tropospheric ozone. As a result, although not emitted directly, ozone in total is ranked as the third most important human-influenced greenhouse gas in the atmosphere (after carbon dioxide and methane).

Aerosol particles affect RF directly through the reflection and absorption of solar and infrared radiation. Some aerosols, such as black carbon, cause a positive RF (climate warming) whereas others, such as sulphates, cause a negative RF (climate cooling). The direct RF summed over all aerosol types is negative. Aerosols also cause a negative RF indirectly through the changes that they cause in cloud properties, which are not shown in webappendix p 1. The observed global temperature records for the 20th century cannot be explained with global climate models without a substantial cooling term after World War 2 from the burning of sulphur-containing fossil fuels that offset partially the global warming from the greenhouse gases. As nitrogen and sulphur oxides are reduced globally owing to health and acid-precipitation concerns, their cooling effect will reduce, thus unmasking the climate warming due to other greenhouse pollutants that is now counteracted.

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Additionally, because control of black carbon emissions is difficult without simultaneously doing so for the associated organic carbon particle emissions from the same combustion sources, the worldwide climate benefits of carbon-particle control measures, including improved combustion efficiency, depend on the ratio of black carbon to organic carbon of each source. Due to recent observations and modelling,[9] however, the estimated warming of black carbon might increase above that in the most recent Intergovernmental Panel on Climate Change (IPCC), which is shown in the figure. This increase would have policy implications because a much broader range of combustion sources would then have net climate benefits from combined control of black and organic carbon.

See Online for webappendix

Since methane and carbon dioxide are well mixed globally, emissions in all places and seasons can be treated as essentially equal, which led to the deployment of so-called global warming potentials by the IPCC, which are used to weight the relative importance of emissions of different greenhouse gases in treaties, inventories, and international carbon-offset programmes. The complexity, short life, and local dependence of the short-lived greenhouse pollutants, however, make it difficult if not impossible to establish official global warming potentials for use in policy making. Thus, at present, short-lived greenhouse pollutants other than methane are not included in many international climate policy deliberations, although they have been the subject of much research and media attention and are featured prominently in scientific assessments.

Long-lived greenhouse pollutants (hundreds of years)

Carbon dioxide poses a low direct health hazard and is the weakest greenhouse pollutant by mass; however, because of the magnitude of emissions it is the most important overall. It also has a much longer lifetime in the atmosphere than do any of the other energy-related pollutants—most is gone in 100 years or so but a proportion of emissions is thought to remain in the atmosphere for thousands of years.

Medium-lived greenhouse pollutants (tens of years and thus globally mixed)

Methane is the second most important greenhouse pollutant. It is produced from a range of energy-related sources, including leakage from oil and gas facilities and coal mines, and from incomplete combustion of biomass and fossil fuels. Its main sources, however, are agriculture and poor waste management. Although not directly damaging to health, methane is a precursor to the global rise in tropospheric ozone concentrations, which is a concern in parts of Asia and is generally separate from urban sources. Although having a shorter overall lifetime than carbon dioxide, because of its large direct and indirect effects on warming, a tonne of methane will have a much bigger warming effect than would a tonne of carbon dioxide for the first few decades after emission.

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Short-lived greenhouse pollutants (days to weeks and thus effects depend on local conditions)
Carbon monoxide is mainly a product of incomplete combustion, and although not having a direct climate effect, acts to sweep up hydroxyl radicals in the atmosphere, thus effectively increasing the lifetime of methane and adding to tropospheric ozone. The effects of carbon monoxide on methane and tropospheric ozone are both potentially climate warming.

Non-methane volatile organic compounds come from several human-generated sources, including incomplete combustion and evaporation from fuels. Emissions of these pollutants contribute to ozone formation and act to reduce the oxidising capacity of the atmosphere, which extends the lifetime of methane. Both of these effects increase global warming. These compounds can also have direct human health effects.

Nitrogen oxides derive from fuel combustion and have a complex relation to and indirect effect on both climate warming and cooling by affecting ozone, methane, and particle concentrations. Emissions from nitrogen oxides act to decrease the oxidising capacity of the troposphere increasing the methane lifetime, but also are a major precursor to tropospheric ozone. Nitrate particles, as with those of sulphate, are lighter in colour and thus generally cooling. There also seems to be a small increase in carbon capture in natural ecosystems due to eutrophication from deposited nitrate.

Sulphur dioxide, which derives mainly from combustion of fuels, partly converts to sulphate aerosols in the atmosphere. Although these aerosols are potentially damaging to health, they are generally thought to exert a net cooling effect on the climate. As with organic carbon, sulphates can sometimes be coated with black carbon to create brown carbon, which has warming potential.

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Black carbon, which is fine particulate matter of dark colour containing a large fraction of elemental carbon, is derived exclusively from incomplete combustion. It is strongly warming in the atmosphere, and increases heat absorption if deposited on ice and snow—eg, on Himalayan glaciers or in the Arctic.

Organic carbon aerosol, a less dark carboneous particulate matter, is produced mainly from incomplete combustion, but also from secondary processes involving biogenic volatile organic compounds. Although not well characterised and sometimes physically combined with black carbon, it is thought generally to produce a net cooling effect globally, although with much local variation. Organic carbon is a major form of health-damaging small particles worldwide.

Very short-lived greenhouse pollutants (hours to days)
Tropospheric ozone is a health-damaging secondary pollutant formed through complex photochemical reactions involving nitrogen oxides and volatile organic compounds, including methane in the presence of sunlight. Stratospheric ozone generally has different sources and, although also warming, protects earth's surface from health-damaging and ecosystem-damaging UV radiation.

species.[17] The results of subsequent studies collectively lend support to this original conclusion.[18] The concentrations used in these studies are much higher than the typical concentrations measured in the environment, even during pollution episodes. Thus, at the concentrations recorded in most countries, sulphate and related sulphur compounds are unlikely to have substantial pulmonary toxicity.

Little toxicological evidence suggests that sulphate itself is toxic to the cardiovascular system. A few experimental studies have investigated the effect of sulphate-containing compounds or mixtures on the cardiovascular system. Such studies have included concentrated air particles,[19] metal sulphates,[20] soluble particulate matter extracts,[21] and residual oil fly ash.[22] Although several cardiovascular variables have been measured across these studies, none has associated the sulphate component itself with cardiovascular effects.

The 1992 Advisory Group on the Medical Aspects of Air Pollution Episodes report, however, identified that "exposure of animals to sulphur dioxide in combination with particulates may be more damaging than the effects of the gas or sulphuric acid alone".[17] Such studies also used high particulate concentrations in animal experiments and focused on pulmonary toxicity, making results difficult to interpret in terms of human health effects from ambient sulphate in the troposphere.

In a new systematic review and meta-analysis of ten (eight from the USA and Canada and two from Europe) single-city time-series studies of sulphate and daily all-cause mortality, a pooled random-effects estimate of a 0·21% (95% CI 0·11–0·30) increase in mortality per 1 μg/m³ increase in sulphate was obtained (table 1 and webappendix pp 26–27). Positive associations were also detected in the fewer studies of cause-specific mortality. The sulphate estimates tended to be independent of other particle metrics and pollutant gases such as ozone. Findings from a meta-analysis of panel studies showed positive associations between sulphate exposure and daily measures of lung function, symptoms, and asthma drug use.[16]

The only long-term exposure studies of sulphate and mortality are from the USA. The most extensive is based on the American Cancer Society (ACS) Cancer Prevention Study II (CPS II).[23] Investigators of this study,

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which included more than 500 000 participants, reported increased mortality from all natural causes, cardiopulmonary and cardiovascular disease, and lung cancer associated with long-term exposure.[23] The Harvard Six-Cities study reported similar results.[27] These findings have been corroborated and extended in our case study.

Black carbon

The term black carbon is used rather loosely with varied meanings in different disciplines.[28] Whereas the colour (albedo) is the key factor for climate scientists, health scientists have shown growing interest in the chemical composition of this greenhouse pollutant. Both groups are concerned with size distributions and atmospheric lifetimes. Elemental carbon is interchangeable with black carbon insofar as it represents the largest proportion of heat-absorbing components in undifferentiated particulate matter.[29] Unlike the major greenhouse pollutants, no official inventories of black carbon emissions have been produced by the UN Framework Convention on Climate Change (UNFCCC), so estimates vary. With data drawn from a widely-cited inventory,[11] the figure shows that most black carbon emissions come from incomplete combustion of biomass or fossil fuel. As regulations for air pollution tighten, global black carbon emissions from fossil-fuel combustion will probably continue to fall. The largest anthropogenic category is household combustion of biomass and coal in developing countries, followed by incomplete combustion of coal in industry and diesel transport.

Studies in volunteers suggest that short-term exposure to diluted diesel exhaust impairs vascular function and induces ischaemic and thrombotic mechanisms.[30–32] The role of elemental carbon is unclear, however, because whole-diesel emissions contain much organic carbon and other aerosol components in both the particle and gaseous phases. Studies in animals[33,34] and in vitro[34,35] with black carbon particles show similar effects, but these particles have very large surface areas compared with atmospheric black carbon. Animal studies have also shown that black carbon can accelerate atherosclerotic plaque formation,[35] suggesting a long-term effect on cardiovascular health.

In-vivo[36] and in-vitro[37,38] modelling studies focusing on pulmonary responses have shown that ultrafine or nano-sized (less than 100 nm) particles are more likely to be toxic per unit mass, in terms of inducing inflammation and oxidative stress, than are larger particles of the same composition,[39] presumably because they penetrate more deeply into the respiratory system. However, the relation between increasing toxic effects and decreasing particle size is not limited to carbon, but also applies for other low-solubility, low-toxicity materials such as titanium dioxide and polystyrene beads.[40] Thus, it is not possible to isolate the size fraction mode from the chemical composition of carbon particles as the source of toxicity.[41]

Epidemiological evidence linking measured black carbon and elemental carbon to health outcomes is scarce, partly because routine government monitoring is not done in a sufficient number of locations and no common measurement method is agreed upon. Most evidence relates to the black smoke index—a standard method that relies on the light-absorbing characteristics of particles less than 4 μm in diameter. The webappendix pp 3–8 provides details of this method. Black carbon and black smoke are highly correlated, suggesting that black smoke is a good marker for black carbon.[42,43] However, epidemiological evidence relating to particulate matter containing black carbon measured as PM_{10} or $PM_{2\cdot5}$ cannot realistically be used as a quantitative surrogate for black carbon, because the ratio of black carbon to total particulate matter varies greatly according to the mixture of sources (ie, industrial, diesel exhaust, wood smoke, refuse burning), which in turn varies by season, site, and time. For example, Li and colleagues[44] investigated carbonaceous aerosol emissions from combustion of household fuels (wheat and woody fuels) in biomass stoves and noted that percentages of black carbon in $PM_{2\cdot5}$ were generally greater for emissions from woody fuel than for emissions from crop waste (3·6% to 71·2% *vs* 1·7% to 33·5%).[44]

