Scoping study on the co-benefits and possible adverse side effects of climate change mitigation: Final report

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Glossary

ACP	Asian co-benefits partnership
AD	Anaerobic digestion (biogas)
AFOLU	Agriculture, forestry and other land use
AQ	Air quality
BAU	Business as usual
BECCS	Bioenergy with carbon capture and storage
CBD	Convention on Biological Diversity
CCC	Committee on Climate Change (UK)
CCS	Carbon capture and storage
CDM	Clean Development Mechanism
CHP	Combined heat and power
CNG	Compressed natural gas
EPA	Environmental Protection Agency (US)
GI	Green infrastructure
HEAT	Health economic assessment tool – a tool developed by the WHO for assessing the health benefits of walking and cycling (physical activity)
HFC	Hydrofluorocarbon
IAM	Integrated assessment model – a macroeconomic model that incorporates the impact of climate change on GDP
IGES	Institute for Global Environmental Strategies
INDC	Intended nationally determined contribution
LCA	Life cycle assessment
LSHTM	London School of Hygiene and Tropical Medicine
MCA	Multi-criteria analysis
MRV	Measuring (or monitoring), reporting and verification
NTIS	National Technical Information Service (part of the US government)
PAH	Polycyclic aromatic hydrocarbon
PES	Payment for ecosystem services
PM; PM_{10}; $PM_{2.5}$	Particulate matter (particle pollution). PM_{10} (fine particles) are less than 10 microns in diameter and $PM_{2.5}$ (ultrafine particles) are less than 2.5 microns in diameter.
REALU	Reducing emissions from all land use
REDD+	Reducing emissions from deforestation and forest degradation plus conservation, sustainable management of forests, and enhancement of forest carbon stocks.
RUK	Research UK (formerly RCUK, Research Councils UK)
SPLiCE	Sustainable Pathways to Low Carbon Energy
T&D	Transmission and distribution

Summary and research priorities

KEY MESSAGES

- **This scoping study is based on a systematic literature review of over 400 papers on the co-benefits and adverse impacts of climate change mitigation actions, plus an expert workshop and a call for evidence.**
- **There is strong evidence that well-designed climate mitigation action can provide substantial co-benefits for health, energy security, economic development, social capital and natural capital. The economic value of these co-benefits can exceed the cost of the climate mitigation action.**
- **Co-benefits can provide a powerful motivation for more ambitious climate change mitigation action both in the UK and in other countries, especially because the benefits are often local and immediate. There can be strong synergies with sustainable development and climate adaptation.**
- **For climate mitigation policy as a whole, the available evidence indicates that co-benefits far outweigh any adverse side-effects, but the balance varies depending on the mitigation action and the context, and there may be winners and losers. Well-designed climate mitigation strategies can maximise the co-benefits and minimise any adverse side-effects.**
- **Demand reduction measures have many co-benefits and few adverse side-effects, but often depend on behaviour change, which is poorly understood, and may face social and political barriers to achieving their full potential.**
- **Energy supply measures have substantial co-benefits but also have a range of adverse side-effects. These can often be reduced or avoided through careful design or improved technologies.**
- **Land use measures (forest and soil carbon, bioenergy and agriculture) have the potential to offer significant co-benefits but this is dependent on implementing safeguards to protect against adverse side-effects.**
- **Eleven research priorities have been identified.**
    1. **Model and data development through a modelling review and modellers forum**
    2. **Establishing a co-benefit network to foster links between sectors**
    3. **Case studies to raise awareness of co-benefits amongst policymakers**
    4. **Real world demonstration projects, especially comparative research**
    5. **Interdisciplinary research on behaviour change, distributional impacts and barriers, including further work on dietary change and active travel**
    6. **Impacts of different climate targets on co-impacts, including impacts of nuclear, CCS, BECCS and afforestation**
    7. **Extending REDD+ to other ecosystems using a landscape approach**
    8. **Cost-effective monitoring of co-impacts for land use options**
    9. **Multiple benefits from green infrastructure and sustainable agriculture**
    10. **Co-impacts of resource efficiency / circular economy / reduced consumption**
    11. **Economic development, innovation, productivity and employment impacts**

Climate change mitigation actions have wider impacts on economy and the environment, beyond the direct benefits of avoided climate change and the direct financial costs of the action. Positive impacts, or 'co-benefits', include substantial air quality benefits from avoided fuel combustion, the health and wellbeing benefits of warmer homes or increased levels of cycling and walking, and a wide range of other economic, social and environmental benefits. These co-benefits can be a powerful incentive for stronger climate action in the UK and overseas. There can also be possible adverse side-effects from mitigation actions, such as risks associated with disposal of nuclear waste, or the impacts of growing certain biofuel crops on food security and biodiversity. Understanding these adverse impacts and identifying means to overcome them where possible is also important.

DECC therefore commissioned Aether and Aether associate Alison Smith to carry out a four-month scoping study to provide an overview and synthesis of existing and planned research on the co-benefits and possible adverse side-effects of climate change mitigation. This study was mainly aimed at providing a summary of current understanding to inform DECC priorities for future research, but could also be of interest to other government departments and research funders. It included a literature review, a call for evidence, a review of grant programmes and a workshop attended by 20 academic experts. This report synthesises the findings of these activities and uses them to assess gaps in the current evidence base and make recommendations on directions for further research. It is important to bear in mind that the study focused only on the literature that discusses the co-benefits and adverse side-effects of climate change mitigation actions – it was not a detailed analysis of all the impacts of energy technologies (this is covered to some extent by the SPLiCE study commissioned by DEFRA, SPLiCE (2015)).

The literature review and call for evidence revealed a very large and rapidly expanding evidence base on the co-benefits of climate change mitigation, with almost 1300 potentially relevant papers identified from screening of abstracts, of which the 500 most relevant papers were analysed in more detail. There is also a considerable body of relevant literature that does not use a 'co-benefit' framework, e.g. literature on sustainable buildings, transport and waste management, as well as the 'external cost' and 'green economy' literature, little of which could be captured within the constraints of this scoping study. Nevertheless, although there is strong evidence on certain benefits, notably the air quality benefits related to reduced use of fossil fuels, and growing evidence in other areas including the health benefits of active travel, there is still a shortage of robust, quantified evidence in many other impact areas – especially empirical evidence on the impacts of real world, rather than purely theoretical, mitigation actions.

Although there are challenges in quantifying many of the impacts, which make it difficult to assess the net impact of climate mitigation policies, a number of key studies that consider both positive and negative impacts conclude that the co-benefits significantly outweigh adverse side effects. The evidence indicates significant net co-benefits for resource efficiency and demand reduction measures, but a mix of co-benefits and adverse side-effects for certain energy supply technologies. For land use options (e.g. forest carbon or bioenergy), the balance between positive and negative impacts is highly dependent on the context (e.g. presence of environmental and social safeguards). Adverse side-effects can often be mitigated.

For active travel, for example, modelling studies conclude that the benefits of physical activity outweigh the risks of increased accidents or exposure to pollution faced by cyclists and walkers, and it is possible to mitigate these risks through safety measures and air quality legislation. For home energy efficiency, studies conclude that the health benefits of increased thermal comfort outweigh the risks associated with decreased indoor air quality (e.g. radon accumulation); these risks can be mitigated through improved ventilation. A scoping review of a wide range of positive and negative health and environmental impacts of the UK's 4th carbon budget for the Committee on Climate Change estimated that the net impact was beneficial, with a net present value of more than £85 billion from 2008 to 2030. A number of robust studies, including the New Climate Economy Report, find that there are major economic benefits from climate change mitigation, plus co-benefits for energy security, reduced traffic congestion, improved quality of life, climate resilience, environmental protection and poverty reduction. There is also growing evidence that clean-tech R&D has particularly high spillover benefits for innovation in other sectors.

Synthesising the results of the literature review, the call for evidence and the workshop, 11 priority areas for further research have been identified. These research priorities span a wide range of sectors and disciplines, and therefore require co-ordinated and co-operative action by DECC and other government departments, and sometimes also by international partners or funding agencies, as noted in the table.

1. Model development

Quantification of co-impacts remains challenging. There are many existing tools and models for assessing co-impacts (28 are listed in Appendix B) but no overview of these tools or co-ordination of model development activities was identified through this study. There is therefore a need for:

- Simple tools (e.g. checklists, matrices, decision trees or spreadsheet models) for decision-makers to use for visualising and evaluating co-benefits and adverse impacts, to allow them to explore policy options that have multiple benefits across different sectors and to avoid unintended adverse consequences.
- Inclusion of a wider range of co-impacts into economic analysis tools (e.g. macroeconomic models, cost-benefit analysis and cost-effectiveness analysis frameworks), linking together sectors such as climate, energy, health, air quality, transport, land use and economy, so that co-benefits can be taken into account in decision-making in other sectors.
- Integrated models to address synergies and trade-offs between impacts in complex systems, e.g. the food-energy-water-land nexus, and the long term impacts of changes in one sector or country on other sectors or countries.
- Extension of co-benefit assessment approaches to include sectors and impacts that are often excluded, especially material efficiency / waste management; water security; land use / ecosystem services / agricultural productivity and the upstream impacts of avoided fuel production.
- Multi-criteria decision analysis tools and participatory stakeholder approaches for taking into account impacts that are hard to quantify or monetise, and evaluating complex trade-offs.

To address these research gaps, it is recommended that:

a) **a review of available tools and models** is commissioned, including their data requirements, to identify the research needs.
b) **the establishment of a modellers' forum is encouraged,** to explore development of simple assessment tools and further integration of models across sectors. This could build on ongoing work undertaken by C40 Cities, the development of the WHO Heat tool and IGES work on simple assessment tools. One aim should be to develop assessment tools to enable inclusion

of co-benefits in climate finance project evaluations, including areas such as sustainable urban design and waste management.

2. Co-benefit research network

Co-benefit research is extensive but fragmented. The call for evidence and the workshop revealed an active, highly engaged research community, although there are currently no formal networks to link researchers studying co-benefits in different sectors and from different disciplines. This is a challenge: researchers and policymakers will need to work across sectors and across government departments to develop an effective understanding of co-impacts, and to put this knowledge into practice. Stronger networking opportunities could enable better integration of fields such as waste management, material efficiency, water security and land use into the co-benefit framework, as well as being crucial for the development of holistic assessment methods and models. There are opportunities to enhance the cost-effectiveness of research by creating a new network of researchers, policymakers and practitioners, building on contacts identified during this project as well as existing networks. Furthermore, this inter-disciplinary approach would help address barriers to implementation, overcoming existing silos. This new network could be focused around a central website and case study database provided by researchers. It would provide DECC with access to latest evidence, and could target researchers in priority countries for which there are research gaps.

3. Compile case studies

Policymakers can have limited knowledge and understanding of co-benefits and adverse side-effects, and this is a major barrier to incorporating co-impacts into policy and practice. To tackle this, there would be great value in compiling a set of co-benefit case studies drawn from around the world, illustrating best practice and lessons learned, to form an evidence base to demonstrate the value of co-benefits. This would raise awareness and facilitate engagement with key stakeholders and policymakers. There are opportunities to partner with the ongoing case study initiatives of the Asian Co-benefits Partnership and C40 Cities. Case studies could include key topics of importance for priority countries, including urban design, waste management, sustainable transport, agroforestry and climate adaptation. Priority countries such as the Middle East and South Africa could be targeted, but some may need support for case study data collection.

4. Real world demonstration projects

Linked to the case studies of existing initiatives, there is a need for new demonstration projects involving comparator sites, especially for active travel and urban design. This could be linked to ongoing model development initiatives, through design of the projects to improve understanding of real world processes and impacts, provide data to inform model parameters, and test new assessment methods. The projects could also be targeted towards the need for more interdisciplinary research (see next point), including better understanding of social barriers, and of how benefits can be more widely distributed.

5. Interdisciplinary research to study behaviour change, distributional effects and barriers

Interdisciplinary research bringing together social, political and behavioural scientists and economists with climate science and policy is urgently needed to address several major research gaps:

- The significant untapped potential for cutting GHG emissions through behaviour change, which could also achieve major co-benefits with few adverse side-effects.

- The lack of understanding of the distributional impacts of climate change mitigation action.
- The need to overcome political, social and institutional barriers to achieving co-benefits.
- The potential role of community engagement in maximising co-benefits and avoiding adverse side-effects, and the potential benefits of climate action for community cohesion.

This could be encouraged via a cross-research council programme of interdisciplinary research on co-benefits and adverse side-effects, perhaps based around the Global Challenges RUK programme. This could address the following priority topics:

- **Dietary change**: Evaluation of the potential co-impacts of low GHG diets, taking into account the health impacts of food substitution and wider socio-economic impacts on the food and farming industry and rural communities.
- **Active travel**: Understanding travel behaviour and how to maximise health co-benefits by ensuring broader uptake of walking and cycling by different socio-economic groups.
- **Barriers:** understanding and addressing political, institutional, social and economic barriers to achieving co-benefits and avoiding adverse side-effects.
- **Distributional impacts** of low carbon technology, e.g. electric vehicles.
- **Co-impacts related to aviation and shipping:** e.g. impacts of reducing air travel demand on noise, air quality, socio-economic and wellbeing; impacts of reduced shipping speeds; impacts of increased energy efficiency or low carbon fuels (including biofuels).

6. Impact of different climate targets on co-impacts

More stringent targets, including the 1.5°C target, are likely to require a different mix of mitigation options and will therefore have different co-impacts. Many co-benefits are likely to increase, but there is also a risk that certain adverse side-effects could increase. Further understanding of these potential co-impacts is urgently needed to inform decisions on the optimum technology mix, and to plan appropriate measures to avoid or reduce adverse side-effects. Research priorities include:

- **CCS:** impacts of CO_2 storage and risk of leakage; impacts of solvent use and disposal; air quality impacts (SO_2 and PM could decrease; NO_x and NH_3 could increase); impacts of increased upstream fuel production as a result of the 25% energy penalty; potential for alternative CCS designs to reduce any adverse impacts.

- **Nuclear energy:** impacts and risks of waste disposal; accident risks; geosecurity (e.g. terrorist activity using illegally obtained radioactive material); impacts of uranium mining and fuel production; choice of appropriate discount rate; potential for new technology (small modular reactors) to reduce adverse impacts.