Our systematic review and meta-analysis of short-term exposure time-series studies of black smoke and daily mortality detected significant, positive associations with all-cause, cardiovascular, and respiratory mortality (table 1

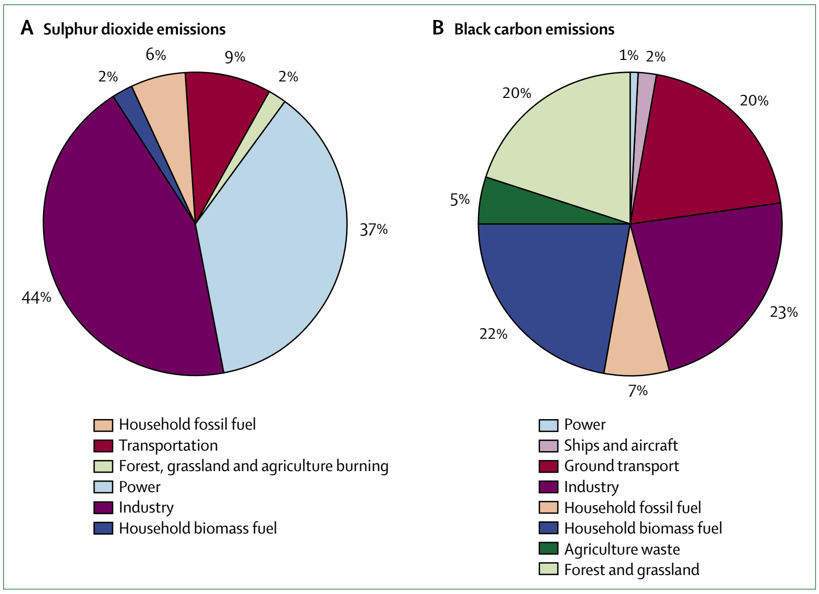

Figure: **Relative contributions of human sources to sulphur dioxide (A) and black carbon (B) emissions**
In each case, the distribution of climate effects differs from the distribution of the primary pollutant. For sulphur dioxide, the extent of transformation to the climate-active species, sulphate, will vary by location. For black carbon, the different sources produce cooling organic-carbon aerosols in varying amounts. The climate implication is due to the net radiative forcing of the two linked emissions. Only half the total forest and grassland emissions are counted here as an estimate of the proportion that is due to human activities. 2005 sulphur dioxide estimates are interpolated between the 1995 and 2030 estimates calculated by Unger and colleagues.[10] Since there are no official inventories and because methods vary across investigators, these estimates should be regarded as approximate. Estimates of black carbon emissions are from the black carbon emissions inventory.[11]

	Outcome	Percentage change in mortality per 1 μg/m³ change in pollutant (95% CI)
Particle sulphate		
American Cancer Society cohort[23]	All-cause	0·88 (0·67 to 1·10)
American Cancer Society cohort[23]	Cardiopulmonary	1·01 (0·75 to 1·38)
Time-series studies		
Single-city estimates (n=10)	All-cause	0·21 (0·11 to 0·30)
Multi-city studies		
10 Canadian cities	All-cause	0·40 (0·10 to 0·70)
6 Californian counties	All-cause	0·12 (–0·76 to 1·00)
6 US communities	All-cause	0·22 (0·13 to 0·31)
Time-series studies		
Single-city estimates (n=5)	Cardiovascular	0·09 (–0·04 to 0·21)
Multi-city studies		
6 Californian counties	Cardiovascular	0·36 (–0·91 to 1·65)
Time-series studies		
Single-city estimates (n=4)	Respiratory	0·37 (–0·15 to 0·90)
Multi-city studies	Respiratory	0·70 (–1·65 to 3·11)
6 Californian counties		
Black smoke		
NLCS-AIR Study[24]	All-cause	0·49 (0·00 to 1·05)
NLCS-AIR Study[24]	Cardiovascular	0·39 (–0·51 to 1·23)
NLCS-AIR Study[24]	Respiratory	2·01 (–0·10 to 4·14)
PAARC[25]	All-cause	0·68 (0·30 to 0·96)
PAARC[25]	Cardiopulmonary	0·49 (0·00 to 1·14)
Time-series studies		
Single-city estimates (n=25)	All-cause	0·05 (0·03 to 0·07)
Multi-city studies		
APHEA 1 (12 European cities)	All-cause	0·03 (0·02 to 0·03)
APHEA 2 (29 European cities)	All-cause	0·06 (0·03 to 0·08)
13 Spanish cities	All-cause	0·08 (0·04 to 0·12)
9 Scottish sites	All-cause	0·17 (0·07 to 0·26)
Time-series studies		
Single-city estimates (n=20)	Cardiovascular	0·04 (0·01 to 0·06)
Multi-city studies		
APHEA 2 (15 cities)	Cardiovascular	0·06 (0·03 to 0·09)
13 Spanish cities	Cardiovascular	0·03 (–0·02 to 0·08)
9 Scottish sites	Cardiovascular	0·04 (–0·10 to 0·18)
Time-series studies		
Single-city estimates (n=20)	Respiratory	0·04 (–0·02 to 0·11)
Multi-city studies		
APHEA 2 (15 cities)	Respiratory	0·08 (0·01 to 0·16)
13 Spanish cities	Respiratory	0·11 (0·04 to 0·18)
9 Scottish sites	Respiratory	0·52 (0·29 to 0·76)

(Continues on next page)

and webappendix pp 9–25). Although the results of the time-series meta-analysis suggest larger effects of sulphate than of black smoke, this distinction is not so clear in the few studies that have measured both.[16] There is strong evidence that these health effects are not confined to mortality, but also include effects on morbidity outcomes such as hospital admissions for cardiopulmonary disorders.[13]

Two European cohort studies have shown positive associations between black smoke and mortality (table 1),[24,25] and these results are supported by a small area analysis in the UK.[45] Studies of occupational exposure to black carbon provide little evidence of increased risk of lung cancer,[46] although abnormal chest radiographs have been reported.[47] Occupational exposure to diesel exhaust is associated with increased risk of mortality from lung cancer and chronic obstructive pulmonary disease (COPD),[48,49] but the role of elemental carbon specifically is unclear since diesel exhaust is itself, as mentioned, a complex mixture of particles and gases that contains many other species including organic carbon.

Ozone

Ozone is a secondary pollutant that is formed through complex photochemical reactions involving nitrogen oxides and volatile organic compounds in the presence of ultraviolet sunlight. Background tropospheric concentrations of ozone have doubled worldwide since pre-industrial times. Remote areas now display concentrations in the range of 30 parts per billion compared with earlier preindustrial estimates of 10–15 parts per billion. Although plants and other natural sources such as forest fires contribute precursors, the major reason for the doubling is anthropogenic release of methane and the emission of nitrogen oxides from fossil-fuel burning (webappendix p 1).[8,50]

Exposure of the airways to ozone can cause effects through two primary mechanisms: direct oxidative stress or by damaging the pulmonary system and draining energy from normal cell functions towards defence mechanisms.[51] Such mechanisms can induce inflammation within cells that can contribute to formation of or exacerbate existing pulmonary disease.[52,53] Human chamber-exposure studies and animal studies suggest that ozone could elicit biological responses at or near environmental concentrations.[52–54]

Time-series studies of daily mortality have consistently noted associations with ozone in Europe, the USA, and Canada (table 1).[55–57] Ozone has also been associated with morbidity, including asthma exacerbation[58] and hospital admissions for respiratory causes.[59] Little evidence exists for associations between long-term exposure to ozone and mortality. A cohort study undertaken in the midwest and eastern USA reported an inverse association between ozone and mortality.[27] Reanalysis of this study replicated these findings, but also suggested a positive association with warm-season ozone exposure.[60] A study of about 6000 non-smoking Seventh-Day Adventists living in southern California recorded increased risks for men after long-term ozone exposure,[61] but this finding was based on a small number of deaths.

An extension of the ACS CPS II with improved exposure data identified a significant association between long-term ozone exposure and cardiovascular, cardiopulmonary, and respiratory mortality (table 1). Effects were most

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pronounced for respiratory mortality and were insensitive to adjustment for several confounding variables and the co-pollutant $PM_{2·5}$.[26] Other findings of chronic effect lend support to the idea that ozone might target respiratory systems, including evidence of lung function deficits in children,[62] increased asthma incidence,[63] and impaired pulmonary function.[64,65]

	Outcome	Percentage change in mortality per 1 μg/m³ change in pollutant (95% CI)
(Continued from previous page)		
Ozone		
American Cancer Society cohort[26]	All-cause	0·02 (–0·08 to 0·14)
American Cancer Society cohort[26]	Cardiovascular	0·22 (0·06 to 0·46)
American Cancer Society cohort[26]	Respiratory	0·57 (0·20 to 0·94)
Ozone (8 h)		
Time-series studies		
Single-city estimates (n=22)	All-cause	0·03 (0·02 to 0·04)
Multi-city study		
APHEA 2 (23 cities)	All-cause	0·003 (–0·018 to 0·024)
Time-series studies		
Single-city estimates (n=19)	Cardiovascular	0·04 (0·03 to 0·05)
Time-series studies		
Single-city estimates (n=19)	Respiratory	0·04 (0·01 to 0·07)

Time-series coefficients for daily mortality are based on a systematic review and meta-analysis (webappendix pp 9–25).

Table 1: **Estimates of mortality effects of ambient particulate matter (sulphate and black smoke) and ozone from cohort and time-series studies**

Case study: effects of sulphate, elemental carbon, and ozone on mortality in the USA

Methods and data

We present a new analysis examining the relative strength of association between major mortality outcomes and short-lived greenhouse pollutants in a national US study. We used data from the ACS CPS II cohort.[66] The analytical cohort for this research included 352 242 participants in 66 metropolitan statistical areas of the USA, with follow-up from 1982 to 2000 (webappendix pp 26–27).[23] We included ozone measurements from the second and third quarters (warm season), $PM_{2·5}$, sulphate, and elemental carbon using government monitors in each of the metropolitan areas. More detail about the exposure estimates for $PM_{2·5}$, sulphate, and ozone is available elsewhere.[23,67] For elemental carbon, we downloaded data from tabulations prepared by the Health Effects Institute for 2003–05, with maximum coverage across metropolitan statistical areas that had ACS participants with other available pollution data. Although these years are after the end of follow-up, the overall spatial patterns in particulate matter are fairly stable over time.[68] Exposures were assigned to individuals on the basis of their metropolitan statistical area of residence at enrolment. We estimated mortality effects with models for independent pollutants and various combinations of co-pollutants. We tested two-way linear interactions between all pollutants.

We used multilevel random-effects Cox proportional hazards models to assess the risk of mortality in relation to pollution exposures, stratifying for age (single-year groupings), sex, and race in the baseline hazard.[23] Some 20 variables with 44 terms were included to control for individual characteristics that might confound the association between air pollution and mortality. The spatial unit of analysis was the metropolitan statistical area for random-effects estimation (webappendix pp 26–27 provides more details).