- **BECCS** (bioenergy with carbon capture and storage — a negative emissions technology): risks and impacts of increased biomass production on biodiversity and water quality (from fertiliser and pesticide use); further work on demand for water, land, fertilisers and energy; potential for carefully managed sustainable biomass production to restore degraded land or provide biodiversity benefits.

7. Extending REDD+ to other ecosystems using a landscape approach

As attention is increasingly focused on the role of bioenergy, BECCS and afforestation to meet challenging climate targets, it is important to consider the impact of expansion of bioenergy crops and afforestation on other land uses, including agriculture and natural ecosystems such as heathlands, grasslands and wetlands. New initiatives such as the Initiative for Sustainable Forest Landscapes take a whole landscape approach to carbon sequestration, building on the REALU approach (reducing emissions from all land use). By offering climate finance for agricultural techniques that add organic matter to the soil, thus improving fertility and water retention, this could provide large co-benefits for development, food security and climate adaptation that are of particular interest to developing countries. However, more research is needed to support this approach, including how to measure and monitor soil carbon sequestration cost-effectively over time, exploring methods of assessing trade-offs between competing land uses, and assessing the risk that it could lead to additional conversion of natural forests to agriculture or agroforestry.

8. Cost-effective MRV for land use climate mitigation options

REDD+ and its extension to other ecosystems offers tremendous potential to achieve co-benefits for biodiversity, ecosystem services and local communities, but this is dependent on effective enforcement of the social and environmental safeguards that have been developed. Similarly, there is a need to enforce safeguards to ensure that bioenergy feedstock production is sustainable. However, monitoring and verifying these safeguards can be expensive and the cost can limit the uptake of these important GHG mitigation options. Research could address the development of more cost-effective MRV options, including further work on the use of remote sensing, and also the use of participatory governance and community involvement. There is also potential to maximise biodiversity co-benefits and minimise adverse impacts by focusing on maintaining and enhancing habitat connectivity when identifying new locations for REDD+ or bioenergy plantings.

9. Multiple benefits from green infrastructure and sustainable agriculture

Green infrastructure can provide multiple benefits for climate mitigation and adaptation, biodiversity and ecosystem services, including flood protection, and can offer a cost-effective alternative or complement to grey infrastructure, e.g. for flood protection or water supply. There is a large evidence base which could be brought into a co-benefit framework to provide additional motivation for climate action. Similarly, sustainable agriculture (soil carbon sequestration, precision fertiliser use and agroforestry) can enhance agricultural production while providing benefits for soil protection, biodiversity and flood protection, but farmers need support to understand the potential benefits.

10. Resource efficiency / circular economy / reduced consumption

Resource efficiency – not just energy but also water and material efficiency – offers huge untapped potential to provide both GHG reduction and co-benefits, with no adverse side-effects. Around 60% of all GHG emissions are associated with production, manufacture, distribution and retail of food and consumer goods, extraction of raw materials, and construction of housing and other infrastructure. Reducing the waste of materials, water and embodied energy through a shift towards a circular economy approach (and use of more sustainable materials) can drive innovation, increase competitiveness and avoid the upstream environmental impacts on air and water quality and habitat loss associated with quarrying, mining, smelting and manufacturing. In addition, dematerialising the economy through alternative consumption patterns which act to decouple economic activity from unsustainable resource use will contribute significantly towards meeting challenging climate targets, but this faces significant social, political and economic barriers. Research priorities are to:

- Quantify potential co-benefits: economic benefits (resource cost savings; productivity); resource security (energy, water and materials); AQ; land use; water quality; biodiversity, drawing on life cycle assessment approaches and input-output analysis.
- Investigate social, political, and economic barriers to new, more resource-efficient business models and consumption patterns, and means of overcoming these, e.g. through more studies of consumer behaviour and the potential to shift towards 'sharing economy' innovations based on hiring or leasing goods rather than individual ownership.
- Investigate the wider socio-economic impacts of reduced material consumption, including impacts on employment and growth, by initiating a dialogue between conventional and ecological economists.
- Investigate the potential co-benefits of sustainable waste management and water security for engaging with priority countries.

11. Economic development and employment

Climate change mitigation has important potential co-impacts for economic development, innovation, competitiveness and employment but although the evidence base is growing, these are still not well characterised. Employment impacts are rarely assessed as net changes, taking account of winners and losers in different sectors. Further work in these areas may help to overcome commonly held myths about the potential adverse impacts of climate mitigation action on the economy. Research could address:

- Net **employment** and **economic** benefits (ex-post interventions) of climate change mitigation technology.
- **Innovation co-benefits** of low carbon technology and resource efficiency.
- **Productivity co-benefits** in non-residential buildings and industry (e.g. due to process improvements, increased comfort).

Research gaps by sector

Priority research gaps for individual sectors are listed in Table 1. Effective research to tackle the wide range of issues relating to co-benefits and adverse side-effects across all sectors will require co-ordinated action by a range of government departments: relevant departments are suggested in the third column.

It should be noted that Table 1 is a broad synthesis of the evidence gathered during this scoping study, and there may be examples where the direction of impact is different in certain circumstances. More detail is provided in chapter 4, and for energy technologies there is further detail available in the SPLiCE report (SPLiCE, 2015).

Table 1. Summary of key findings, priority research gaps and potential barriers for individual sectors. See Section 4 for more detail.

(+) mainly positive impacts (co-benefits); (+/-) mixture of positive and negative impacts; (-) mainly negative impacts (adverse side-effects)
(?) impact not clear, or depends on context
Green text: High relevance to industrialising and low income countries

Climate Change Mitigation Action	Co-benefit (+) and/or adverse side-effect (-) areas	Relevant government departments	Priority research needs	Potential barriers
Energy				
Renewable energy generation (non-bio-energy)	Air quality (+) Energy security (+) Energy access (+) Energy cost (+/-) Local employment (+)	DECC	Net employment and economic benefits (ex-post interventions). Review of indicators for energy security. Link between fuel poverty and renewable energy.	Cost of initial investment in local energy generation. Vested interests in high carbon energy Local planning issues and lack of public acceptance (e.g. for onshore wind in some locations). Need for storage and balancing mechanisms Lack of flexibility and/or speed in transition to distributed local energy generation.
Small scale energy (renewable/clean cook-stoves) projects in developing countries	Air quality (+) Energy security (+) Social equality (+) Local employment (+) Biodiversity (+)	DECC DFID International	Role of social enterprise and community engagement in maximising the benefits. Cook-stoves – potential impacts of a carbon tax in slowing a transfer from traditional biomass to gas or electric stoves.	Lack of community involvement in design of suitable technologies can slow their uptake.
Bio-energy including feedstock production for BECCS	Air quality (+/-) Water quality (-) Water security (-) Food security (-) Biodiversity (-) Flood/erosion protection (+/-) Livelihoods (+/-)	DECC Defra DFID	Implications of bioenergy feedstock production for land use (direct and indirect), water quality, biodiversity, and socio-economic impacts; extent to which sustainable bioenergy from woody crops can mitigate impacts.	Drive towards need for BECCS in the light of 1.5 degree target could exceed availability of sustainable bioenergy and thus increase adverse side-effects.
CCS and BECCS	Air quality (+/-) Energy security (+/-) Energy costs (-)	DECC Defra	Life-cycle analysis of CCS and BECCS including (but not limited to) AQ and fuel	Drive towards negative emission technologies in light of 1.5 degree target could increase

Climate Change Mitigation Action	Co-benefit (+) and/or adverse side-effect (-) areas	Relevant government departments	Priority research needs	Potential barriers
	Hazardous waste (solvent) (-) Risk of CO_2 leakage (-) Water availability (-)		security impacts and long term impacts of CO_2 storage.	adverse side-effects if these effects are not mitigated. Public understanding and acceptance of new technologies. Absence of political will or financially suitable environment for carbon disposal.
Nuclear energy	Air quality (+) Energy security (+) Energy costs (?) Hazardous waste (-) Accidents (-) (very low risk, potentially high impact) Discharges of radionuclides (-) Geo-security (risk of prolifer-ation/ terrorist activity) (-)	DECC Defra	Management and evaluation of long term risks of new and old nuclear energy, including use of discount rate in CBA.	Drive towards nuclear energy in light of 1.5 degree target could increase risk of adverse side-effects if these effects are not mitigated.
Transport				
City wide low carbon/smart travel choices and transport.	Health (physical activity)(+) Air quality (+) Water quality (+) Biodiversity (+) Social equity (+) Congestion (+) Noise (+) Accidents (+)	DCLG DfT	Tools for planning low carbon cities to maximise co-benefits and quantify impacts of urban design options. Benefits and/or negative impacts of modal shift. Wider environmental co-benefits of low carbon travel (beyond health), e.g. avoided habitat loss from road infrastructure; upstream fuel production impacts. Social impacts of smarter travel choices. Drawing from the broader literature for monetising congestion costs.	Existing city infrastructure. Long timescales for change.

Climate Change Mitigation Action	Co-benefit (+) and/or adverse side-effect (-) areas	Relevant government departments	Priority research needs	Potential barriers
			Use of fuel and vehicle taxation policy to maximise co-benefits. Connect to broader city stakeholders (Covenant of Mayors and C40 Cities etc.).	
Low carbon vehicle technologies and fuels.	Air quality (+?) Energy security (+) Socio-economic impacts (+?)	DECC DfT	Economic, social (including distributional) and environmental impacts associated with electric vehicles and other new technologies (e.g. innovation, jobs, battery manufacture, and disposal).	Long timescales for development of technologies. Existing industry ties to fossil fuel industry.
Active travel	Health (physical activity) (+) Air quality (+) Congestion (+) Noise (+)	DfT DoH	Evaluation of real world active travel interventions. Distributional impacts: e.g. how to maximise physical activity benefits by addressing barriers to wider uptake by less active people.	Lack of commercial incentives for change. Limited carbon benefit (because of limited vehicle km avoided).
Aviation and Shipping (efficiency; lower carbon fuels; demand reduction)	Air quality (?) Energy costs (+) Noise (-)	DECC DfT	Co-benefits and adverse impacts related to aviation and shipping.	Political conflicts regarding the demand for aviation and its role in the economy.
Buildings				
Low carbon urban/building design and building retrofitting.	Health (thermal comfort) (+) Air quality (+) Energy security (+) Social equity (+) Fuel poverty (+) Sustainable buildings (water, waste)(+) Economy (+/-)	DECC Defra DCLG DFID International	Evaluating the benefits of real life interventions, including both mental and physical health benefits of both warmer and cooler buildings, as well as fuel poverty impacts. Potential benefits from use of fewer or more sustainable materials in buildings (including wood). Reaching builders and planners with co-benefit messages, ensuring work is achieved to required standard.	Current planning systems and lack of ambitious building standards. Co-ordination between national and local government and across different departments to design developments that integrate low carbon buildings and transport solutions.

Climate Change Mitigation Action	Co-benefit (+) and/or adverse side-effect (-) areas	Relevant government departments	Priority research needs	Potential barriers
			Linking transport and buildings for city wide planning solutions. Connect to Covenant of Mayors and C40 Cities Leadership Group.	
Community engagement for energy conservation behaviour change.	Community cohesion (+) Health benefits of inclusion (+)	DCLG DECC DoH	Social benefits of community engagement in neighbourhood-wide programmes. Case study examples of benefits of low carbon lifestyles.	Rebound effect & restrictions to perceived quality of life (use of energy in leisure activities).
Industry				
Emission abatement and low GHG feedstocks	Air quality (+) Innovation (+) Economic (+/-)	Defra BIS	Distributional impacts e.g. should investment be focused on polluting plants in highly populated areas? Air pollution prevention drivers and GHG mitigation. Innovation and productivity benefits.	Increased production cost.
Industrial resource efficiency (materials, feedstocks, water, energy).	Air quality (+) Material security (+) Water security (+) Innovation (+) Cost savings (+) Economic (+)	Defra BIS	Innovation and productivity benefits, e.g. due to process improvements, higher quality products, lower product rejection rates, better working conditions. Bringing research on material and water efficiency into a co-benefit framework.	High initial investment cost. Government subsidies to industry.
Change in demand for industrial products and services.	Air quality (+?) Energy security (+?) Water quality (+?) Economic (-/+)	BEIS	Long term socio-economic impact of shift to lower GHG materials (e.g. steel/concrete to wood).	Loss of income and earnings to some business sectors.

Climate Change Mitigation Action	Co-benefit (+) and/or adverse side-effect (-) areas	Relevant government departments	Priority research needs	Potential barriers
Waste				
Modernising waste treatment in industrialising countries	Economic (+) Health (+) Energy security (+) Water quality (+)	FCO	Case studies for co-benefits of waste management and waste to energy. Use of climate finance to incentivise action.	High initial investment. Behavioural change required for waste collection systems.
Shift to a circular economy and "material efficiency".	Air quality (+) Energy/material security (+) Energy and material costs (+) Water quality (+) Economic innovation (+) Biodiversity (+)	Defra DCLG BIS	Role of material efficiency as a climate change mitigation option with multiple co-benefits, and developing an assessment framework for these co-benefits. Behavioural aspects of current 'buy new' culture; Production/ procurement decisions on waste generation and GHG emissions. Gather evidence on benefits of reduced waste from industry leaders.	Current marketing practices and "buy new" cultures; need for behaviour change. Implementing systems and services for re-use and reduction of waste.
Agriculture, Forestry and Land Use				
Dietary change (eating less meat and dairy produce)	Health (diet) (+?) Food and water security (+) Water and air quality (+) Biodiversity (+) Socio-economic impacts (+/-?) Balance of trade (+/-?)	Defra	Further consolidation of evidence of impacts of low GHG diet, e.g. what foods would people substitute for meat; impacts on vulnerable groups. Socio-economic impacts on global and local food systems, e.g. rural and farming communities; food industry. Further research into co-impacts related to the food-water-energy nexus including impacts of dietary change on water use, fertilisers, biodiversity, AQ etc.	Economic threat to livestock industry and socio-economic impacts on rural economy. Complexity and mixed messages from industry, pressure groups and health/fitness industry. Complex interactions related to global trade of food, e.g. potential increase in exports if less meat consumed within country.

Climate Change Mitigation Action	Co-benefit (+) and/or adverse side-effect (-) areas	Relevant government departments	Priority research needs	Potential barriers
Green Infrastructure enhancement	Recreation (+); Aesthetic value (+); Water regulation (+); Air quality (+); Microclimate (+); Biodiversity (+); Social cohesion (+); Economy (+?)	Defra DCLG	Integrate evidence from existing research into a co-benefit framework, and evaluate co-benefits of real life interventions.	Current planning processes.
Forest protection, sustainable forest management and afforestation (including REDD+)	Biodiversity (+/-) Socio-economic impacts (+/-) Water security (+/-) Flood/erosion protection (+) Cultural and social value of forests (+/-)	DECC Defra DFID	Cost-effective monitoring (e.g. remote sensing) to ensure that social and environmental safeguards are enforced, thus delivering co-benefits and avoiding adverse impacts without pricing carbon credits out of the market. Evaluating synergies between mitigation, adaptation, and ecosystem services, e.g. co-benefits of forests for flood prevention and for cultural and social value.	Potentially high cost of effective monitoring and verification arrangements to provide social and environmental safeguards.
Agriculture: soil carbon sequestration; agroforestry; precision fertiliser use	Air quality (+) Water quality (+) Food security (+) Biodiversity (+) Socio-economic impacts (+/-)	DFID, Defra	Development of more accurate methods of measuring soil carbon sequestration, to determine effective soil management strategies. Building on this, develop cost-effective MRV to enable use of climate finance for soil carbon sequestration in developing countries.	Barriers to uptake by farmers, related to unfamiliarity with techniques, lack of local demonstration projects, high investment costs, and time lag before productivity benefits are realised.

1 Introduction

1.1 Background

The IPCC's 5th Assessment Report showed that many actions to reduce greenhouse gases not only reduce the risks associated with climate change, but can also affect the achievement of other objectives, such as those related to air quality, human health, food security, biodiversity, local environmental quality, energy security and access, growth, livelihoods, poverty reduction and equitable sustainable development. This information can offer important incentives, or potentially disincentives, for strong action on emissions reductions, both at home and abroad.

A detailed understanding of the co-benefits and potential adverse side effects of climate change mitigation action is important to DECC and to other government departments for both domestic and international policy making. From a domestic perspective, better information on the wider impacts of mitigation across multiple policy areas would provide a more accurate indication of the effectiveness and economic benefits of Government's plans and policies to meet its climate targets. It can also help to inform the design of more cost-effective integrated policies to address a range of issues such as health, environment, infrastructure and the economy as well as helping to reduce any potential adverse impacts.

There is also a need to build on the outcomes of the international agreement reached in Paris in December 2015, and continue to increase global action to meet the international goal of limiting warming to well below 2°C. Understanding of country-level co-benefits can facilitate discussions on the benefits of ambitious climate action, raise awareness of opportunities to achieve multiple objectives, inform policy, and help increase future action as well as cement political will to deliver on the commitments made by countries during the climate change negotiations process.

DECC therefore commissioned Aether and Aether associate Alison Smith to carry out a four-month scoping study to provide a comprehensive overview and synthesis of existing and planned research on co-benefits and possible adverse side-effects of climate change mitigation, and to make recommendations for further research. This is the final report of the study.

1.2 Definitions, framing and caveats

What are co-benefits and adverse side-effects?

In this study, co-benefits are defined as additional benefits of climate change mitigation actions, beyond the benefits of avoided climate change, such as the air quality benefits of reduced fuel combustion or the biodiversity benefits of forest carbon protection schemes. Similarly, adverse side-effects are defined as the negative impacts of climate change mitigation actions, beyond the direct cost of implementing the action, such as the risk of impacts associated with disposal of nuclear waste. Sometimes, for brevity, co-benefits and adverse side-effects are referred to jointly as co-impacts.

The purpose of assessing co-benefits and adverse side-effects is to take into account other costs and benefits of climate change mitigation policies that are not usually included in cost-effectiveness assessments in terms of the cost per tonne of greenhouse gas reduction. Therefore the direct economic costs of investing in climate change mitigation technologies, and the benefits in terms of avoided climate damage, are, by definition, not counted as co-benefits or adverse side-effects and are not assessed in this study. This means that indirect climate impacts of mitigation actions, such as removal of the sulphate aerosol cooling effect or the albedo effect of increased afforestation, are also excluded because these climate-related impacts should, in theory, be included within climate models and assessments. However, co-benefits for climate adaptation are included, such as the role of forests in flood protection.

The boundary between direct costs and adverse side-effects can be hard to define in some cases, for example when assessing impacts on energy costs and fuel poverty. For example, energy cost savings are consistently treated as a co-benefit in the literature, although these may also sometimes be included as part of the cost-benefit assessment of mitigation measures. However, increases in household energy prices as a result of investing in low carbon energy are generally assumed to be factored into climate policy assessments and are therefore not treated as co-impacts unless they have unintended side-effects, e.g. if they fall disproportionately on particular sectors of society. There can also be grey areas related to co-benefits: for example, many papers include revenue from climate finance (e.g. REDD+ or the CDM) as a co-benefit, which is also debatable – although it could be argued that these payments have a beneficial impact on equity if they accrue to low income groups. However, the benefit of avoiding the need for fossil fuel subsidies is not included.

Framing

Although most studies of co-benefits are framed in terms of the wider impacts of actions aimed primarily at climate change mitigation, some are framed in the opposite direction, i.e. they assess the impacts of other policies (e.g. air quality legislation) on greenhouse gas emissions. This report covers both of these types of studies. It also covers papers that assess the multiple climate and non-climate benefits (or side-effects) of a technology or policy on an equal basis, without stating a single primary aim. Indeed, although co-benefits have sometimes been defined as 'benefits not related to the primary aim of a policy or action', there is now an increasing recognition that not all policies or actions have a single primary aim, and it might be better to assess all impacts within a 'multiple objective, multiple impact' framework (Ürge-Vorsatz et al., 2014).

Mitigation actions

Some literature identifies specific measures, e.g. deployment of renewable energy or provision of cycling infrastructure, whereas some refer in more general terms to the imposition of a carbon tax or cap to achieve a specific mitigation target. Often both are referred to in the same paper, e.g. a carbon tax results in a shift from fossil to nuclear and renewable energy. All of these mitigation actions are captured in an Access database (developed as part of the literature review) and included in the charts in Section 4 that show the number of papers referring to each type of mitigation action.

Extraction of gas by hydraulic fracturing (fracking) has not been included, because strictly speaking this is not a climate mitigation action, even though climate targets may drive a large scale shift from coal to gas that indirectly could increase unconventional gas extraction. The SPLiCE review recently conducted for Defra assessed the adverse impacts arising from fracking, including impacts on air and water quality, visual impacts from infrastructure, and the risk of significant methane leakage that could offset any climate benefit from the shift from coal to gas.

Bioenergy with carbon capture and storage (BECCS) is included, as many climate models predict significant deployment of this negative emission technology, but geo-engineering options such as direct air capture, ocean fertilisation, enhanced weathering and aerosol injection have not been included.

Caveat: Using co-impacts in decision-making

It is important to remember that policymakers need to take all impacts into account when making decisions, balancing co-benefits and adverse side-effects alongside the cost-effectiveness and abatement potential of each mitigation option for greenhouse gas reduction, and their importance for meeting climate targets. However, understanding co-impacts can help to focus more attention on mitigation options that have strong co-benefits and few adverse side-effects, and also encourage consideration of methods of overcoming any adverse side-effects.

1.3 Study objectives and research questions

The aim of the study is to provide a more in-depth understanding of the current state of knowledge on co-benefits and adverse side-effects, in order to inform the strategic direction for DECC's evidence work programme in 2016/17. Use of this evidence will help DECC to engage a broad range of stakeholders and build support for appropriate and well-considered climate action following the Paris climate negotiations in December 2015. The overall objectives are to provide:

- A comprehensive overview and synthesis of existing and planned research;
- Gap analysis and recommendations for a future research work programme.

These objectives are underpinned by the following research questions:

- What research, including key international research, already exists on the co-benefits and possible adverse side effects from climate change mitigation?
- What research, including key international research, already exists on the co-benefits of action to tackle other issues, such as air pollution, on climate change mitigation?
- What research capability exists in the UK and internationally on global, UK and overseas co-benefits from climate change mitigation?
- What is the magnitude of co-benefits in different countries and regions, e.g. Europe, China, India, Indonesia, Brazil, South Africa and the Middle East? Can a co-benefit approach offer opportunities for enhanced international co-operation that accelerates climate action, delivers local benefits and avoids adverse side-effects?
- What are the biggest research gaps in terms of co-benefits and possible adverse side effects from climate change mitigation?
- What research is there on barriers to integrated policy making that prevent co-benefits from being realised in practice, such as institutional structures, legal frameworks and national priorities?
- Where could DECC and others most effectively focus future research in this field?

1.4 Structure of the report

Section 2 of this report describes the scoping study approach. Section 3 presents an overview of the findings of the literature review and section 4 presents findings for individual sectors (energy, transport, buildings, industry, waste and land use). In section 5, cross-cutting themes and issues are discussed, including comments on four main categories of co-impact: economic, social, health and natural capital, as well as discussion of models and barriers. The international context is discussed in section 6, with reference to selected countries. Section 7 presents an analysis of research capability, identifying centres of expertise on co-benefits as well as relevant research networks. Finally, conclusions and recommendations are presented in section 8. Appendix A lists some key evidence papers and Appendix B lists centres of research expertise and models.

2 Scoping study approach

The study comprised an extensive evidence search to gauge the current state of knowledge and identify potential research gaps, followed by an expert workshop at which these gaps were discussed and prioritised.

The evidence search used a three-way approach, to achieve complete coverage of recent research, overseas sources and grey literature:

- Systematic literature search;
- Call for evidence to researchers in the UK and overseas;
- Review of current grant programmes.

Additional evidence was considered where appropriate, including relevant studies already known to the study team, and evidence which emerged through follow-on discussions with experts who were unable to attend the workshop, including Professor Harry Rutter of the London School of Hygiene and Tropical Medicine (LSHTM), and Dr Christian Brand of the Environmental Change Institute, University of Oxford.

Certain areas of interest have already been covered by two recent studies. The Defra-funded SPLiCE project (2015) summarised evidence on the positive and negative impacts of energy technologies, by conducting a 'review of reviews'. This provides good coverage on the adverse side-effects of energy technologies, which is useful because many of these are not covered in the co-benefit literature. The Met Office Hadley Centre also reviewed the scientific evidence on the interactions and relationships between climate change and air pollution. The evidence search was therefore focussed on areas not covered by these studies.

2.1 Literature review

The major challenge of this project was the size of the evidence base. Research on co-benefits has accelerated markedly over the last few years (Figure 1), and there is also a large evidence base that does not use the co-benefits terminology, e.g. technology assessments, external cost studies, and literature on sustainable buildings, transport, waste management, ecosystem services and the 'green economy'. Only a small part of this wider evidence base has been captured.

The literature search took place in December 2015 and January 2016 and covered five online sources:

- Scopus (good coverage of research articles, including articles in press, and books)
- Repec (economics articles and working papers)
- NTIS (technical reports; US focus)
- ResearchGate (articles, working papers and conference papers)
- Google Scholar (all of the above)

Each of these sources was searched using the following keywords (or equivalent):

> ('co-benefits' OR cobenefits OR 'ancillary benefits' OR 'multiple benefits') AND (climate or carbon)

The abstracts of all 954 papers retrieved from the Scopus search were screened, of which 822 appeared relevant. The Repec search produced 3770 hits of which the first 500 were screened (ordered by relevance), with 194 being relevant. For the other three searches, the first 200 hits of each were screened, retrieving a further 150 papers (after removing duplicates).

To capture adverse side-effects, Scopus was also searched using:

> (co-cost* OR dis-benefit* OR disbenefit OR "adverse side-effect" OR externalit* OR "external cost") AND (climate OR carbon OR "greenhouse gas") AND (reduc* OR low* OR mitigat*)

This produced 660 hits of which the first 400 were screened, producing 84 relevant references.

In addition, to cover economics literature not using the co-benefit terminology, Repec was searched using the following search string:

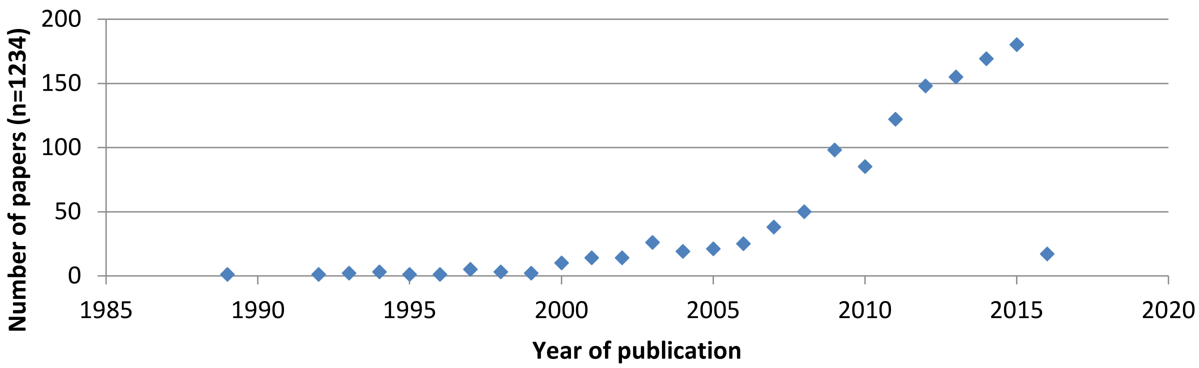
("green growth" OR "low carbon economy" OR "climate mitigation") AND (employment OR jobs OR livelihoods OR skills OR innovation OR competitiveness OR "fuel poverty" OR equity)

This produced 2114 hits of which the first 200 were screened, producing 46 potentially relevant papers.

Relevant grey literature was searched for on the websites of key organisations including the European Environment Agency, the IEA, the International Monetary Fund, the OECD, the World Health Organisation and the World Bank. Some further references were added by 'snowballing', i.e. adding important papers referred to by some of the papers reviewed.