Results

Tables 2 and 3 show the results of single-pollutant and multiple-pollutant models for the four pollutant estimates for all-cause and cardiopulmonary mortality. Relative risks (RRs) presented in the first row for each cause of death show the effects in single-pollutant models, whereas subsequent rows under each cause of death indicate pollutants simultaneously included in the survival model. We have included $PM_{2·5}$ for comparison with the other pollutants and with previously published studies.[23] $PM_{2·5}$ is not included in any of the co-pollutant models because the other particle metrics are constituents of it. Additionally, multiple-pollutant results for $PM_{2·5}$ and ozone have been investigated elsewhere.[26] To provide a basis for comparison, all RRs are assessed over a 1 μg/m³ change in each pollutant measured as the percentage excess RR, specifically, as (RR–1)×100. Because the distributions of pollutants vary greatly, table 3 shows the percentage increase in the RR assessed against the IQR of the pollutant distribution used to generate the risk estimates. This analysis provides a basis for comparison of relative effects of the pollutants that more accurately indicates the real-world difference over their distributions in the USA than does the 1 μg/m³ change.

Sulphate, $PM_{2·5}$, and elemental carbon have positive, significant associations with all-cause mortality. On the basis of the 1 μg/m³ contrast, the percentage increase in all-cause mortality for $PM_{2·5}$ was 0·58 (95% CI 0·22–0·95). Sulphate effects were about twice those of $PM_{2·5}$, and effects of elemental carbon about ten times greater, although this estimate has poor precision (table 2). We noted a small increased risk for ozone with all-cause mortality (table 2). For all causes of death, when assessed against the IQR in the pollutants, effect sizes were largest for sulphate, followed by $PM_{2·5}$, elemental carbon, and ozone.

For cardiopulmonary mortality, effect sizes of $PM_{2·5}$ and sulphate were similar over the 1 μg/m³ exposure contrast, with sulphate having slightly larger effects than those of $PM_{2·5}$ (table 2). Elemental carbon effects were roughly seven or eight times greater than were those of sulphate and $PM_{2·5}$, respectively (table 2). We also noted significantly increased risks of cardiopulmonary death from ozone

	$PM_{2.5}$ (1·0 μg/m³)	Ozone (1·0 μg/m³)	Sulphate (1·0 μg/m³)	Elemental carbon (1·0 μg/m³)
All-cause mortality (deaths=93 358)				
Single-pollutant	0·58 (0·22 to 0·95)	0·04 (–0·01 to 0·09)	1·11 (0·78 to 1·44)	5·51 (0·74 to 10·51)
Multiple-pollutant	..	0·01 (–0·06 to 0·07)	..	5·16 (–0·51 to 11·17)
Multiple-pollutant	..	0·02 (–0·01 to 0·06)	1·09 (0·76 to 1·43)	..
Multiple-pollutant	..	..	1·06 (0·73 to 1·40)	2·70 (–1·01 to 6·57)
Multiple-pollutant	..	0·01 (–0·04 to 0·06)	1·07 (0·73 to 1·40)	2·11 (–2·44 to 6·89)
Cardiopulmonary mortality (deaths=46 168)				
Single-pollutant	1·27 (0·76 to 1·79)	0·12 (0·03 to 0·21)	1·55 (1·03 to 2·08)	10·60 (2·92 to 18·86)
Multiple-pollutant	..	0·08 (–0·02 to 0·18)	..	6·55 (–2·05 to 15·91)
Multiple-pollutant	..	0·10 (0·04 to 0·16)	1·54 (1·05 to 2·03)	..
Multiple-pollutant	..	..	1·46 (0·94 to 1·97)	7·05 (1·11 to 13·35)
Multiple-pollutant	..	0·09 (0·01 to 0·17)	1·51 (1·01 to 2·01)	2·09 (–4·53 to 9·18)

Data from the American Cancer Society Cancer Prevention II cohort (n=352 242), with follow-up from 1982 to 2000. Spatial survival model included random effects at the 66 metropolitan statistical areas that had all pollutants recorded for the national cohort. Survival model is stratified by age (1 year), sex, and race. Pollution effects adjusted for 44 covariates measured at the individual level and seven covariates measured at the ecological level for the zip code area of residence and for the zip code area deviated from the metropolitan area average. Relative risks presented in the first row for each cause of death are from single-pollutant models, whereas those in subsequent rows indicate pollutants simultaneously included in survival models. See webappendix pp 26–27 for details. $PM_{2.5}$=particulate matter with aerodynamic diameter 2·5 μm or less.

Table 2: **Percentage changes of relative risk based on μg/m³ range of pollutant concentration by selected causes of death for single-pollutant and multiple-pollutant models**

exposure (table 2). Assessed against the IQR distributions, both $PM_{2.5}$ and sulphate had significantly increased risks of 5–6%, whereas the increased risks were about 3% for ozone and elemental carbon (table 3). For the all-cause multiple-pollutant models, only sulphate remained significantly increased. In cardiopulmonary models, ozone and sulphates were both raised and significant in two-pollutant models, whereas ozone was confounded in a model containing elemental carbon alone (table 2). Sulphate and elemental carbon remained significantly raised in two-pollutant models. In the three-pollutant model, only ozone and sulphate were significantly increased (table 2).

Discussion of new evidence

Sulphate has the most robust association with all-cause and cardiopulmonary mortality. Ozone was significantly associated with cardiopulmonary mortality only, although this association was confounded by inclusion of elemental carbon. Elemental carbon has the largest effects on all-cause and cardiopulmonary mortality per μg/m³, followed by sulphate, $PM_{2.5}$, and ozone. These rankings change when the actual US distributions employed to generate the risk estimates are used, with sulphate having the largest effects, followed by $PM_{2.5}$, elemental carbon, and ozone. In all instances, the confidence intervals overlap, and we were unable to establish conclusively whether any of the pollutant effects differed significantly from each other. Moreover, definitive conclusions about the relative importance of each pollutant were difficult to make because of high amounts of correlation between pollutant estimates. Sulphate seems to have the most robust effects on mortality when account is taken of confounding in the multiple-pollutant models.

We fitted a model estimating a multiplicative interaction between ozone and sulphate (data not shown). The results suggested that cardiopulmonary mortality associated with ozone was greatest at low concentrations of sulphate, and vice versa. This finding might indicate differences in the spatial patterns of both pollutants across the USA: sulphate concentrations are high in the midwest and northeast USA, whereas ozone concentrations are high in southwest regions, particularly in California. The single-pollutant models suggest that both pollutants are associated with increased mortality. Thus, if valid, we would infer that, if one pollutant is less prominent, the effects of the other become more pronounced. Further investigation of multiple-pollutant interactions seems to be warranted.

Conclusions

The findings from toxicology and epidemiology with respect to sulphates differ substantially. In most toxicology studies, which use a pure form of sulphate, the effects are negligible, whereas epidemiological studies that use measured particle sulphates, representing a mixture of sulphates and other species from combustion sources such as metals, find significant associations. Some characteristic of this mixture, associated or interacting with sulphates, probably explains the differences between these two sets of findings.[16] Therefore, the epidemiological associations should be regarded as quantifying the health effects of particle species and other co-pollutants associated with sulphate. Furthermore, since control measures might not affect all components equally, we cannot assume that control of sulphur emissions will result in a directly corresponding fall in health effects. The assessment of policies to reduce emissions of sulphur provides, however, good evidence that these interventions do have major

	$PM_{2.5}$ (4·30 μg/m³)	Ozone (22·38 μg/m³)	Sulphate (3·75 μg/m³)	Elemental carbon (0·31 μg/m³)
All-cause mortality (deaths=93 358)				
Single-pollutant	2·56 (0·96 to 4·18)	0·93 (–0·35 to 2·23)	4·23 (2·96 to 5·51)	1·67 (0·22 to 3·14)
Multiple-pollutant	..	0·16 (–1·34 to 1·69)	..	1·57 (–0·15 to 3·33)
Multiple-pollutant	..	0·57 (–0·38 to 1·54)	4·18 (2·90 to 5·46)	..
Multiple-pollutant	..	..	4·05 (2·77 to 5·36)	0·83 (–0·31 to 1·99)
Multiple-pollutant	..	0·25 (–0·92 to 1·45)	4·07 (2·78 to 5·38)	0·65 (–0·76 to 2·08)
Cardiopulmonary mortality (deaths=46 168)				
Single-pollutant	5·60 (3·31 to 7·95)	2·83 (0·84 to 4·86)	5·96 (3·91 to 8·04)	3·17 (0·89 to 5·49)
Multiple-pollutant	..	1·86 (–0·46 to 4·24)	..	1·98 (–0·64 to 4·67)
Multiple-pollutant	..	2·42 (0·99 to 3·87)	5·90 (4·01 to 7·82)	..
Multiple-pollutant	..	..	5·59 (3·60 to 7·62)	2·13 (0·34 to 3·95)
Multiple-pollutant	..	2·10 (0·34 to 3·88)	5·79 (3·87 to 7·74)	0·64 (–1·42 to 2·75)

Data from the American Cancer Society Cancer Prevention II cohort (n=352 242), with follow-up from 1982 to 2000. Spatial survival model included random effects at the 66 metropolitan statistical areas that had all pollutants recorded for the national cohort. Survival model is stratified by age (1 year), sex, and race. Pollution effects adjusted for 44 covariates measured at the individual level and seven covariates measured at the ecological level for the zip code area of residence and for the zip code area deviated from the metropolitan area average. Relative risks presented in the first row for each cause of death are from single-pollutant models, whereas those in subsequent rows indicate pollutants simultaneously included in survival models. See webappendix pp 26–27 for details. $PM_{2.5}$=particulate matter with aerodynamic diameter 2·5 μm or less.

***Table 3*: Percentage changes of relative risk based on IQR of pollutant concentration by selected causes of death for single-pollutant and multiple-pollutant models**

health benefits.[69,70] Additionally, sulphur is initially emitted from fuel combustion in the form of sulphur dioxide—a gas that does not actively affect climate itself, but does probably exert an independent effect on health.[13]

Unlike sulphate, pure black carbon does seem to exert effects in toxicological studies. Nevertheless, as with sulphate, it should be regarded as an indicator of a mixture of pollutants from combustion, especially when interpreting associations between proxies, such as black smoke, and health effects.

Plausible biological mechanisms link ozone exposure to direct oxidative stress and secondary damage through associated inflammatory processes. Evidence from human and animal toxicology studies lends support to these mechanisms. Epidemiological evidence suggests a wide range of health effects. The ACS case study indicates ozone effects on the cardiopulmonary system, although these effects are not easily separated from those of elemental carbon. As with black carbon and sulphates, however, the toxicology of pure ozone probably does not replicate the actual effects in ambient settings in which ozone is closely associated with other oxidative pollutants.