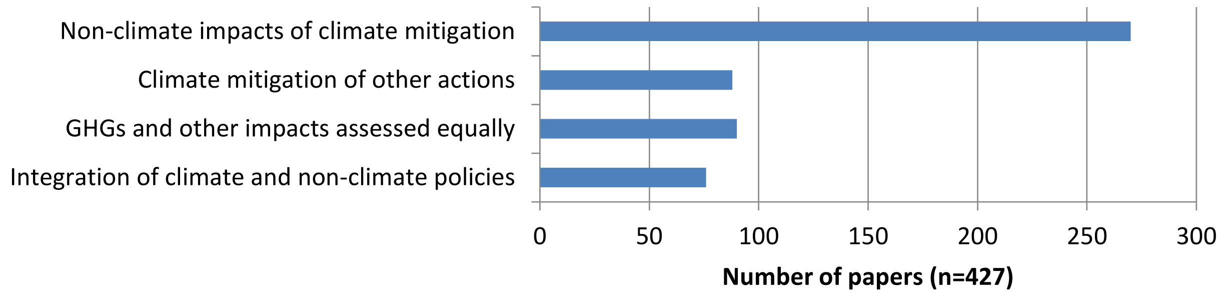
In total around 1250 potentially relevant papers were identified, and their bibliographic details were entered into a database. These were roughly prioritised based on their relevance ranking according to the literature search engines (first 250 of the Scopus and Repec main searches), research ranking (focus on top journals), a 'sense check' of the paper titles, and date (priority given to more recent papers). Priority was also given to papers covering large industrialising countries: China, India, Indonesia, South Africa, Brazil and the Middle East. The 450 highest priority papers were then analysed by skim-reading the full text, and details of the countries covered, sectors, mitigation actions, co-benefits and adverse side-effects were entered into the database. Around 35 of these were rejected at this stage as being not relevant, and another 35 because full text versions were not available. The summary figures presented in this report are based on the remaining 375 papers, and it is important to remember that this represents only a third of the papers retrieved by the searches, although the general patterns identified are likely to be reasonably robust. Around 30 records of papers or planned research from the call for evidence (see section 2.2) were also added, bringing the total number of records to 1291 (1234 excluding rejected papers) and the number of papers analysed in depth to 427.

Figure 1. Number of papers retrieved by the literature search, by year of publication



Although Figure 1 shows all 1234 papers, all other figures in this report are based on the subset of 427 papers that were analysed in more detail. Figure 2 shows the number of papers analysed according to the way in which co-benefits were framed (as discussed in section 1.3). Most papers were framed in terms of the non-climate impacts of climate change mitigation, but a number also considered the greenhouse gas impacts of non-climate actions, or assessed both climate and non-climate impacts on an equal basis. The figure also shows the number of papers that mentioned barriers to the integration of climate and non-climate policies. These categories are not mutually exclusive: many papers were recorded as fitting more than one of these categories.

Figure 2 Framing of papers analysed



2.2 Call for evidence and research grant analysis

A call for evidence was directed at key research organisations, identified from the literature search, and other UK and international networks such as the UKERC network. This resulted in over 100 submissions with responses from a broad range of organisations within the UK and internationally. These were added to the evidence database as appropriate.

A research grant analysis was undertaken to understand current and planned research relevant to the co-benefits agenda within the UK and internationally. Research funding sites reviewed included:

- UKERC Research Register and Research Atlas
- UK Research council funding including NERC, EPSRC and ESRC
- European Commission funding via the Cordis database[2] (including H2020; FP5,6,7; other)
- US Environmental Protection Agency Grant funding

The analysis identified a number of studies of relevance, including EPA-funded work on cook-stoves[1] and green infrastructure[2] and future work by Research Councils UK China in response to a current open call on new commercial solutions to socio-economic challenges. Relevant studies were added to the evidence database.

2.3 Workshop

Engagement with experts on climate-related co-benefits, through the call for evidence and the workshop, was a key aspect of the study. A workshop was held in London on 10th February 2016, with around 30 attendees. The workshop aimed to:

- Gather expert feedback on the preliminary results emerging from the scoping study;
- Collect new information and ideas not identified in the analysis to date;
- Facilitate networking and knowledge exchange between co-benefits experts and between the academic and policy-maker communities.

Specific objectives for the workshop were to:

[1] For example Colorado State University - on Quantifying the Climate, Air Quality and Health Benefits of Improved Cookstoves: An Integrated Laboratory, Field and Modeling Study – due for completion August 2016

[2] Taking it to the Streets: Green Infrastructure for Sustainable Philadelphia Communities University of New Hampshire – Main Campus, due for completion September 2017

1. Check the emerging findings on the magnitude of the main co-benefits and adverse side-effects for different mitigation actions.
2. Identify areas where the evidence base is mature, and other areas (gaps) where more research is needed, based on critique of emerging findings and participants' own expertise and ideas.
3. Ensure that academic, policy and economic priorities for co-benefits research are fully understood.
4. Prioritise research gaps according to size of the gap and potential impact.
5. Identify barriers to realisation of co-benefits, e.g. lack of co-ordination between climate change mitigation and other policies, and potential solutions.
6. Explore opportunities for increasing effective engagement with other countries via a co-benefit approach.

The workshop discussions were used to inform the development of the recommendations presented in the final section of this report.

3 Overview of evidence base

The figures in the following sections show the number of papers found in the literature search that cover particular countries, sectors, mitigation actions or impacts. This is useful in gaining an impression of the nature of the evidence base and where gaps might be, bearing in mind that the papers analysed represent about a third of those retrieved in the literature search (see section 2.1). However, it is important to remember that the number of papers does not necessarily indicate the level of certainty or understanding of each topic, or the magnitude or significance of the co-benefits or side-effects.

Papers were categorised according to a broad assessment of the strength of the evidence, as follows:

'Strong' quantitative evidence is an apparently robust experimental, observational or modelling study that relates a co-benefit to a specific climate change mitigation target, e.g. a 20% cut in GHGs will result in a 40% cut in PM_{10} emissions. A smaller number of studies were categorised as **strong qualitative evidence**, e.g. where a number of quantitative assessments are used to inform an overall qualitative assessment of the direction and magnitude of the impact.

'Weak' evidence includes:

- Weak or indirect assessment of co-benefits, e.g. technology assessment where both GHG and air pollutant emissions are reported, but it is not easily possible to relate the magnitude of a co-benefit to a specific climate change mitigation action.
- Papers that mention co-benefits without assessing them, or cite other papers rather than presenting new evidence. However, systematic reviews or meta-analyses are classed as 'strong' because they add new knowledge through the systematic evaluation of the evidence base.

It should be noted that each paper received a single rating for evidence strength, based on the highest rated evidence in the paper, but many papers consider multiple co-benefits, sectors or countries, and the evidence strength may vary across these. This means that the evidence strength will be over-estimated in some cases.

3.1 Geographical and sectoral coverage

Figure 3 maps the number of papers reporting co-impacts for specific countries, excluding papers that were categorised as considering country 'groups', such as 'global' or 'Europe'. The literature is dominated by papers from China, India, Europe and North America, with some papers from Australasia and Brazil, but very few from other regions, although it must be noted that large industrialising countries (China, India, Indonesia, Brazil, South Africa and countries from the Middle East) were prioritised when selecting papers to analyse in depth. Despite this prioritisation, the large number of papers from China is particularly striking; these are dominated by papers on air quality.

Figure 4 shows the coverage including country groups, including ‘global’, ‘Europe’ and ‘developing countries’, and also shows papers that did not refer to any specific country. Figure 5 shows the split of papers between those with strong or weak evidence by continent, with continent groups shown in grey. This shows that many of the ‘global’ or ‘no specific country’ papers have only weak evidence, as they refer to co-benefits only in general terms. Figure 6 shows a similar split for the 20 most commonly covered countries.

Figure 7 shows the split of papers by sector for selected countries, bringing into focus the contrast between the extensive literature for China, with good coverage across the power, industry, buildings and transport sectors, and the lack of coverage for some other large industrialising countries such as Brazil, Indonesia, Mexico and South Africa, where the limited evidence base is dominated by papers on land use (mainly dealing with REDD+).

Very few papers mentioning any countries in the Middle East were found. It is possible that this may reflect language barriers, with fewer papers and reports from these countries being published in the academic literature databases used in the search. However, a separate internet search conducted using the Arabic language failed to reveal any additional papers. Given the pivotal role played in climate negotiations by oil producing countries in this region, this is a significant research gap.

Figure 3. Coverage of individual countries (excluding country groups)

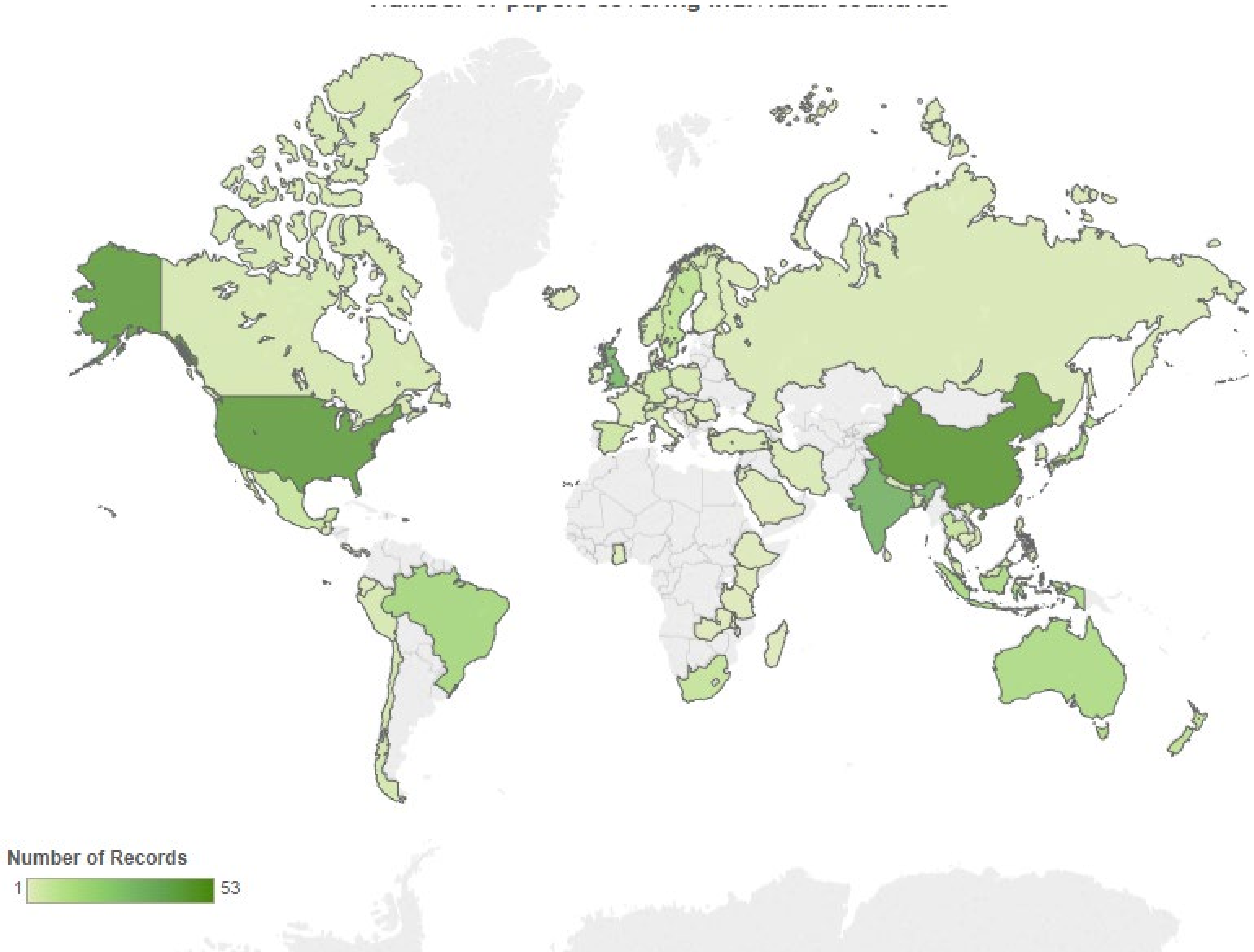


Figure 4. Coverage of countries and country groups

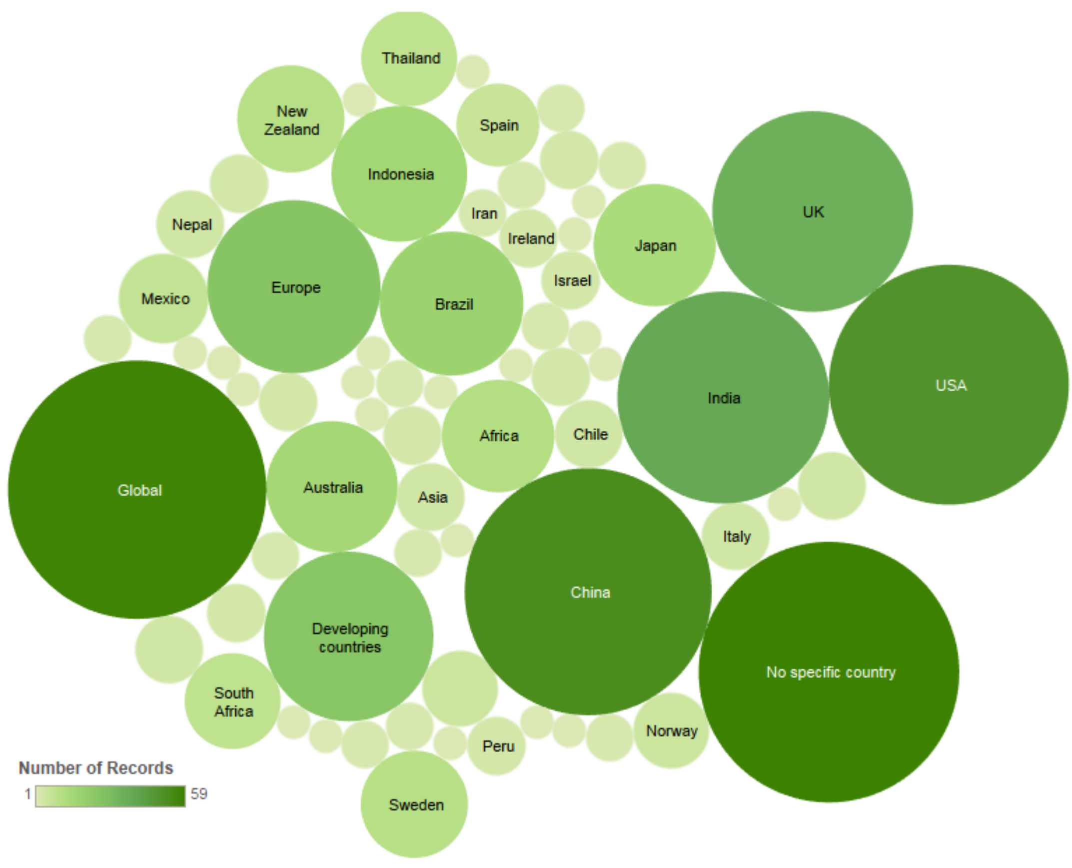


Figure 5 Coverage of continents, ordered by number of strong papers

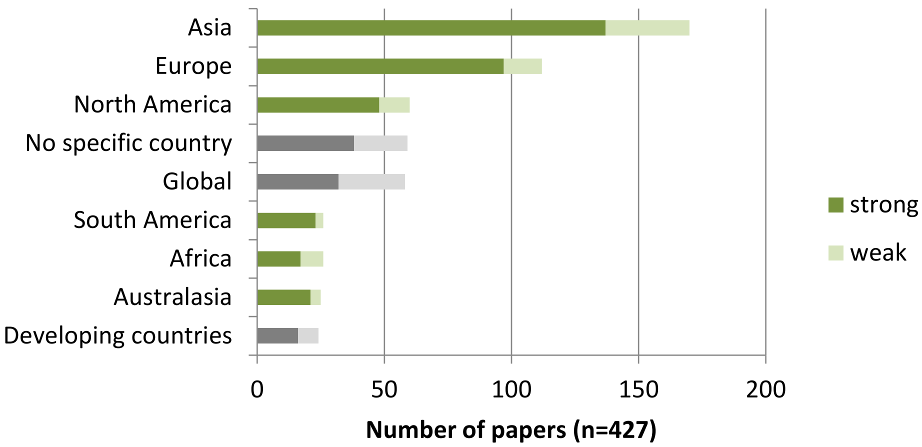


Figure 6 Coverage of countries and country groups ranked by number of papers found (first 20)