Evidence associating ozone with morbidity strengthens the case for causality and intervention justification. Such evidence might also identify effects on special subgroups (eg, children with asthma). However, in most cost–benefit analyses of air pollution that are used to justify public health interventions, mortality dominates estimates of benefit. Until recently, the mortality effects of long-term ozone exposure were not clear,[13] but new studies[67] and the analysis in this report provide evidence that the mortality effects from long-term exposures are real, and probably independent from those of sulphate. In view of the large risks noted in these long-term studies, the co-benefits of reductions in ozone might be greater than those previously estimated. Further replication in other cohorts and settings is needed to ensure estimates of benefits are accurate and reliable for policy decisions.[71]

Elemental carbon seems to exert the strongest effects per unit mass in the presence of other major co-pollutants for chronic exposures in the ACS case study, but sulphate seems to have larger effects per unit mass in the time-series studies (tables 2 and 3). Although the results of the time-series meta-analysis suggest larger effects of sulphate than of black smoke per μg/m³, this distinction is less clear in the few studies that have measured both (table 1). Additionally, most studies of black smoke were done in Europe and most sulphate studies in North America, so comparisons are difficult. Furthermore, comparison of the two metrics on a mass basis is variable because the black smoke measurement is based on an optical, not gravimetric, technique.

Differential amounts of measurement error might also be present because sulphate, a secondary pollutant formed in the atmosphere, tends to vary regionally, but not within cities compared with concentrations of elemental carbon or black smoke. For this reason, estimates of elemental or black carbon are likely to have more measurement error than are the assigned sulphate exposures. Additionally, because it is highly reflective, sulphate can cause negative artifacts for reflectance-based measurements of black carbon that might vary by day, season, and location, complicating health-effect comparisons of sulphate versus black smoke or elemental and black carbon.[72] When measurement error is present in a regression analysis, variables measured

	Main human sources	Measurement	Toxicology	Epidemiology (mortality)	Climate	Ecosystems	Control
Sulphate particles	Power plants, industry, and transport from sulphur in fuels; concentrations falling worldwide	Little ambiguity, although emissions are mainly sulphur dioxide, complicating calculation of extent and location of transformation	Pure sulphate not shown to be toxic at concentrations encountered in the environment	Could have larger relative effects than undifferentiated fine particles that seem to be independent of other pollutants; sulphur dioxide, the emitted precursor, probably has additional effects	Generally cooling with some difference by location and complexity when in mixtures	Acid precipitation is of little uncertainty, but wide difference in effect by location	Control of sulphur dioxide has some, but not large interaction with other types of control
Black carbon particles	Household solid fuels, industrial coal, forest/grassland burning, and diesel from incomplete combustion; fossil-fuel proportion falling slowly	Basic measurement methods and metrics in some confusion across disciplines	Pure EC not very toxic in human and animal studies at environmental levels	Measured as EC, might have larger effects than undifferentiated fine particles, but results are not stable when other pollutants are included in models	Major uncertainties, but high warming potential that is complicated by location, short life, and mixtures with other aerosols	Melting and warming effects if it falls on ice or snow, particularly in Arctic and Himalayas; not yet well understood	Controls also reduce organic carbon emissions, which are generally cooling; net climate effect thus varies depending on source OC/BC ratio
Ozone (tropospheric)	Precursors: methane and NMVOCs with combustion and non-combustion sources and NOx mainly from combustion; concentrations rising worldwide	Ozone itself has little uncertainty, but precursor emission measurements are uncertain; might be formed far from sources; needs sunlight to form	Oxidative stress and inflammation pathways established for toxicity of pure ozone at or near environmental concentrations	Might have mortality effects that are independent of major types of small particles; evidence is more extensive for short-term exposure, but results from one large cohort study[26] suggest much larger effects from long-term exposure	Warming potential well established, but total effect shared across precursor emissions in complex ways	Adversely affects agriculture and ecosystems; might reduce carbon storage	Complex atmospheric chemistry determines importance of VOCs *vs* NOx control locally

As noted in the text, epidemiological methods are not able to identify the mortality effects of the pure material in the environment, but rather the mixture of pollutants for which each material is an indicator. See panel for more details on climate interactions. EC=elemental carbon. OC=organic carbon. BC=black carbon. NMVOC=non-methane volatile organic compounds. NOx=nitrogen oxides. VOC=volatile organic compounds.

***Table 4:* Summary of health, climate, emissions, and ecosystem issues related to sulphate, black carbon, and ozone**

with high precision will tend to overpower effects from other variables measured with less precision.[73] This notion might partly explain why sulphate seems to be more robust to confounding by other co-pollutants than was elemental carbon in the ACS study and also in other chronic studies that have used black smoke. Table 4 qualitatively summarises the evidence presented in this paper about the health, climate, and other characteristics of the three short-lived greenhouse pollutants; however, we cannot confidently quantify the differences in effects between them.[14,16]

The distinction between short-lived greenhouse pollutants with regard to emissions, ambient concentrations, and effects is important. What is emitted is not exactly what is detected in the environment in all cases, because of both atmospheric transformations and closely associated co-pollutants. For example, several geographic, meteorological, and seasonal factors, such as the interaction with clouds, can transform emissions and change climate effects. Health effects can vary because of the differences in intake fraction or exposure efficiency—ie, people might breathe more pollution from sources nearer to them than from those at a greater distance, even if those at greater distance contribute importantly to environmental concentrations.[74]

Black carbon could have effects both chemically and as a generic function of being a particle. The toxicological evidence suggests that the ultrafine fraction is more toxic than other fractions, but the chemical composition might account for the health effects recorded in epidemiological studies. In the troposphere, ultrafine concentrations often quickly fall after the primary emission source,[75] and black carbon is often detected in sizes greater than the ultrafine fraction. For example, the peak black carbon concentration of anthropogenic haze over the Indian Ocean (far away from sources) occurred at 0·3–1·0 μm diameter, which is larger than is the size of black carbon particles detected near sources—eg, in fresh engine exhaust (0·1–0·2 μm).[76,77] Even within a city, ambient black carbon particles are generally smaller than are those found far away from sources—eg, 0·2–0·4 μm in ambient air in Los Angeles, CA, USA.[78] So far, neither toxicology nor epidemiology provide a clear answer as to the relative toxic effects of black carbon by size, number, or chemical composition, including any differences for combustion particles associated with black carbon, such as those termed organic carbon.[14]

One of the recurring suggestions to slow climate change is the deliberate injection of sulphates into the atmosphere because of their climate-cooling properties and low toxic effects.[79,80] Any such so-called geoengineering needs to be analysed carefully and implemented cautiously. The present epidemiological evidence for mortality effects of sulphate is not conclusive because of the strong association with other pollutants from the same combustion sources. Moreover, studies are needed to understand how artificially injected sulphate from non-combustion processes transforms in the atmosphere to affect human beings and ecosystems. Another widely discussed option for mitigation of climate change is to use biofuels instead of fossil fuels. Research suggests that a switch from fossil fuels to ethanol could increase

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emission of volatile organic compounds (aldehydes), which are known precursors of tropospheric ozone. Thus, the health effects could potentially rival those of the fossil fuels that ethanol is intended to replace.[81]

Black carbon is always emitted along with particles of organic carbon, which are cooling but also health-damaging. Thus the effects of an emissions reduction of black carbon on climate will depend partly on the ratio of black to organic carbon emissions—reducing emissions from a source with a low ratio of organic to black carbon such as diesel exhaust would have greater benefit for climate than would reducing emissions with a high ratio such as biomass smoke. For health, however, both types of particles have effects.

Climate mitigation planning for short-lived greenhouse pollutants is increasingly difficult because of the absence of official climate-weighting factors for these pollutants (panel). As the world seeks to reduce global warming risks in ways that are cost effective and compatible with other goals, including protection from outdoor air pollutants, some version of weighting factors will be needed, although creation of these factors might need acceptance of rough average values for effects that vary in time and space. Alternatively, in addition to those for long-lived greenhouse gases, completely separate agreements for short-lived greenhouse pollutants may be needed.

Integrated models incorporating global warming and air pollution health effects are needed to enable the exploration of the wide range of options available for control of short-lived greenhouse pollutants. Such models would benefit from additional research to quantify the relative toxic effects of specific climate-relevant components of air pollution mixtures, including ozone and the elemental and organic components of fine particulate matter. Finally, to establish policy, multidisciplinary approaches are needed to model and assess the health and climate co-benefits of aerosol control, both primary and secondary, which could in some cases lead to undesirable effects in one or the other sector.

Contributors

KRS conceived of the paper and wrote the abstract, introduction, climate primer, parts of the conclusion, and some of the tables. He also edited contributions from other authors and contributed interpretive expertise on the epidemiological results. MJ led the American Cancer Society (ACS) analysis, wrote all sections of the ACS analysis, assisted with the meta-analysis summary, wrote the ozone toxicology section, wrote portions of the conclusion, edited contributions from other authors, and coordinated the response to the review comments. HRA and RWA led the meta-analysis, drafted text related to the meta-analysis, supplied expert medical-epidemiological advice about interpretation of toxicology and epidemiology studies, and edited the paper. RTB designed the random effects program used for the ACS statistical analysis, supervised the statistical modelling, assisted with preparation of the tables, interpreted results, undertook quality assurance tests on the ACS results, and edited the paper. VS wrote the toxicology sections on sulphates and black carbon and supplied edits to the paper. RD wrote sections of the climate primer, supplied expert commentary and review of climate and pollution measurement sections, and edited the paper. AC helped to outline the paper, wrote parts of the conclusion, supplied detailed edits on each draft, and assisted with all revisions. SBS wrote parts of the sections on black carbon, contributed to the interpretation of the ACS results, wrote parts of the conclusions, edited contributions from other authors, helped to coordinate the response to the review comments, and wrote the primer on black smoke, black carbon, and elemental carbon metrics in the webappendix. DK edited the document and assisted with the ACS analysis and the statistical modelling. CAP edited the document and assisted with the ACS analysis and the interpretation of the ACS results. MJT collected all the ACS data, provided quality assurance, edited the document, and supplied expert medical-epidemiological advice. GT assisted with compilation of the sulphate and elemental carbon data, wrote parts of the conclusion, and supplied expertise on interpretation of the epidemiological results.

Conflicts of interest

We declare that we have no conflicts of interest.

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Health and Climate Change 6

Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers

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This Series has examined the health implications of policies aimed at tackling climate change. Assessments of mitigation strategies in four domains—household energy, transport, food and agriculture, and electricity generation—suggest an important message: that actions to reduce greenhouse-gas emissions often, although not always, entail net benefits for health. In some cases, the potential benefits seem to be substantial. This evidence provides an additional and immediate rationale for reductions in greenhouse-gas emissions beyond that of climate change mitigation alone. Climate change is an increasing and evolving threat to the health of populations worldwide. At the same time, major public health burdens remain in many regions. Climate change therefore adds further urgency to the task of addressing international health priorities, such as the UN Millennium Development Goals. Recognition that mitigation strategies can have substantial benefits for both health and climate protection offers the possibility of policy choices that are potentially both more cost effective and socially attractive than are those that address these priorities independently.