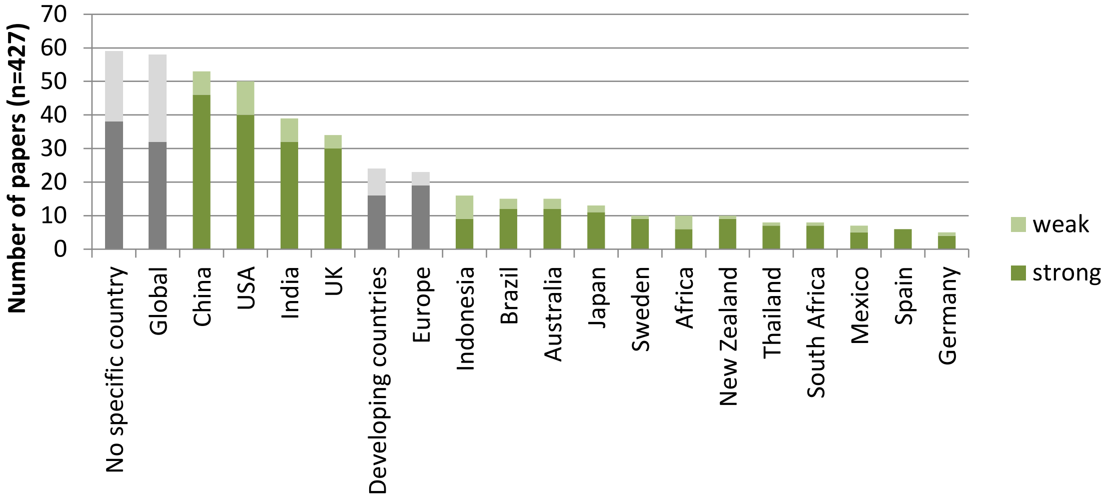


Figure 7 Selected countries

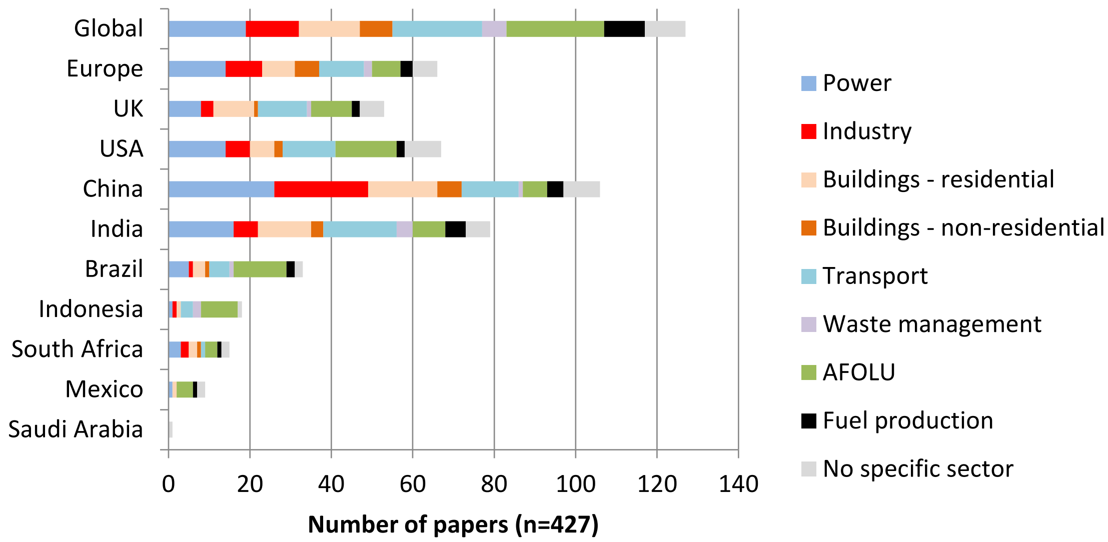
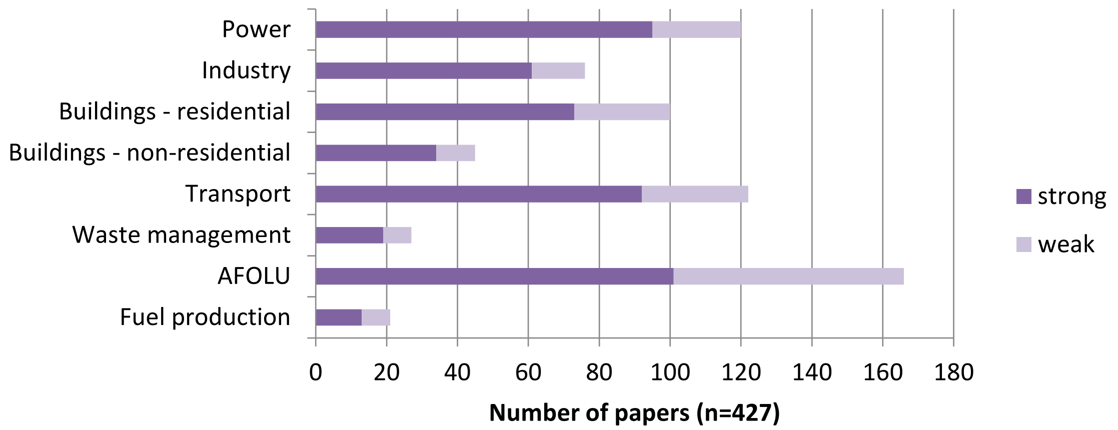


Figure 8 shows papers by sector. Although agriculture, forestry and land use (AFOLU) is the most commonly studied sector, many of the papers contain only weak evidence. Waste, fuel production and non-residential buildings sectors rarely feature in co-benefit papers.

Figure 8 Coverage by sector



3.2 Co-benefits and adverse side-effects

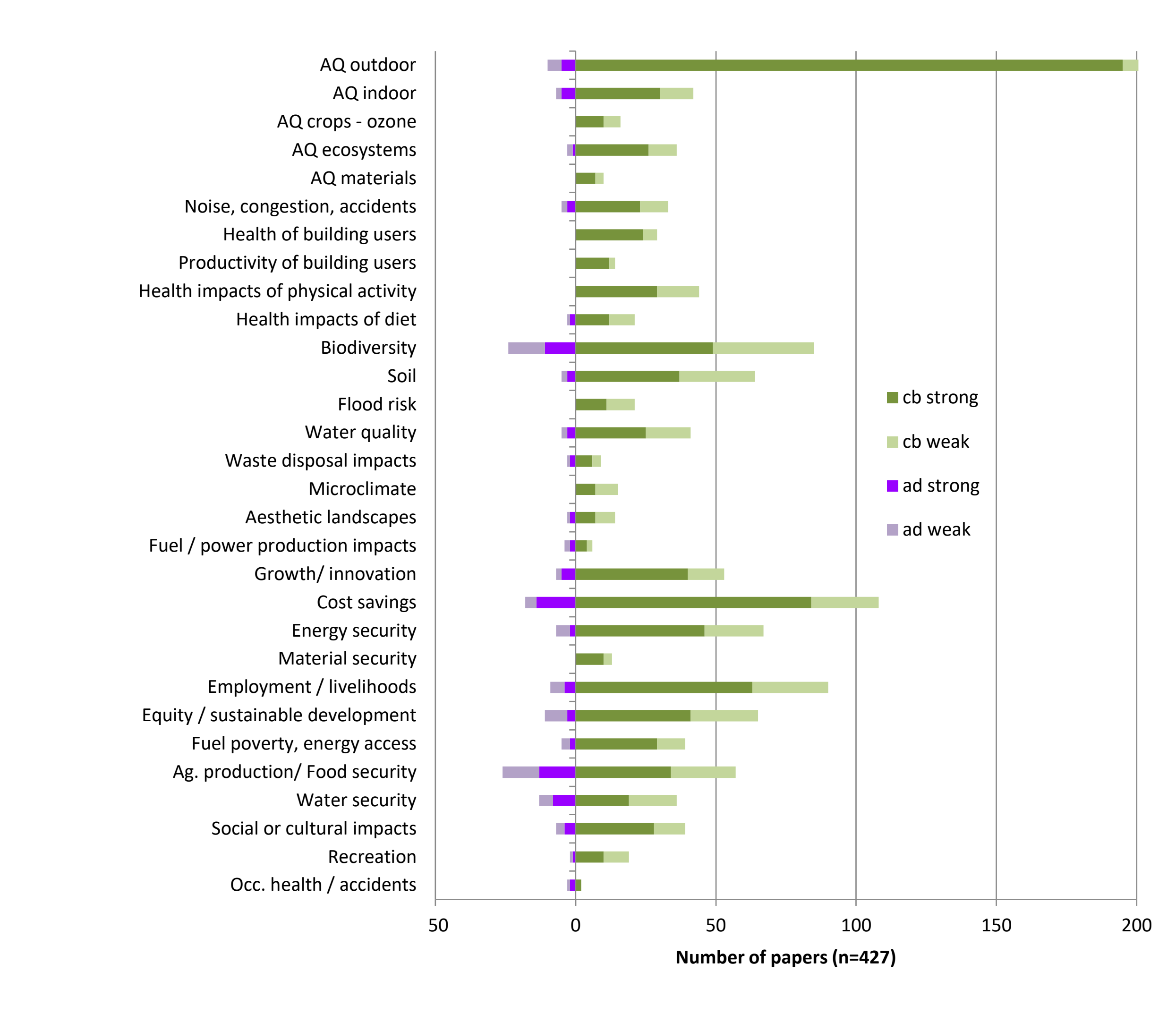
Figure 9 shows the number of papers analysed that mention different types of co-benefit or adverse side-effect, split into papers with strong and weak evidence. In order to enable visualisation of the relative number of papers on co-benefits and adverse side-effects, these have been shown on the same chart, with adverse side-effects plotted on the negative axis: this does not imply a negative number of papers reviewed.

Outdoor air quality is by far the most commonly studied impact, followed by cost savings (typically for energy but sometimes other costs such as fertiliser use), and then biodiversity (typically for forest carbon protection). Soil fertility and erosion protection are also commonly addressed in the literature on the potential for carbon sequestration in soil.

The most commonly mentioned adverse side-effects are biodiversity and food security, both related to concerns over the potential for forest carbon plantings and first generation biofuels (from starch and oil-based crops) to displace native ecosystems and compete with land for food production. Cost impacts are mentioned in the context of high initial investment costs for certain low carbon options such as renewable energy or smallholder agroforestry.

The figure shows that papers mentioning co-benefits far outweigh those discussing adverse side-effects. As mentioned in section 2.1, it is likely that more papers on adverse impacts can be found within the wider literature on external costs or energy technology assessment, but this study was able to draw on the recent SPLiCE review which comprehensively covers the adverse impacts of energy technologies (SPLiCE, 2015). It is also important to bear in mind the caveat that the number of papers addressing positive or negative impacts does not necessarily indicate the magnitude of those impacts. Also, in many cases, the direction of impact depends entirely on the details of how the mitigation action is implemented. For example, the impacts of forest carbon projects on biodiversity can be positive or negative depending on whether native forests are preserved, or non-native monoculture plantations are created. Many papers discuss examples of both positive and negative impacts that can arise from the same mitigation action. This means that there are often options available for mitigating the negative impacts, or even turning them into benefits, through careful policy design. The balance between positive and negative impacts is discussed in more detail in the next section.

Figure 9. Co-benefits and adverse side-effects (the latter plotted to the left of the axis)



3.3 Direction and magnitude of impacts

One of the main aims of this review is to synthesise available evidence on the magnitude and direction of co-benefits arising from climate change mitigation actions. However, this presents a number of challenges.

- Objective comparison requires all impacts to be expressed in a common metric, with monetisation being the only realistic option, yet monetisation is difficult or inappropriate in some cases, e.g.:
  - When there is a small risk of a catastrophic impact (such as a nuclear accident), and risk analysis is a more appropriate framework than monetisation of the impact;
  - For macroeconomic impacts (economic growth, employment, innovation), where the results are highly dependent on the design and assumptions of the model;
  - For social impacts (sustainable development, social capital, equity, fuel poverty), which cannot (by definition) be addressed within an economic efficiency framework such as cost-benefit analysis.
- Most actions have a range of impacts, many of which are hard to quantify in monetary terms, so the full range of impacts cannot be summed and net impacts (co-benefits minus adverse side-effects) cannot be calculated. Indeed, it is not possible to develop an assessment framework that will allow objective comparison of the full range of impacts using a single metric. As a result, though there are

fairly robust studies of particular groups of co-benefits, especially for the health impacts of air quality, there are no studies that quantify the full range of impacts in a consistent manner.