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This is the sixth in a **Series** of six papers about health and climate change

*Based on the work of the Task Force on Climate Change Mitigation and Public Health, which is described in the preceding papers of this Series. Members listed at end of paper

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Introduction

Climate change threatens the health of human populations worldwide, but particularly in low-income countries.[1] These adverse health consequences are among the many important reasons why governments need collectively to act with resolution and urgency to reduce global greenhouse-gas emissions. What has been less widely understood, however, is that policies to reduce greenhouse-gas emissions (climate change mitigation policies) could often have more immediate and potentially large effects on population health. These ancillary effects are important not only because they can provide an additional rationale to pursue mitigation strategies, but also because progress has been slow to address international health priorities such as the UN Millennium Development Goals (MDGs)[2] and reductions in health inequities. Mitigation measures can thus offer an opportunity not only to reduce the risks of climate change but also, if well chosen and implemented, to deliver improvements in health—the so-called co-benefits of mitigation, although not all effects are necessarily positive.

Key messages

- Many measures to reduce greenhouse-gas emissions in the sectors of household energy, transport, food and agriculture, and electricity generation have ancillary health benefits (or health co-benefits), which are often substantial.
- The health co-benefits resulting from such measures can help address existing global health priorities, such as child mortality from acute respiratory infections, ischaemic heart disease in adults, and other non-communicable diseases.
- Improvement of access to affordable, clean energy (especially for disadvantaged populations), together with other appropriate strategies in several sectors, can contribute to a reduction in the risk of dangerous climate change while improving health, reducing poverty, and supporting development .
- Specific policies that can reduce greenhouse-gas emissions and result in health benefits include increased active transport (walking and cycling) and reduced private-car use in urban settings, increased uptake of improved cookstoves in low-income countries, reduced consumption of animal products in high-consumption settings, and generation of electricity from renewable or other low-carbon sources rather than from fossil fuels, particularly coal.

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- The varying costs of implementation of such strategies can be offset at least partly by the benefits to health and development, and these co-benefits should be taken into account in international negotiations.
- Some measures, however, can have negative health effects; therefore assessment of health effects of greenhouse-gas mitigation strategies is important.
- Mechanisms to transfer resources for clean development from high-income to low-income countries should take into account health consequences of the technologies and strategies in decisions about priorities for funding.
- The methods for assessing the health effects of mitigation strategies for climate change outlined in this Series should be further developed and applied, to inform policy making.
- Health professionals have an important role in the design of a low-carbon economy, motivated by evidence of the projected benefits to public health.

	Country, city, or region	Mechanism of health effect	Main health outcome(s) affected	Approximate reduction in burden of disease (in DALYs per million population)	Approximate cost (US$)	Potential adverse health effects
Household energy						
Housing-related energy efficiency	UK	Changes in indoor pollution (radon, particles, carbon monoxide, second-hand tobacco smoke); mould; winter indoor temperature	Lung cancer (radon), cardiovascular disease, acute and chronic respiratory disease, winter/cold-related death	850	$5000–50 000, one-off cost per household, off-set by lower recurrent fuel costs*	Increase in pollution concentration from reduced ventilation and increased cold-related risk from cooler indoor temperatures
Clean-burning cookstoves	India	Changes in exposure to indoor pollution	Acute lower respiratory tract infection, ischaemic heart disease, chronic obstructive respiratory disease	12 500	$50 cost per stove, perhaps every 5 years, continual fuel savings and/or time savings	No adverse effects identified
Transport system						
Lower carbon and more active transport	London, UK	Altered air pollution, changes in injury risk, changes in physical activity	Ischaemic heart disease, cerebrovascular disease, dementia, breast cancer, lung cancer, colon cancer, diabetes, depression, road traffic injuries	7400	Unclear: possibly negative (cost-saving) to households	Trade-off between reduced road traffic danger from less motor travel and increased exposure to remaining danger from more walking and cycling
Lower carbon and more active transport	Delhi, India	As for UK	Ischaemic heart disease, road traffic injuries, cerebrovascular disease, lung cancer, diabetes, depression	13 000	As for UK	As for UK
Food and agriculture						
Lowering consumption of animal products	UK	Lower saturated fat intake	Ischaemic heart disease	2900	Unclear: possibly negative (cost-saving) to households and society	Childhood growth and development from reduced animal-product consumption (low-income countries)
Lowering consumption of animal products	São Paulo city, Brazil	As for UK	As for UK	2200	As for UK	As for UK
Electricity generation						
Low-carbon fuels/ technologies	European Union	Reduced (particulate) air pollution	Cardiopulmonary mortality, lung cancer, occupational mortality	100	$140 per tonne carbon dioxide	Increase in fuel poverty from higher electricity costs, health risks from nuclear generation and carbon capture and storage
Low-carbon fuels/ technologies	China	As for European Union	As for European Union	550	$70 per tonne carbon dioxide	As for European Union
Low-carbon fuels/ technologies	India	As for European Union	As for European Union	1500	$40 per tonne carbon dioxide	As for European Union

DALY=disability-adjusted life-year. *More detailed explanation of these costs is given in the first paper in this Series.[3]

Table: **Summary of the scenarios considered in the four sectoral assessments**

Overview of sectoral assessments

This Series focused on the health effects of mitigation strategies in four sectors—household energy,[3] transport,[4] food and agriculture,[5] and electricity generation[6]—using examples from high-income and low-income or middle-income settings. In each sector, the potential links between reduction in greenhouse-gas emissions and health seem to be strong. The methods and results are summarised in the table and figures 1 and 2. A fifth paper[7] in the Series both reviews and provides new evidence for the health effects of short-lived greenhouse pollutants, which are emitted from several sectors.

Figures 1 and 2 show the assessments of the effect of mitigation scenarios both in terms of changes in health (disability-adjusted life-years [DALYs] saved) and reductions in carbon dioxide equivalent (CO_2e) emissions per million of the 2010 population, and in terms of absolute numbers (ie, the total change for the relevant populations as a whole). It is important to note that the sector-specific and setting-specific results shown in figures 1 and 2 are not exactly comparable with each other, since each assessment had its own set of assumptions and detailed methods of estimation. The results should therefore be interpreted only as broad indications of magnitude of effect.

For the case studies of the household energy and food and agriculture sectors (figure 1), the estimated health effects of strategies to reduce greenhouse gases were calculated from the difference between baseline (2010) exposures and those that would occur under mitigation, with the assumption that circumstances are otherwise held constant at 2010 conditions. This approach has the advantage of reducing the need for uncertain projections, and makes the stand-alone mitigation effect clear, but it takes no account of potentially important trends over time, particularly in exposure, which could arise as a

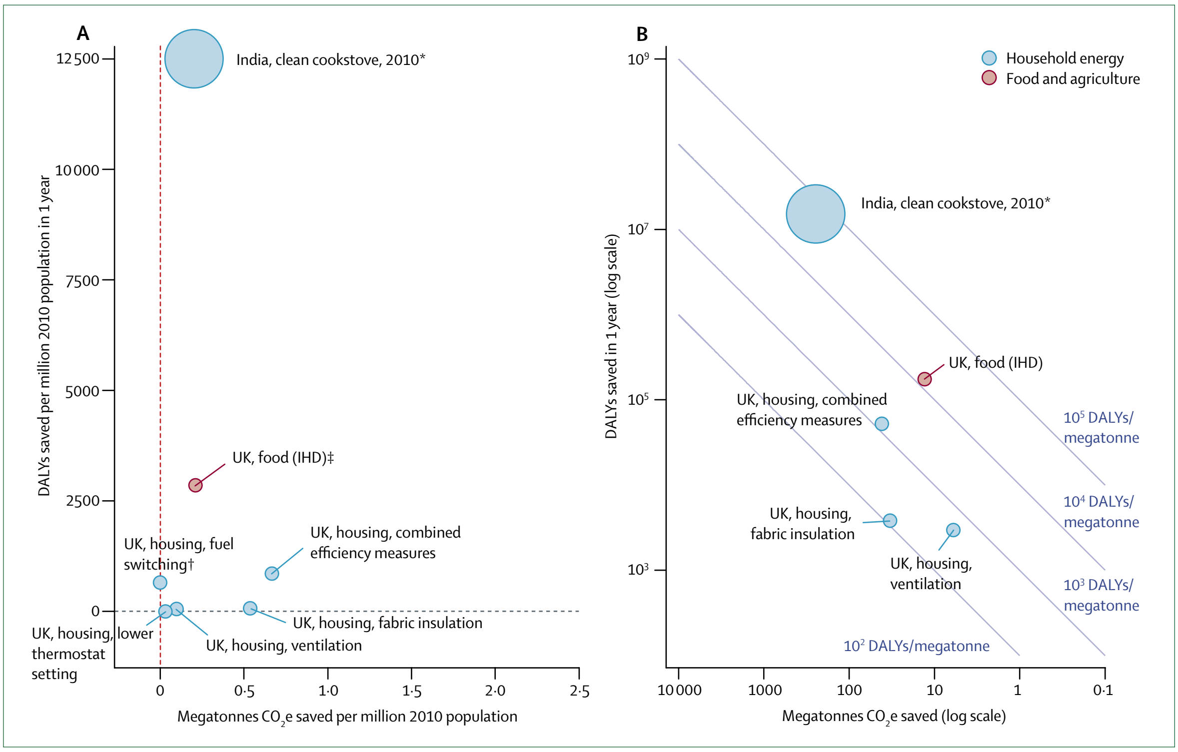

Figure 1: **Attributable reduction in disease burden and in carbon dioxide equivalent emissions for household energy and food and agriculture case studies**
(A) Disability-adjusted life-years (DALYS) saved and carbon dioxide equivalent (CO_2e) reduction per million of the 2010 population. (B) Reduction in total of DALYs and CO_2e for each country. Circle sizes proportional to population of the relevant country. DALYs saved are based on attributable burden calculations comparing the health of the 2010 population with and without the specified mitigation measures. Scenario results with negative or zero change are not plotted in B. IHD=ischaemic heart disease. *Alternative calculations based on the staged implementation of the cookstove programme over 10 years are given in the first paper in this Series.[3] The reduction in emissions of greenhouse gases is based mainly on non-carbon-dioxide pollutants, and the carbon dioxide equivalence should be interpreted as approximate. †Zero change has been shown, but a net change in carbon dioxide emissions is probably dependent on the alternative primary fuel sources. The São Paulo city case study was not included because of uncertainties about livestock-related greenhouse-gas emissions. ‡The changes shown in greenhouse-gas emissions are those occurring directly from the UK only, and do not include possible emission savings from countries that produce livestock for consumption in the UK. About 20–30% of the livestock products consumed in the UK are imported.

result of policies or societal changes unrelated to climate change mitigation.