- Actions are commonly implemented in groups: for example, a carbon tax can result in multiple actions including improved energy efficiency and increased use of nuclear energy, renewable energy and CCS, all with very different impacts.
- As discussed above, both the magnitude and the direction of impact can depend on the exact details of how a mitigation action is implemented.
- Values from different studies cannot easily be combined, for example through a quantitative meta-analysis, or transferred to different contexts, because they make different assumptions about the level of mitigation and the types of action adopted. Many impacts may not scale in a linear fashion with the degree of implementation, making it hard to compare values from studies that assume different mitigation targets.

A qualitative approach to indicate the likely direction and magnitude of various types of impact has therefore been adopted, as shown in Table 2. The table shows a qualitative assessment of the direction and magnitude of potential impacts for each of the main categories of mitigation action applicable to the UK, taking account of the potential scale of each action envisaged by the Committee on Climate Change (CCC) in the UK's 5th carbon budget advice (CCC, 2013). For simplicity, the impacts have been aggregated into broad categories of health (air quality, lifestyle, accidents), economic competitiveness (resource costs, resource security, innovation), social (equity, community, poverty) and environmental (water, soil, biodiversity, waste), though many of the impacts listed under 'environmental' may also have effects on human health.

To enable comparison of the co-benefits and adverse side-effects with the scale of the potential GHG savings from each type of mitigation action, the third column of the table shows the estimated GHG emission reductions for different sectors according to the CCC's Medium Abatement Scenario, with larger emission reductions in deeper shades of blue. It should be noted that this is just one possible scenario and more ambitious abatement actions are also possible, and indeed probably needed to meet the new Paris targets. Some mitigation action categories shown with a question mark were not included in the Medium Abatement Scenario: these are material efficiency in industry; recycling / reuse / waste avoidance in the waste sector (although diversion of biodegradable waste from landfill was included in the scenario); and dietary change (although this was assessed separately by the CCC, outside the Medium Abatement Scenario).

Note that this is a subjective analysis based on the study team's interpretation of the weight of evidence according to the papers analysed, although it is partly informed by a scoping study of health and environmental benefits of the UK's 4th carbon budget carried out for the CCC in 2013 (Smith et al., 2015a). The table should be interpreted with caution as it does not show the relative magnitude of the different impacts, and it also aggregates many impacts into single broad categories. Section 4 contains more detail.

The table shows significant net co-benefits for resource efficiency and demand reduction measures, but a mix of co-benefits and adverse side-effects for certain energy supply technologies. For example, renewable energy provides air quality benefits when replacing fossil fuel, so health impacts are classed as positive. However the impacts on economic competitiveness are classed as mixed: there will be benefits for innovation, increased use of indigenous energy sources and low operating costs, but high up-front investment costs and further costs from modifying the energy system to allow a high contribution from intermittent renewables. Nuclear power also reduces conventional air pollution but carries a very low risk of a serious accident and creates long-lived radioactive waste. CCS has positive impacts for some air pollutants and negative impacts for others, as well as increasing fuel demand and associated upstream environmental impacts. As mentioned above, it is worth noting that adverse side-effects can often be mitigated if appropriate measures are put in place. There is also a mix of positive and negative impacts for forest carbon and bioenergy, with the balance being highly dependent on the context (e.g. presence of environmental and social safeguards).

To give a rough indication of the potential relative magnitude of some of the main impacts, the CCC study estimated that the net effect of a wide range of positive and negative health and environmental impacts was beneficial, with a net present value of more than £85 billion from 2008 to 2030, excluding the potential health benefits of dietary change (Smith et al., 2015a). The largest impact (although not part of the core scenario) was the potential health benefit of dietary change: the study gave a crude estimate of a net present value of £162 billion from 2008 to 2030 from halving consumption of meat and dairy produce, leading to a 50% reduction in saturated fat, though this was probably an overestimate as it did not take account of food substitution. The next highest impacts were substantial benefits from active travel: reduced congestion (£48 billion) and increased physical activity (£26 billion), followed by the health benefits of improved air quality from reduced fuel combustion, and reduced noise from electric vehicles and improved double glazing, at around £6 billion each. The adverse side-effects that were quantified added up to less than £2 billion, of which £1 billion was adverse health impacts from air pollution associated with increased biomass combustion (Smith et al., 2015a).

This table was presented for comment at the expert workshop, and there was no disagreement over any of the direction or magnitude ratings. Although the table was developed within the UK context, it is in broad agreement with the ratings in Table 6.7 in the IPCC's 5th Assessment Report for WGIII (Clarke et al., 2014, pp. 469-71), which was developed for the international context, and with subsequent analysis by von Stechow et al. (2015), which builds on the IPCC synthesis to illustrate the challenges and research needs relating to assessment of multiple co-impacts.

Although no robust quantitative assessments have been carried out across the full range of possible mitigation actions and impacts, a number of key studies (outlined below) that consider both positive and negative impacts conclude that the positive impacts significantly outweigh adverse side effects.

- The IPCC 5th Assessment Report, mentioned above, concluded that 'The compilation of sectoral findings in Table 6.7 suggests that the potential for co-benefits clearly outweighs that of adverse side-effects in the case of energy end-use mitigation measures (transport, buildings and industry), whereas the evidence suggests this may not be the case for all supply-side and AFOLU measures'. Although this is only a qualitative assessment, it is based on the consensus of a very wide range of experts, and therefore carries significant weight (Clarke et al., 2014, p. 472).
- For active travel, modelling studies conclude that the benefits of physical activity outweigh the risks of increased accidents or exposure to pollution faced by cyclists and walkers (Woodcock et al., 2009 and others); in addition it is possible to mitigate these risks through safety measures and air quality legislation.
- For home energy efficiency, modelling studies conclude that the health benefits of increased thermal comfort outweigh the risks associated with decreased indoor air quality (e.g. radon accumulation); in addition these risks can be mitigated through improved ventilation (Wilkinson et al., 2009 and others).
- The IEA report on 'The Multiple Benefits of Energy Efficiency' found that including health improvements from warmer buildings in cost-benefit analysis can result in cost: benefit ratios of 4:1, and that industrial productivity and operational benefits can be up to 2.5 times the value of energy savings (IEA, 2014).
- The New Climate Economy report (GCEC, 2014) finds that there are major economic benefits from climate change mitigation, plus co-benefits for energy security, reduced traffic congestion, improved quality of life, climate resilience, environmental protection and poverty reduction, with growing

evidence that clean-tech R&D has particularly high spillover benefits for innovation in other sectors. Investing in a low carbon future would add only a few trillion dollars to the $90 trillion investment in infrastructure expected over the next 15 years.

- A review by the LSE (Green, 2015) argues that most of the mitigation action needed to decarbonise the global economy this century is likely to be nationally net-beneficial, and therefore nationally self-interested. This paper emphasises that co-benefits are likely to be enhanced if groups of complementary, self-reinforcing actions are implemented, such as recycling the revenue from a carbon tax into development of low carbon technologies, an electric vehicle charging network and active travel infrastructure.
- A modelling study for the IMF (Parry et al., 2014) calculated the level at which carbon pricing has net benefits, i.e. the point at which the value of the co-benefits exceeds the carbon price. For the top 20 CO_2 emitting countries, the nationally net-beneficial carbon price averaged $57.5 per tonne of CO_2 in 2010. This mainly reflected the value of health benefits from reduced use of coal in power plants plus reduced pollution, congestion and accidents in the transport sector. This level of carbon pricing would reduce CO_2 emissions from the top twenty emitters by 13.5%.
- Stern (2015) argues that the low carbon transition could stimulate a new wave of innovative, creative economic growth.

The review identified a number of key references that contain robust quantitative evidence for particular groups of sectors, mitigation actions, countries and impacts (including the references listed above). These papers form a robust evidence base that can be used to demonstrate the potential benefits of climate action to a wider audience. These key evidence papers are listed in Appendix A.

Table 2. Qualitative summary of direction and magnitude of co-impacts for the main categories of climate change mitigation actions. Note that decision makers need to take into account the magnitude of climate mitigation benefits (as indicated by blue shading in column 3) as well as the magnitude of co-benefits and adverse side-effects.

Sector	Contribution to total UK emissions (2014)[1]	2030 Carbon budget reduction (CCC advice) (Mt CO2e/y)[2]	Health (AQ, lifestyle, accidents)	Economic competitiveness[3] (Resource costs, resource security, innovation etc.)	Social (equity, community, poverty)	Environment[4] (water, soil, biodiversity, waste)
Transport	23%					
Active travel / smarter choices/freight logistics		8	✓✓	✓✓?[5]	✓?	✓
Efficient / electric / hybrid vehicles		49	✓	✓?	?	✓
Sustainable biofuels		7	–	?	?	?
Buildings – residential	16%					
Energy efficiency		13	✓✓	✓	✓	✓
Heat (solar, heat pumps, efficient boilers etc.)			✓	✓	✓	✓
Buildings – non-residential						
Energy efficiency		10	✓	✓	✓	✓
Heat (solar, heat pumps, efficient boilers etc.)			✓	✓	?	✓
Power	23%					
Renewable power (wind, solar, hydro)		80	✓	?	–?	✓
CCS			?	x?	–	x
Nuclear			✓	?	–	x
Industry	21%					
Energy efficiency / process improvements		17	✓	✓✓	–	✓✓
Low carbon heat			✓	?	–	✓
Material efficiency		?	✓	✓	–	✓
Waste	7%					
Diversion of biodegradable waste from landfill		4	✓	✓	--	✓
Recycling, reuse and waste avoidance		?	✓✓	✓✓	✓?	✓✓
Agriculture, forestry and land use	9%					
Reduced fertiliser use and improved husbandry		8	✓	✓	–	✓
Dietary change		?	✓✓?	?	?	✓✓
Green infrastructure / forests / agroforestry		2	✓	–?	✓	✓✓

✓✓ Strong benefit; ✓ Moderate benefit; – Neutral; x Adverse effect; xx Strong adverse effect; ? Unclear or mixed

[1] DECC (2015) Provisional UK Greenhouse Gas Emissions National Statistics; CCC Analysis
[2] CCC 5th Carbon Budget Central Scenario– Figure 3.6 and sectoral scenarios technical report
[3] Excludes direct investment cost – this focuses only on additional costs or benefits
[4] Includes upstream impacts of avoided fuel production. Many of the environmental impacts may also have effects on human health.
[5] Includes potential economic benefit of reduced congestion.

3.4 Answering the research questions

This overview concludes by considering the extent to which the scoping study has been able to address the research questions presented in section 1.3.

Q1. What research, including key international research, already exists on the co-benefits and possible adverse side effects from climate change mitigation?

> A1. The literature base is extensive and growing, although robust evidence is lacking for certain sectors and co-impacts. This section has presented an overview, and sections 4 and 5 present the findings in more detail.

Q2. What research, including key international research, already exists on the co-benefits of action to tackle other issues, such as air pollution, on climate change mitigation?

> A2. Of the papers analysed in detail, 88 papers framed co-benefits in terms of the GHG impacts of non-climate policies (see Figure 2), which is approximately a third of the 270 framed as co-benefits of climate change mitigation actions for other sectors, but still substantial. In addition, 90 were framed in terms of the multiple benefits of actions.

Q3. What research capability exists in the UK and internationally on global, UK and overseas co-benefits from climate change mitigation?

> A3. Section 7 presents an overview of research capability in the UK and internationally. The study revealed an active and engaged research community, which was nevertheless fragmented between sectors. In section 7.2, opportunities to enhance and co-ordinate research activity through networking are considered.

Q4. What is the magnitude of co-benefits in different countries and regions, e.g. Europe, China, India, Indonesia, Brazil, South Africa and the Middle East? Can a co-benefit approach offer opportunities for enhanced international co-operation that accelerates climate action, delivers local benefits and avoids adverse side-effects?

> A4. Research is highly concentrated in Europe, the USA and China (section 3.1) but there is a high potential for a co-benefit approach to achieve synergies between climate change mitigation, adaptation and development in other countries (see sections 6 and 8.2).

Q5. What are the biggest research gaps in terms of co-benefits and possible adverse side effects from climate change mitigation?

> A5. Research gaps are analysed by sector in section 4, and cross-cutting themes are drawn out in section 5, with recommendations presented in section 8. Gaps for specific sectors are summarised in Table 1 of the Summary.

Q6. What research is there on barriers to integrated policy making that prevent co-benefits from being realised in practice, such as institutional structures, legal frameworks and national priorities?

> A6. Barriers to integrated policymaking are significant, but little research specifically addresses this topic (see sections 5.6 and 8.1.1).

Q7. Where could DECC and others most effectively focus future research in this field?

> A7. See section 8 for recommendations.

4 Findings and research gaps by sector

The scoping study findings for each sector are presented below.

Each sector comprises:

- An overview box listing the main co-benefits and adverse side-effects mentioned in the literature. Note that the relative numbers of co-benefits or adverse side-effects mentioned in these lists obviously do not indicate their relative magnitude or importance, i.e. the balance between positive and negative impacts, and the role of the sector in climate mitigation.
- A chart summarising the main mitigation actions mentioned for that sector.
- Description of the main findings reported in the literature.
- A table of potential research gaps, including prioritisation by the delegates at the expert workshop.

The overall research gaps and priorities are summarised in Table 1 in the Summary section.

4.1 Energy supply

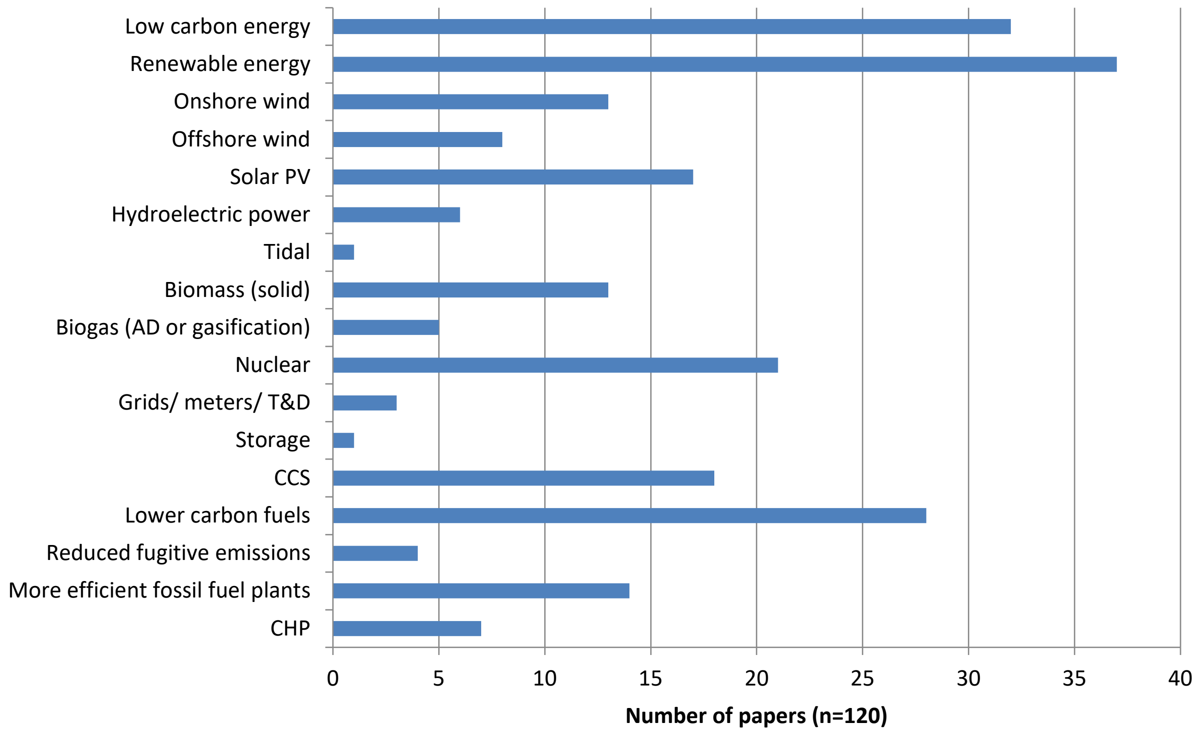
Main co-benefits of climate change mitigation in the energy sector

- **There are substantial air quality co-benefits** associated with low carbon energy (nuclear, non-bioenergy renewables, more efficient fossil fuel plants).
- Low carbon energy (nuclear, renewables, more efficient fossil fuel plants) can also offer benefits for **energy security.**
- There are **upstream benefits associated with avoided fossil fuel production** (e.g. avoided oil spills, coal mine accidents and habitat loss from opencast coal mining), but these are rarely mentioned in the literature.
- **Distributed renewable energy** offers very significant co-benefits for **energy access, social equity and economic resilience** in remote regions.
- **Wind and solar energy use much less water** than fossil power plants and thus reduce vulnerability to water shortages in the power sector.
- There is growing evidence that developing clean, low carbon energy technologies offers additional benefits for **innovation and growth** compared to traditional energy technologies**.**

Potential adverse side-effects and means of overcoming them

- **Most energy supply technologies can have adverse environmental side-effects**, e.g. waste disposal impacts and accident risks associated with nuclear power; visual impacts of wind turbines; land-use implications of bio-energy. Some of these can be reduced (e.g. careful siting of wind turbines; 2nd generation biofuels).
- **The use of rare metals in new energy technologies** (e.g. neodymium in wind turbines, lithium in batteries) has material security, environmental and social impacts; these can be reduced through recycling.
- **The high investment costs of nuclear, renewable energy and CCS** could result in social impacts because of higher fuel costs to consumers (fuel poverty), though this could be mitigated through energy efficiency support for low income households.
- **The intermittency of some renewable energy sources** has implications for energy security; this can be handled through improved storage, interconnection, smart grids /demand management and diversified sources including bioenergy.

Figure 10 Mitigation actions for energy



Air quality benefits of a move to low carbon energy are well understood, typically through the use of economic models that assume a change in the electricity supply mix as a result of a carbon tax. This usually represents some combination of an increase in nuclear and renewable energy, a shift from coal to gas, more efficient fossil fuel plants and CCS. For example, the ClimateCost project estimates that under a 2°C climate stabilisation scenario, the EU27 gains 480,000 life years annually by 2050, worth €44-95 bn/y; equivalent to €24/t CO_2 abated (Holland et al., 2011). There are some adverse side-effects. For solid biomass, there can be an increase in particulate emissions if it is replacing gas, but net benefits if replacing coal or oil (Environmental Protection UK, 2013). For the most mature form of CCS, post-combustion with amine absorption, the indications are that there will be a reduction in SO_2 and PM emissions compared to the same plant without CCS (because these must be scrubbed from the gas prior to carbon capture), but an increase in NO_x because of the energy penalty (25%-30% more fuel must be burnt to power the capture process), plus emissions of NH_3 and toxic nitrosamines from degradation of the amine solvent. Alternative capture technologies such as membrane separation or cryogenic distillation could have different impacts (achieved for example through avoiding use of the amine solvent) but are further from commercialisation (EEA, 2011; Leung et al., 2014).

Attention is now being turned to distributional impacts, related to where the emission reductions occur and who benefits. For example, Boyce and Pastor (2012) show that low income and minority communities in the US are more likely to live next to polluting point sources such as refineries, so co-benefits for social equity can be maximised by targeting these sources through climate policy.

Energy cost savings are commonly reported as a benefit: both the savings to individual households, e.g. from energy efficiency, and the savings on fuel imports at a national level, which is reflected in the balance of payments. **Energy security** is a major policy driver for national governments, but is less often reported in the co-benefit literature, as the choice and value of indicator depends on the local context (though see von Stechow et al. 2015 for a synthesis of studies from the general climate policy literature). Some studies report indicators such as total oil and gas use (where gas is imported), total energy imports, the diversity of the energy mix, or the cost of disruption due to interrupted oil supply or price volatility (GCEC, 2015). Cox (2014) proposes a comprehensive framework of 24 energy security indicators reflecting affordability, long term availability (including public acceptability, reliance on imports, diversity and choke points), short term reliability (including balancing of intermittent sources) and sustainability (including fuel reserve depletion, carbon emissions, water use and reliance on secondary materials). Energy system modelling can help to assess the benefit of diversified energy supplies and the cost of incorporating non-dispatchable sources into the grid (i.e. sources that cannot be turned on and off quickly to meet demand fluctuations, such as nuclear power, wind and solar).

Investment costs are obviously a major factor in most analyses, although there is a methodological issue over how much of the investment cost can be considered to be the direct cost of the climate change mitigation action and thus not, strictly speaking, an adverse side-effect. Costs for renewable energy are rapidly decreasing but costs for nuclear remain significant, with governments usually having to underwrite investment costs by offering favourable advance power purchase contracts to investors, or providing indemnity insurance against the risk of accidents and the unknown long term costs of radioactive waste disposal. It is recognised that high up-front investment costs for particular technologies could result in **fuel poverty** impacts, although there is high potential for mitigating this impact through home energy efficiency programmes targeted at vulnerable groups, or through general taxation policies.

Employment impacts of a shift to low carbon energy are not well studied: despite estimates of the large potential for employment in renewable energy (e.g. Ferroukhi et al., 2016), few studies look at net impacts (jobs lost as well as jobs gained) throughout the fuel chain. Those that have assessed net impacts tend to report a small increase in net employment due to a shift from centralised fossil fuel generation to distributed renewable energy, at least in the short to medium term (e.g. Blyth et al., 2014). However, this small net change may mask large job losses in high carbon energy supply and large gains in low carbon energy, pointing to the need for government support to enable displaced workers to retrain (the 'just transition'). These changes may also be spatially variable, if manufacture of low-carbon technology is concentrated in particular locations (e.g. solar panels in China), but in other cases the majority of jobs will be locally generated (e.g. installation of solar panels, retrofitting of building energy efficiency measures and operating public transport).

Innovation and competitiveness: there is significant potential for national economies to benefit through development of the low carbon energy sector (Green, 2015; GCEC, 2014), though many studies on this are in the grey literature and tend to originate with industry groups (Aldy & Pizer, 2009; Ni & Qiongjie, 2014).

Adverse side-effects such as waste, accident and geopolitical risks of nuclear power, or visual impacts of wind turbines, are significant for many energy technologies. These are well covered by the SPLiCE review and the literature on external costs, but are rarely addressed in the co-benefit literature.

CCS scores poorly for co-benefits: it has mixed impacts for air quality (see above), potential negative impacts for waste disposal (both for waste solvent and for the risk of CO_2 leakage), high water usage[3], and negative impacts for energy security due to the high energy penalty (25-30%) involved in separating out the CO_2, transporting it and injecting it into the storage location. In the absence of internationally agreed CCS best practice there could also be high spatial variability of the risks of CO_2 leakage. The SPLiCE study identifies the long term safety of CO_2 storage and the environmental impacts of CO_2 storage on the marine environment

[3] E.g. Environment Agency (2013) cites unpublished research showing that CCS can increase power plant water use by 44-140%

and biodiversity as priority areas for future research. **BECCS** has the same issues, plus the additional range of impacts associated with biofuel production (see section 4.6).

Upstream impacts associated with fuel production are hardly ever mentioned in the co-benefit literature, although Smith et al. (2015a) did attempt to quantify these impacts based partly on fuel life cycle data dating from the EU's ExternE study. Quantification is problematic as it raises the issue of whether the impacts of rare but damaging events such as oil spills and coal mine accidents should be averaged across total global fuel production, or whether it is possible to allocate these impacts based on the typical supply chain for each country. Impacts also vary significantly depending on the context (e.g. opencast or deep mined coal; onshore, offshore, deep water or Arctic oil or oil sands; conventional or fracked gas and oil). Updating the available figures to incorporate more recent impacts and to account for regional differences would be useful.

Energy access in industrialising countries can be facilitated by the diffusion of small scale renewable energy technologies such as solar panels, small scale hydro and wind, and biogas digesters. These provide economic, environmental and social benefits related to lower use of traditional biomass, kerosene lamps or diesel generators (see also section 4.3, buildings). There can be associated benefits for social equity and livelihoods if the projects employ local people to install and maintain the technology, but local fieldwork is essential to ensure that the technology matches community needs.

Table 3 shows possible research gaps for the energy sector. Those prioritised by the workshop delegates are shown in bold font, with the three highest priority gaps being research into the net employment and economic benefits of a shift to renewable energy; the potential for small-scale renewable energy projects in industrialising countries to increase energy access and social equity; and the co-impacts of changes in the energy sector that will be needed to meet a range of targets from 1.5°C to 3.0°C. It was also suggested during workshop discussions that there was a need for a full life cycle analysis of CCS, and that more studies were needed on the co-benefits and adverse side-effects of geo-engineering, the impacts of energy efficiency on fuel poverty, and the long term risks of nuclear waste disposal.

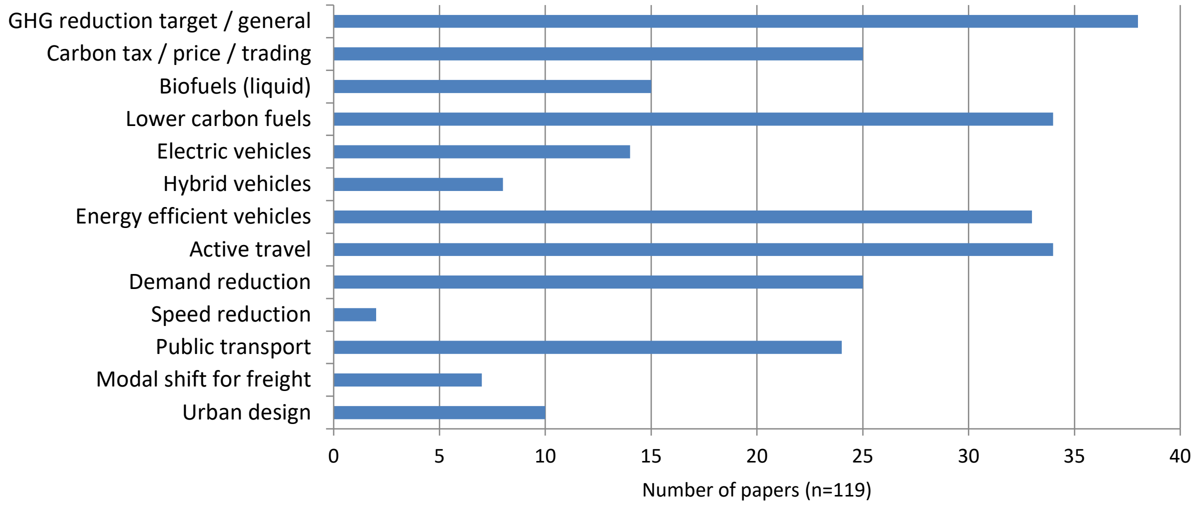
Table 3. Energy: potential research gaps (priorities identified by workshop delegates shown in bold)

Mitigation action	Impact	Gaps/ future directions
General	**AQ, energy security, economic**	**Co-benefits and adverse side-effects of changes in the energy sector that will be needed to meet a range of targets from 1.5 to 3°C.**
	AQ	**Understanding the distributional impacts of air quality benefits for different beneficiaries.**
	Energy security	Review of range of possible indicators for energy security, and how to monetise the benefits.
	Energy efficiency	Rebound effect – understanding and quantifying the impacts.
Renewable energy (solar, wind etc.)	**Employment, innovation, economic growth**	**Net employment and economic benefits of a shift to renewable energy.**
	Material security	Facilitating re-use and recycling to minimise potential adverse material security and end-of-life disposal impacts of low carbon technologies such as solar panels, wind turbines and batteries.
	Avoided fuel production impacts	Quantification of the benefits of avoided upstream impacts, e.g. oil spills, coal mine pollution and accidents, opencast coal mines (existing data is sparse).
	Energy access; equity/ sustainable development	**Potential to engage with industrialising countries regarding the co-benefits of small scale renewable energy for enhanced energy access and social equity; the role of social enterprises in maximising these co-benefits, and critical success factors such as community engagement.**
Wind energy	Visual impact and noise	Impact of community engagement and careful siting on public acceptability of wind farms.
	Bird strikes	Further work on how to avoid bird strikes.
Bioenergy (including for BECCS)	AQ	Information on real world emission factors for modern bioenergy production for a range of technology and feedstock combinations, and how they vary between different users and appliances; information on the technologies and equipment being used.
	Social and environmental	**Implications of feedstock production for land use, water quality, biodiversity, food security, social impacts (can be positive or negative).** Criteria for sustainable production; monitoring and verification.
Nuclear	**Waste disposal, accidents, security (terrorist threat)**	**Quantifying the uncertain impacts of radioactive waste, accidents and geo-security in various countries. How far can new nuclear technologies mitigate the risk of impacts?**
		Appropriate discount rate for evaluating very long term impacts.
	Fuel production (mining): water quality, occupational health	Evaluating the adverse impacts; identifying mitigation methods.
CCS	**AQ**	**Deriving emission factors for CCS. How far can new CCS technologies mitigate any adverse impacts?**
	Waste disposal impacts	Can new CCS technologies mitigate waste impacts (from disposal of used solvent)?
	Risk of CO_2 leakage	Further work on assessing the long term risks of CO_2 leakage.
	Upstream fuel production impacts	Evaluating the upstream fuel production impacts.
	Energy security	Evaluating energy security impacts associated with fuel use penalty. Trade-off with enabling continued use of domestic fossil fuel.