The assessment of mitigation measures in the electricity generation and transport sectors (figure 2), by contrast, used projections of exposures to 2030, partly because models were readily available to the investigators, but also because in these sectors the pace of technological and societal development is likely to result in large changes in exposures during coming decades, especially in countries such as India and China. Thus, we calculated the effects on health for a 2010 population using the differences in estimated exposures in 2030 between business-as-usual and mitigation scenarios.

Most, although not all, of the mitigation scenarios are estimated to have net benefit for population health, at least in terms of the direct pathways modelled. In some cases, notably the cleaner cookstoves in India, and sustainable transport based on increased participation in walking and cycling together with much lower car use in Delhi, the benefits seem substantial—more than 10 000 DALYs per million of the 2010 population. These scenarios and the reduced saturated fat intake example for the UK also had large reductions per megatonne of CO_2e saving—greater than 10 000 DALYs saved in 1 year per megatonne CO_2/CO_2e emissions reduction (figures 1 and 2). These interventions affect the risks of major causes (large burdens) of mortality and morbidity, which explains the large reductions in DALYs per million population suggested for these scenarios. The transport case studies for Delhi all show an increase in emissions compared with 2010 because of the substantial projected rise in population and, in some scenarios, motorised transport, compared with 2010, although all three scenarios represent savings of CO_2 emissions compared with 2030 business-as-usual projections. These CO_2 emission savings would be substantial for the scenarios that entail less private motorised travel.

These overall positive changes disguise some potential negative health effects that need to be guarded against—eg, possible negative nutritional consequences of decreased consumption of livestock products on childhood growth and development in low-consumption settings; and possible increased exposure to radon, mould, and indoor air pollution due to reduced

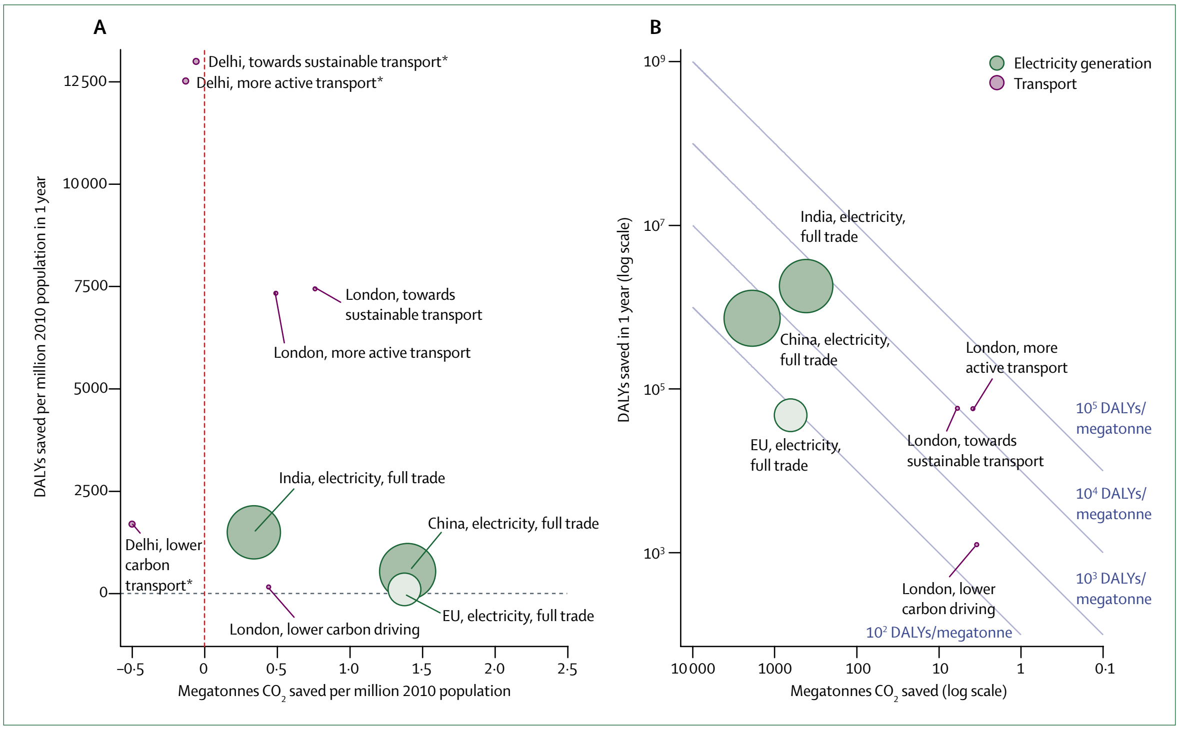

***Figure 2:* Attributable reduction in disease burden and in carbon dioxide equivalent emissions for electricity generation and transport case studies**
(A) Disability-adjusted life-years (DALYS) and carbon dioxide (CO_2) reduction per million of the 2010 population. (B) Reduction in total of DALYs and CO_2 for each country, city, or region. Circle sizes proportional to population of the relevant country, city, or region. Estimates of DALYs saved based on attributable burden calculations comparing 2030 mitigation scenarios with 2030 business-as-usual scenarios. Scenario results with negative or zero change are not plotted in B. EU=European Union. *Although there are small increases (negative savings) in CO_2 emissions for the transport mitigation scenarios in Delhi compared with 2010, all three scenarios entail appreciable savings of CO_2 emissions against business-as-usual projections. The reductions per million of the 2010 population against business-as-usual projections are: 0·14 megatonnes for lower carbon driving, 0·52 megatonnes for more active transport, and 0·58 megatonnes for the scenario of towards sustainable transport.

household ventilation rates in high-income settings. Furthermore, while decreased use of motor vehicles could lead to less road traffic danger, thus reducing road traffic injuries, more walking and cycling could increase exposure to remaining road traffic danger, thus increasing road traffic injuries. The trade-off between these effects will vary by setting but can be improved by use of appropriate policies. Measures can be taken to protect against such adverse consequences where these are recognised, underscoring the value of modelling studies, together with assessment of interventions, to test and refine major policy decisions.

The extent of changes in emissions, local environmental conditions, and associated behaviours has inevitable uncertainties that affect what could be achieved in complex real-world settings. Reduced greenhouse-gas-emitting electricity generation, and increased household energy efficiency in the UK, seem to have modest although still important benefits for health, but greatly affect greenhouse-gas emissions. Economic costs are also important in choosing between mitigation strategies, but their assessment is not straightforward because of methodological challenges (panel 1). The costs of changes, particularly in the agriculture and transport sectors, are very difficult to assess because implementation could entail a complicated combination of changes in taxation, subsidy, regulation, infrastructure development, and many other policies, with wide-ranging indirect effects. Account also needs to be taken of who pays the costs of the policies and who benefits from potential savings—eg, the cost of efficiency interventions and the savings in fuel costs that might follow. Identification of all these factors is a major exercise in its own right, warranting further research.

Nevertheless, the costs of the different interventions can be considered in broad terms (table). An improved cookstove programme in India, for example, would entail a yearly cost per household of, at most, a few tens of US dollars and continual savings in terms of expenditure that can take the form of cash outlays for fuel or time outlays that have an opportunity cost. Stove costs, particularly for the poorest households, can be reduced via carbon finance to support subsidies or other pro-poor financial instruments. However, a household energy efficiency programme in the UK, to achieve the exacting standards specified, would cost in the range \$5000–50 000 per dwelling, resulting in reduced fuel bills by an average of around \$500 a year at current prices, but much more as fossil-fuel and electricity prices increase. Reductions, relative to business as usual, in greenhouse-gas emissions from electricity generation by the full-trade model—the national targets for which can be met through buying and selling of emissions permits in a global market for such permits—are estimated to range in cost from a few tens of dollars per tonne of CO_2 in India to more than $100 per tonne in the UK. The changes in transport, which achieve substantial increases in walking and cycling with reductions in urban motor vehicle use, and the changes in dietary consumption patterns, are both potentially cost-saving to households and society at present prices, although policies to bring about these changes will entail some costs not determined in our analysis.

The UK National Health Service (NHS) spends about $5000 a minute on treating diseases that could be prevented by regular physical activity.[9] Reducing this expenditure and other benefits would help to offset any costs of implementation. Furthermore, the potential for benefits could increase in the future—eg, by 2050, modelling undertaken for the Foresight report[10] suggests that 60% of adult men, 50% of adult women, and about 25% of all children younger than 16 years could be obese. The NHS costs attributable to overweight and obesity are projected to double to £10 billion per year by 2050. The wider costs to society and business are estimated to reach about £50 billion per year (at present prices).

In terms of strategic choices, the greatest health gains seem likely to result from changes towards active transport, and from diets that are low in animal source foods, at least for adult populations in high-income countries. The clean cookstove programme for India also seems a priority low-cost intervention for its public health benefits, even though its effect on greenhouse-pollutant emissions is less easily determined (and mainly relates to non-CO_2 greenhouse-gas emissions: methane, carbon monoxide, and black and organic carbon in circumstances in which biomass fuel is renewably harvested, resulting in no net CO_2 emissions).

The evidence suggests that very substantial health gains are achievable (in addition to substantial reductions in greenhouse gases and black carbon emissions) for little cost by improvement of the combustion of solid household fuels (coal and biomass) in confined and unventilated housing in many low-income countries. Household exposure to indoor air pollutants from inefficient or unventilated combustion—which is widespread in China, South Asia, and much of sub-Saharan Africa and Latin America—causes an estimated 1·6 million premature deaths per year, predominantly in women and children.[11] Although interventions in electricity generation and in household energy efficiency in high-income countries have lower benefits in terms of DALYs saved per head than they do in low-income countries, they nonetheless seem to bring about appreciable public health benefits if implemented well.

In the medium term the world does not have the luxury of choosing one intervention over another, since only the combined effect of all these mitigation actions, in addition to many others, will achieve the substantial reduction in greenhouse-gas emissions that is needed. Societies, however, have the choice of which to pursue most vigorously at first, and of how to prioritise the use of resources to avert climate change compared with addressing present social priorities—decisions that can be informed by health cost-effectiveness analyses. Examples include cutting transport-related greenhouse-gas emissions by encouraging active transport and reducing car use in urban centres rather than by changes in technology and, (an example that affects international cooperation and development) a transition to low-greenhouse-gas electricity generation in countries such as India and China compared with Europe and

Panel 1: Methodological challenges

One of the key challenges is development of credible scenarios of greenhouse-gas emissions under mitigation and business-as-usual projections during future decades. This challenge is especially difficult in the case of societies undergoing rapid development, in which, for example, transport patterns could change substantially in a short time with major implications for public health. Public health researchers should work closely with those involved in research and strategic planning in the relevant sector to ensure that the scenarios that are used are grounded on the best available evidence about probable trends, and that the assumptions on which they are based are made transparent. The selection of the business-as-usual scenario and the assumptions underlying it are important and can affect the estimates of the health co-benefits dependent on, for example, what assumptions are made about reductions in air pollution as a result of legislation or the introduction of cleaner engines unrelated to policies for climate change. Assumptions about underlying trends in the prevalence and mortality from disorders such as ischaemic heart disease can materially affect estimates of effect. Sensitivity analyses exploring several potential assumptions about future trends and relations between relevant policies and health outcomes are needed. Estimates of effect should be revisited as new scientific insights into exposure–response relations or technological options for reduction of greenhouse-gas emissions become available.

Cost–benefit or, more commonly, cost-effectiveness analysis, is widely used to assess health interventions. In the particular context of health co-benefits of climate change, cost–benefit analysis is not especially useful since such analysis would entail comparison of the benefits of reductions in emissions (health benefits in the short to medium term as well as those arising in the long term from reduced greenhouse gases) against the costs entailed in achieving those reductions. Integrated assessment models that incorporate reductions in greenhouse-gas emissions across a range of sectors and strategies should take into account health co-benefits.

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In the design of mitigation measures, reduction targets for greenhouse gases at different periods are often taken as fixed, and a cost-effectiveness analysis allows us to choose the least cost options for meeting these targets. The main purpose of mitigation activity is to curb greenhouse-gas emissions. Incidental, direct gains to health are an additional bonus to the value to the mitigation action, and if these benefits can be valued in monetary terms they can be offset against the costs of these actions, giving a resulting net cost per tonne of greenhouse gases reduced. This analysis has been done extensively for interventions reducing carbon dioxide and other greenhouse pollutants from electricity and household stoves. However, the cost-effectiveness analysis can be difficult to do. Some of the issues that have been raised include:

- How should the indefinitely continuing stream of health gain be valued, especially reductions in premature mortality? Is it ethical to take different values for this benefit dependent on how wealthy a country is?
- Is discounting of future gains relevant, or would it undervalue the mitigation and introduce intergenerational inequity?
- How should benefits be traded against costs? For example, reduction of car use and increase of active transport in cities might reduce fuel bills and vehicle ownership costs for households but might increase travel times, at least until land use and trip destinations change.
- How should direct and indirect economic effects of major social change be assessed? These effects could include benefit for specific industries and disadvantage for others, and increased comparative advantage for local versus distant suppliers. These effects are not amenable to cost-effectiveness analysis but rather need to be investigated through macroeconomic models.
- Could sustainable cities, with lower resource use and reduced greenhouse-gas emissions, achieve equivalent or improved social goals compared with those that consume higher amounts of resources? Moreover, this raises questions about what type of cities we want to live in and how we want to live within them.
- Not all health gains and losses can be quantified, so the monetary values will represent only a part of the full set of health gains and losses from the various social, economic, and technological ramifications of the initial intervention.

For these reasons, we have not attempted to undertake a cost–benefit analysis of all the options, and a systematic cost-effectiveness analysis has not been possible to do, at least at this stage of the research programme, for each of the various mitigation actions. Meanwhile, the cost-effectiveness of the mitigation action can be assessed for strategies for which estimates of cost can feasibly be developed.[8] Every mitigation activity can be assessed, at least in theory, in terms of cost per unit of health gain and per unit of reduction in greenhouse-gas emissions.

North America. This benefit provides an incentive for early action in countries such as India and China, although clearly it is not an argument for Europe and North America to postpone the urgent reductions in their own emissions that are needed.

The fifth paper in the Series[7] draws attention to the importance of a set of short-lived greenhouse pollutants that are emitted in several sectors and are often left out of policy and public discussions: sulphate and black carbon particles and tropospheric ozone. All have adverse health effects and all are climate active. The importance of paying much closer attention to them in mitigation policy relates to the fact that changes in emission rates are quickly reflected in atmospheric concentrations. Cutting the responsible emissions therefore has immediate effects on climate warming. At the same time, there are questions of whether different types of particles from different sources may be more or less detrimental to health. Evidence for the adverse health effects of combustion products and their large global health burdens is well established,[11] but there is uncertainty whether sulphates, which largely derive from power and transport sectors, and black carbon, which is produced by the incomplete combustion of biomass and fossil fuels, mainly in the household and transport sectors, are equally important for health.

New evidence is presented in the fifth paper[7] in this Series on the health effects of elemental carbon, the closest equivalent to the metric of black carbon used by climate scientists. This analysis finds some evidence that particles of elemental and black carbon cause more mortality risk by mass than do undifferentiated fine particles, but also pronounced interaction with ozone in the risk models, leaving the issue unsettled. For sulphates, however, the evidence from both reviews and the new study is more consistent and indicates, by mass, sulphate particles are no less damaging than undifferentiated fine particles and might indeed be somewhat more so. These findings have important implications for mitigation efforts.

Since interventions to reduce black carbon emissions will also control the associated organic carbon particles, which are health-damaging but mildly cooling, the net climate effect will depend on the ratio of these two particle types in the original mixture. Strategies to reduce sulphate concentrations, however, although desirable from a public health perspective, could exacerbate climate change in the near term because of a loss of cooling aerosols, implying that even deeper cuts in greenhouse-gas emissions might be needed than are proposed in present official targets if dangerous climate change is to be avoided.

Ozone concentrations are rising worldwide due to increasing anthropogenic precursor emissions including methane, the second most important greenhouse gas. Ozone is not only a powerful greenhouse gas, but is increasingly implicated as a cause of premature

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mortality in its own right, which is further supported by the new study. It also damages crops and ecosystems. Future analyses of co-benefits need to consider ozone creation and its effects in detail.

Policy implications

Estimation and comparison of ancillary health effects is, unavoidably, imprecise. Nevertheless, it benefits from developments in the discipline of impact science (eg, WHO's Comparative Quantification of Health Risks[11] and assessments of the health effects of power generation in Europe[12]). Despite many scientific uncertainties (panel 2), the models provide useful evidence about the type and approximate scale of health effects that can be expected from pursuit of major mitigation policies. The finding of generally positive health effects of mitigation shows that strategies promoting a low greenhouse-gas emission economy can also have potential to improve public health.[13] It also provides a rationale to reduce greenhouse-gas emissions that is not wholly confined to the achievement of climate change mitigation. Some commentators suggest that many features of climate change are now irreversible and that the most important objective is to try to adapt to it and other global environmental threats.[14] However, the case for mitigation is greatly strengthened if it has direct collateral benefits in addition to restriction of climate change.

Much of the disease burden in the poorest countries is still due to category I conditions, which are dominated by infectious and parasitic diseases, maternal mortality, adverse pregnancy outcomes, and malnutrition.[15] However, the risk factors for non-communicable diseases and consequent category II burdens are rising in many low-income countries.[16] Rapid urbanisation, industrialisation, and growth of motor transport have resulted in levels of fine particles and ozone that greatly exceed health-based international guidelines,[17] despite air quality management efforts that have reduced levels of air pollution in some locales. Further, as low-income societies modernise, the risks of inactivity and a transition away from traditional diets (eg, obesity) are emerging quickly, especially in urban populations in which population growth and congregation are great. The apparent rise in the importance of non-communicable disease is also partly due to its unmasking, as the infectious disease burden falls and the global population ages.[18]

Activities for climate change mitigation would in a few cases also directly reduce, via co-benefits, the risks of infectious diseases in low-income countries. An example presented in this Series is that of the reduced incidence of acute lower respiratory infection with improved combustion efficiency or switching to clean fuels for household cooking in poor populations.[3] Indeed, as shown in the household energy paper,[3] a full-scale cookstove intervention in India could reduce deaths attributable to acute lower respiratory infection, the main cause of child mortality worldwide, by nearly a third by 2020. Present estimates suggest that indoor air pollution is responsible for more than 2% of the entire world burden of disease, or close to 4% in the poorest countries.[11] Furthermore, evidence of effects of household air pollution on several other health outcomes, including low birthweight and cataracts, is growing, potentially adding to this total.[19]

This Series has not included assessments of all important strategies to reduce greenhouse-gas emissions. One strategy not included is the reduction in population growth, from which potentially major additional health co-benefits would result from provision

Panel 2: Uncertainties in estimation of co-benefits to health

Even for specific causal pathways, important sources of uncertainty arise in relation to exposure–response functions (both parameters and mathematical form) and the extent to which exposures would in fact change. In this Series, we have shown some of these uncertainties—eg, use of confidence intervals for exposure–response indices in the food and agriculture paper,[5] and contrasting different models for effects of particulate pollution in the transport and electricity papers.[4,6] We have not routinely calculated summaries of uncertainty such as confidence intervals, because doing so would inevitably capture only some sources of uncertainty, and thus give only a partial picture. However, we have quantified effects only when evidence for them is strong, and thus we believe that they provide estimates of the broad magnitude and direction of effects.

Our analyses omit several important pathways by which mitigation strategies for climate change might affect health, such as the effect of fuel prices and conversely the effect of providing equitable access to clean energy for resource-poor populations. We also did not consider the health effects of reducing the extent of climate change, which is the topic of other work.

The timing in which the potential benefits to health from strategies to reduce greenhouse-gas emissions are manifested will vary. These benefits include likely immediate reductions in acute respiratory infections in children from decreases in indoor air pollution in low-income countries, short-term and medium-term reductions in cardiovascular disease incidence and mortality that might occur over a period of years, and reductions in cancer incidence and mortality related to obesity that might take place over decades. Potential health benefits can therefore be regarded as committed benefits that can accrue over variable time spans dependent on the health outcome. The distribution of change in exposure will usually vary between individuals and between regions, economies, and cultures; homogeneous change in the actual dose received is unlikely. Additional important uncertainties are the speed and completeness of any intervention, but especially those needing substantial behavioural change and those needing much investment and political will.

For more about the **European Consortium for Modelling of Air Pollution and Climate Strategies** see http:// www.ec4macs.eu/home/index.html

For more about the **Network for Integrated Assessment Modelling** see http://www.niam.scarp.se/

Panel 3: Research priorities

A recent WHO publication outlined the need for expansion of research into health and climate change encompassing effects, vulnerability, adaptation, and mitigation.[26] The analyses presented in this Series might be improved through extension in scope, detail, and methodological and data refinements. Further work might complement other efforts at integrated assessment modelling—eg, EC4MACS, a European Consortium for Modelling of Air Pollution and Climate Strategies funded through the EU-LIFE programme.

During our own programme of research and modelling, several topics were identified for which additional research is needed to reduce uncertainties and clarify the potential of greenhouse-gas reduction strategies to improve (or in some cases worsen) health. These issues are listed below.

Cross-cutting issues

- Costs of implementation of mitigation strategies with substantial health benefits
- Visioning and modelling of the broader economic and social effects of the transition to low-carbon futures
- Closer linkage of climate mitigation strategies to major health targets, such as those in the Millennium Development Goals
- Modelling uncertainties, including timing of exposure and health effects
- The effect of global population growth, including issues of socioeconomic equity and immigration
- Complete accounting of climate and health effects of non-carbon-dioxide greenhouse pollutants
- Assessment of combined mitigation and adaptation strategies
- Alternative methods to the Comparative Risk Assessment approach, strategies for dealing with double-counting of health effects

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More specific to task groups

- Identify additional mitigation efforts across a wider set of sectors with substantial health effects
- Additional primary research into the short-lived greenhouse pollutants, particularly to understand the effect of sulphate concentrations on climate cooling and health, and the negative effects of black carbon, organic carbon, and ozone on health and climate
- Exploration of sensitivity to assumptions: time discounting, exposure models, and anticipated changes in health over time in pollution-health models
- Use of refined air-pollution emission-dispersion models to estimate concentration changes by country to yield country-specific estimates of health effects, building on integrated assessment approaches such as those from the Network for Integrated Assessment Modelling
- Exploration of methods to characterise economic effects on health due to changes in fuel prices
- Detailed exploration and model development for indoor particulate matter ($PM_{2.5}$) and radon concentrations and associated health effects
- Further exploration of the performance of household ventilation systems and associated health effects
- Further accounting of different types of saturated fat from animal products (eg, stearic, palmitic, myristic)
- Health impact assessment of new and emerging greenhouse-gas mitigation technologies such as carbon capture and storage and geoengineering schemes such as emissions of sulphates from non-combustion sources
- Potential for climate change and mitigation strategies to affect crop production and risk of hunger

of universal access to reproductive health services.[20] The increased birth spacing and reduced fertility that results when women have access to education and contraceptives to control their reproduction can create major health benefits by reducing both maternal and child mortality.[21] Achievement of these benefits is not a matter of coercion, but of provision of the same level of reproductive health services that women already have in more than half the world. Although the exact effect on greenhouse-gas emissions is not easily measured, bringing the world to replacement fertility sooner rather than later will undoubtedly reduce effects on the planet in the long term. Although per head emissions are low in many resource-poor countries, population growth is projected to increase in coming decades in some high-emitting countries such as the UK and USA,[22] thus making the attainment of deep cuts in greenhouse-gas emissions in these countries even more challenging.

A controversial approach to mitigation is the production of biofuels, particularly to meet growing demands for liquid fuels for transport. Many factors affect greenhouse-gas emissions from the biofuels supply system, such as the inputs of energy used to grow the plants from which they are derived and land-use change as a result of growing plants for biofuels. There has been particular concern that production of ethanol from corn needs substantial fossil fuel and fertiliser, thus resulting in large emissions of both greenhouse gases and fine particulates.[23] Biofuels could potentially make an important contribution to reductions in greenhouse gases if they came from “feedstocks produced with much lower life-cycle greenhouse-gas emissions than traditional fossil fuels and with little or no competition with food production”.[24] For meeting transportation needs though, recent evidence suggests that combustion of biomass to generate electricity for charging battery-powered vehicles outperforms ethanol in terms of land-use efficiency and greenhouse-gas emissions offsets per unit area of crops.[25] The potential implications of biofuels and bioenergy for health and harmful emissions need further investigation.

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This Series has not considered the many other potential benefits with less direct bearing on health that could accrue from the implementation of appropriate policies and strategies to reduce greenhouse-gas emissions. These initiatives include new employment opportunities in renewable energy industries, increased productive time of women in particular who no longer need to collect so much biomass for fuel, reduced time spent in traffic congestion, and increased energy security that has the potential to reduce conflict about scarce reserves of fossil fuels. In panel 3 we summarise research areas identified by the Task Force as needing further work.

Aligning health, development, and climate change mitigation

The UN Framework Convention on Climate Change (UNFCCC) states that mitigation measures bringing about societal benefits should be prioritised. Health is one of the clearest of the societal benefits (as mentioned prominently in the opening section of the UNFCCC 1992).[27] Benefits to health readily attract public support for political action, as shown by experiences in which health benefits have dominated the externalities of environmental interventions such as clean air legislation in many countries.

The Clean Development Mechanism emerged from the Kyoto Protocol,[27] and established mechanisms for trading of carbon permits. Although low-income and middle-income countries were exempt from the binding requirements on Annex 1 (industrialised) countries to achieve specific cuts in greenhouse-gas emissions, these countries can, at least theoretically, benefit by selling carbon credits, for projects that will enhance their sustainable development. Although the Clean Development Mechanism has made some contribution in channelling funds to beneficiary nations, difficulties have arisen,[28] including the absence of an effective standard way to quantify the extent of development in such a project, or to choose one project over another according to how much development it achieves. Thus, although the mechanism was meant to lend support to sustainable development, approved projects have largely focused on greenhouse-gas mitigation, with some consideration of employment. Further, data from 2006[28] showed that only a few projects have benefited in sub-Saharan Africa (1·8%), whereas Asian countries (particularly China) have had much more success. The Nairobi Framework initiative was launched in November, 2006, with the support of the UN, World Bank, and African Development Bank to foster participation of poor countries, particularly in Africa.[29]

Achievement of a reasonable health status within populations is an essential element in development, as is recognised by almost every country in the form of the MDGs.[2] Although not without uncertainties, we believe that the assessment of the health co-benefits of climate mitigation projects is sufficiently advanced to allow estimation of the magnitude of their effects. We propose therefore that assessment of the health co-benefits of projects submitted to the Clean Development Mechanism and other such international efforts should be one criterion of suitability for funding. Indeed, the establishment in 2007 of the MDG-Carbon Facility by UN Development Programme, UN Foundation, and others suggests a potential mechanism through which this effort could begin.[30] Our work could contribute to development of standardised approaches for assessment of health and development co-benefits.

Panel 4: **Action points**

Policy makers in sectors that are responsible for substantial greenhouse-gas emissions should:

- Take into account health co-benefits and potential harms when considering different mitigation options for greenhouse gases so that they enhance progress towards the Millennium Development Goals and other health and development priorities
- Ensure that new technologies and strategies for greenhouse-gas mitigation are subject to health impact assessment before being disseminated
- Implement policies to reduce inequities in access to clean energy sources
- Consider removal of subsidies that encourage the consumption of animal products in high-consuming nations
- Increase expenditure for measures to encourage cycling and walking and discourage private-car use in urban centres

Research funders should:

- Increase funding for interdisciplinary collaboration, including methods development, between health researchers and scientists working on climate change mitigation technologies and strategies across several sectors
- Build capacity by supporting the career development and training of researchers in relevant disciplines
- Promote strategies and policies for low greenhouse-gas emissions in their own working environment and in their allocation of funding

Health policy makers should:

- Promote and support policies to achieve low greenhouse-gas emissions while delivering co-benefits to health and encourage simple behavioural changes that result in reduction of greenhouse gases
- Ensure that the health workforce is encouraged to reduce their personal greenhouse-gas emissions, including through increased active transport

Health professionals should:

- Advocate for policies to reduce greenhouse-gas emissions and achieve health co-benefits on the basis of the best available evidence
- Promote education on this topic in schools, universities, and the wider community
- Promote strategies and policies to lower greenhouse-gas emissions in their own working environment

Bridging of the equity divide

A major difficulty in international greenhouse-gas negotiations is the difference in historical and future perspectives between rich and poor countries. Observers in low-income countries point out that the historical activities in rich countries have caused most climate change so far.[31] Since low-income countries have many urgent needs for development, they do not see mitigation of their own greenhouse-gas emissions as a high priority at present. Yet, if climate change is to be brought under control, in addition to urgent and far-reaching reductions in high-income countries, there will also soon be a need for many low-income and middle-income countries to take mitigation action.

Policies to promote mitigation activities that have strong co-benefits in health and other development needs provide a potential political bridge across the development gap between rich and poor countries. These initiatives would directly address the major needs of development, with recognition of the imperatives of climate change. Indeed, the provision of affordable clean household energy in developing countries can contribute to the attainment of all eight MDGs, both through the co-benefits to health and through contributions to poverty reduction, provision of productive work, reduction of unproductive time, and thereby reduction of gender inequities.[32]

Considerations of intergenerational equity will also apply, for at least some of the decisions about mitigation actions. For example, if present trends in animal production methods and per head animal-product consumption continue, today's generation will bequeath to future generations a more impoverished and damaged natural environment than at present. Conversely, reformation of urban layout and changes in city planning and housing standards can create, over several decades, an infrastructural base yielding life-long enduring benefits to present and future generations.

Call to action and conclusions

In panel 4 we summarise the implications for several stake-holder groups of the evidence from this Series. Health improvement (via both co-benefits and the avoidance of health effects related to climate change) needs to be integrated into policies to reduce greenhouse-gas emissions and the risk of dangerous climate change. We call on health professionals to reach beyond conventional professional boundaries to collaborate with policy makers and scientists concerned with the study, development, and implementation of policies and technologies to mitigate climate change.

This Series makes clear that health co-benefits can accrue as a direct result of many mitigation activities for greenhouse-gas emissions. If societies change their energy systems in ways that improve outdoor and indoor air quality, change their methods of transport in ways that encourage physical activity and social contact, and modify intensive food production practices and consumer choices in ways that reduce dietary risks to health, then many positive health consequences will result. Despite uncertainties about the magnitude and timescale, health co-benefits from mitigation can be anticipated. Therefore, commitment to mitigation actions producing many such benefits becomes very appealing, especially if (as is likely) the health gains entail substantial national cost savings as an offset to the costs of the mitigation actions. The strategic significance of this issue is potentially great. If the health co-benefits from mitigation activities in lower-income countries were sufficiently large, it would strengthen the rationale for achieving convergence of mitigation schedules between low-income and high-income countries.

The potential co-benefits from selected mitigation measures for greenhouse-gas emissions should heighten the profile of health as a criterion in discussions at the Climate Change Conference in Copenhagen, Denmark, in December, 2009. So far, awareness of the importance and long-term significance of health to the challenges of climate change has been low. Health professionals therefore have an important role in educating the public and policy makers about the health aspects of climate change, including the potential health co-benefits of mitigation measures for greenhouse gases.[33]

As countries consider reductions in their own greenhouse-gas emissions or whether to invest in clean development, the health co-benefits (and potential negative health consequences) should be weighed up carefully in advance. Further research, methodological development, and analytical work are needed to improve prioritisation of mitigation in different sectors and regions. Since trillions of dollars are likely to be spent on greenhouse-gas mitigation in the next decades, it is essential to allocate the fairly small research resources that are needed to guide these investments along paths that bring the world closer to both its health and climate goals.

Contributors

AH chaired the Task Force. All authors participated in the development of ideas for their papers. The text of this paper was drafted mainly by AJM, AH, KRS, and PW, with contributions from all other authors.

Task Force on Climate Change Mitigation and Public Health

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Conflicts of interest

We declare that we have no conflicts of interest.

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