4.2 Transport

Main co-benefits of climate change mitigation in the transport sector
• **Efficient vehicles, demand reduction and some low carbon fuels (hydrogen, natural gas) offer substantial health benefits from improved air quality,** because urban transport is the most damaging source of air pollution. • **Active travel (walking and cycling) offers the potential for very large health benefits from increased physical activity**, even exceeding the air quality benefits of low carbon travel. However there are challenges in encouraging behaviour change towards active travel**.** • **Active travel, demand reduction and public transport offer large co-benefits from reduced congestion, noise and accidents, and improved social interaction and mobility.** • **All transport mitigation measures offer benefits for energy security** which are particularly significant because they reduce dependence on imported oil. Demand reduction and efficient vehicles also offer **energy cost savings.** • **Demand reduction measures that result in fewer vehicle km also reduce the need for road infrastructure,** which has benefits for land use and biodiversity, though this is rarely addressed in the literature**.**
Potential adverse impacts and means of overcoming them
• Active travel will reduce the number of vehicles on the road and therefore will reduce the individual risk of an accident, but **the total number of accidents could increase** due to greater participation in walking and cycling, and possibly if reduced congestion leads to increased vehicle speed. This can be mitigated by road safety and traffic calming measures, and especially by provision of off-road cycle paths. • There is a risk of **increased exposure to pollution** by increased walking/cycling in close proximity to exhausts of remaining vehicles, which can be mitigated by air quality legislation, a shift to cleaner vehicles and off-road cycling and walking infrastructure. • **Biofuel production can result in adverse impacts** (see section 4.6, AFOLU), which can be mitigated by enforcing strict sustainability criteria for biofuels. • There are **adverse air quality impacts associated with a switch from gasoline to diesel**. • **Some end-of-pipe vehicle emission reduction technologies** such as particulate filters carry an energy penalty and thus lead to increased GHG emissions**.**

Figure 11 Mitigation actions for transport



Air quality benefits of climate change mitigation options involving reduced motorised travel and more efficient vehicles are well established and are substantial, as transport emissions are responsible for the bulk of health impacts from outdoor air pollution in urban locations. However, one exception is fuel switching from gasoline to diesel, which has adverse air quality impacts (e.g. see Met Office, 2015). This has been highlighted by recent concern over the use of 'cheat' devices for emissions testing. Research is emerging on autonomous vehicles, which can provide energy efficiency and broader benefits, e.g. Anderson et al. (2016).

'Reverse' co-benefits may also occur if air quality legislation leads to improvements in vehicle efficiency or the use of clean low-carbon fuels (e.g. switching from diesel to CNG buses in some countries). However, some end-of-pipe air quality control options such as particulate filters on diesel vehicles may increase fuel consumption and CO_2 emissions. In developing countries where diesel emissions are high, this could be partly offset by the short term warming benefit from reduced black carbon (Zusman et al., 2014).

Health benefits of active travel arising from increased physical activity are clearly established and potentially very large, outweighing the air quality health benefits in industrialised countries and possibly even in industrialising countries (Woodcock et al., 2009). However, GHG benefits of active travel are limited by the short distance of trips displaced. This could be addressed through **integrated transport strategies** that implement a co-ordinated programme of measures, combining cycling and walking infrastructure, personalised travel plans and school travel plans, traffic calming measures and improved public transport. Good public transport has a role to play in facilitating the shift away from car use: this can free up road space for more active travel infrastructure and encourage displacement of longer car trips, thus increasing the GHG benefits while reducing accident rates (e.g. UK Sustainable Travel Towns – Sloman et al., 2010). Most active travel research is focused on cycling, but walking is also important, especially as a link to public transport. Emerging research includes work funded by Public Health England on opportunities and barriers for functional walking for disabled people (Living Streets, forthcoming) and research on the role that electric bikes can play in facilitating active travel in harder to reach groups, (e.g. Cairns et al., 2015). Although there is strong theoretical and modelling evidence on the benefits of active travel, there is also a need for more robust observational evidence from 'real life' interventions (Shaw et al., 2014).

Beneficiaries of active travel interventions are poorly known. Take-up may (initially at least) be by people with an existing propensity to cycle rather than less active people who could benefit more. On-going research on take-up mechanisms includes the National Propensity to Cycle study and the EU PASTA (Physical Activity Through Sustainable Transport Approaches) project.

Social impacts of travel interventions and new vehicle technologies are important: good public transport and urban design can have key benefits for accessibility and mobility for vulnerable groups and boost urban vitality and social cohesiveness, while the impact of electric vehicles on society is identified as a research priority in the SPLiCE study. There is limited research in the co-benefit literature, but see work for the DfT on the Social and Distributional Impacts of Transport Measures (Skinner et al., 2011).

Economic benefits stem from reduced congestion, as well as health-related benefits of reduced time off work and lower healthcare costs. Few quantified studies of congestion benefits were found, but there may be useful studies in the broader transport literature. Political and public acceptability of demand reduction measures (e.g. congestion charging) is critical, and there is also concern that reductions in travel demand can be transient. Investment in transport infrastructure is seen as being key to economic growth, but typically this investment is geared towards car travel. Mechanisms to ensure that the economic co-benefits of more sustainable travel options are accounted for in transport planning are urgently required, both in industrialised and industrialising countries. For example, the European Cyclists Federation is leading work on the employment and economic benefits associated with cycling.

Wider environmental impacts, beyond the impact of air quality on health, were rarely mentioned in the co-benefit literature reviewed in this study, though some papers assessed the benefit of reduced ozone emissions on crops (e.g. Aunan et al., 2007; Avnery et al., 2013; Heagle, 1989; Schwanitz et al., 2015), or reduced acidification and eutrophication of ecosystems from NO_x and SO_2 emissions (e.g. Holland et al., 2011; Smith et al., 2015a). There is additional work on these impacts in the wider literature, e.g. the work of the Convention on Long Range Transport of Air Pollution (CLRTAP). Other potential co-benefits include avoided air pollutants such as trace metals; improved water quality (linked to runoff from roads); reduced wildlife collisions; and avoided road and car parking construction, leading to potential benefits for habitat connectivity.

In industrialising countries, the large unmet demand for motorised transport means that the emphasis is on cleaner and more efficient vehicles rather than active travel or demand reduction, although Woodcock et al. (2009) indicates large potential active travel co-benefits in Delhi. However, active travel investments, urban design and affordable public transport could also offer equity and sustainable development benefits for those who cannot afford cars (WHO, 2011b). Awareness of these benefits could be raised via case studies of industrialising cities which are dealing with similar challenges and opportunities (Rutter, 2016, forthcoming).

Potential research gaps are shown in Table 4. Those prioritised by the workshop delegates are shown in bold, with top priority being the development of tools for planning sustainable transport in cities.

Table 4. Transport: potential research gaps

Mitigation action	Impact	Gaps/ future directions
Smarter choices (active travel, public transport, demand reduction) and urban design	**All (AQ, physical activity, accidents, congestion, noise, energy security, social equity etc.)**	Packages of measures: e.g. fuel taxes, parking restrictions and traffic calming reduce traffic and decreases accident and pollution exposure; public transport frees up road space for cycle paths; etc.
		Tools for planning low carbon cities to maximise co-benefits: Quantification of the impacts of urban design options, e.g. optimum housing density; optimum mix of styles of building (low / mid / high rise) for socially connected and walkable neighbourhoods.
		Climate finance to incentivise better urban design in industrialising countries.
	Social impacts	Social impacts, e.g. impacts on crime rates, social cohesiveness, job creation, poverty reduction, urban vitality and social equity (benefits for people without access to a car) Social barriers to active travel and use of public transport (e.g. fear of crime), and how to overcome them.
	Economic impacts	Further work on economic impacts (e.g. from cycling-related jobs) - potential for a synthesis study?
	Habitat, biodiversity and ecosystem services	Wider environmental impacts (beyond PM health impacts) e.g. air quality impacts on crops and ecosystems; trace metals; water quality; reduced habitat loss due to less need for roads and car parks; better connectivity for wildlife; fewer wildlife collisions.
	Accident impacts	Effect of smarter choices on accident rate; strategies for reducing accidents (e.g. traffic calming; segregated cycle routes).
	Congestion	Better evaluation of the impacts of smarter travel on congestion, taking into account the time and location of trips.
Active travel - infrastructure, awareness	Physical activity benefits for health and wellbeing	Distribution of benefits – how to maximise physical activity benefits by addressing barriers to wider uptake by less active people.
		Evaluation of real life interventions. Longitudinal studies to capture long term evolution of behaviour, e.g. as social norms change.
		Timescales for uptake, i.e. when would cycling reach such a level that the health benefits would be achieved in the broader population?
		Walking (current research dominated by cycling).
Demand reduction: behaviour change	Multiple benefits, as above	Evaluation of benefits from real life demand reduction interventions, e.g. to encourage homeworking, teleconferencing, logistics, lifestyle change.
	Economic, social, cultural and wellbeing impacts	Economic, social and cultural impacts of reduced travel (though may be economic assessments on airport and road expansion outside the co-benefit literature).
Modal shift (road/ air to rail or water)	**Multiple benefits, as above**	**Little research found though may be research outside co-benefit framing.**
New vehicle technologies		Economic, social and environmental impacts associated with electric vehicles and other new technologies (e.g. innovation, jobs, battery manufacture and disposal).
Biofuels		Social, economic and environmental impacts of biofuels, including extent to which biofuels from woody biomass can improve sustainability.
Speed reduction		Potential benefits for reducing congestion, noise, accidents and wildlife collisions (including marine mammal collisions for shipping).
Aviation and shipping		**Co-benefits and adverse side-effects (research currently dominated by the road transport sector).**

4.3 Buildings

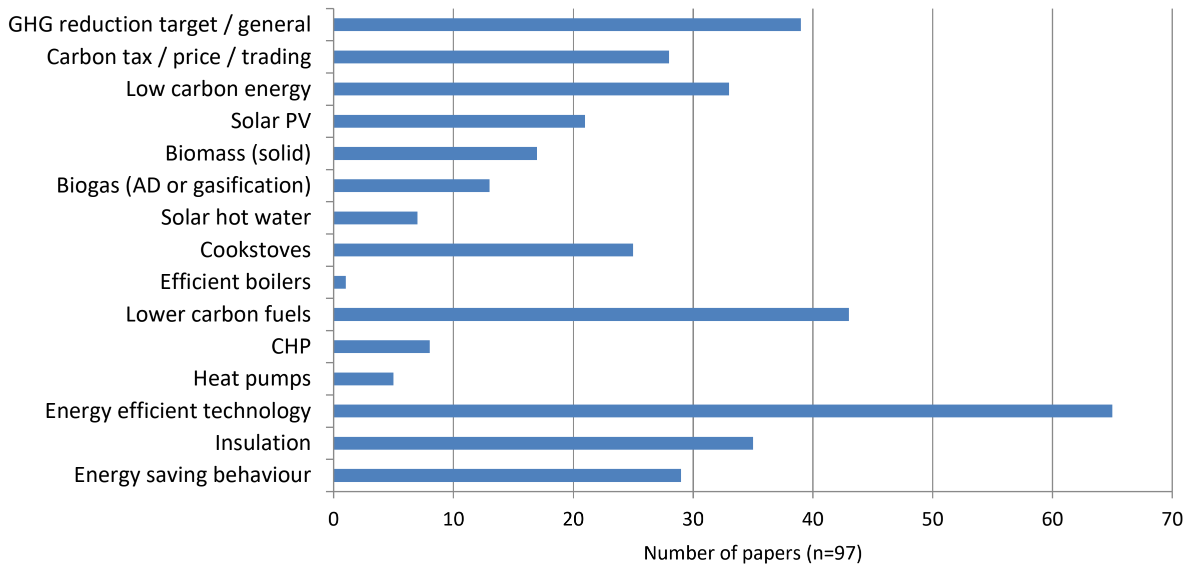
Main co-benefits of climate change mitigation in the buildings sector

- **Low carbon buildings offer major co-benefits for physical and mental health:** they are warmer in winter, cooler in summer, and eliminate dampness, mould and draughts.
- **Building energy efficiency offers fuel cost savings** for households and reduces fuel poverty, and improves **energy security** and the balance of payments a national scale if there is a reliance on imported fuel for heat and power.
- In developing countries, **cleaner cook-stoves provide very large health benefits** through improved indoor air quality, as well as socio-economic benefits from reducing time spent gathering firewood, especially for women and children.
- There is a limited amount of evidence to indicate that low carbon non-residential buildings may also offer significant economic benefits by **raising the productivity** level of the occupants.

Potential adverse side-effects and means of overcoming them

- There is a risk that **radon and other indoor air pollutants** can accumulate due to improved air-tightness of energy efficient buildings, but this can be addressed through better ventilation.

Figure 12 Mitigation actions for buildings



Health benefits through improving the heating and cooling of buildings are well established, with large potential social equity benefits for vulnerable groups in both industrialised and industrialising countries (e.g. WHO, 2011a; Wilkinson et al., 2009; Sovacool, 2015; Liddell et al., 2016; Howden-Chapman et al., 2015). There is ongoing research into potential adverse impacts of air tightness on indoor air pollution from radon and other pollutants, and the need for better ventilation to counter this (e.g. Wilkinson et al. 2009; Gupta and Kapsali 2015; Shrubsole et al., 2015).

Cleaner cookstoves are a dominant theme in industrialising and low income countries. Replacing inefficient stoves or open fires burning traditional biomass leads to very large health and social benefits from improved indoor air quality, and reduces the burden of gathering fuelwood, especially for women and children (e.g.

Raji et al., 2015; Anenberg et al., 2012), though additional funding for energy access may be needed to offset the risk that higher energy prices as a result of climate policy could make a shift from traditional biomass to cleaner gas or electricity unaffordable for many (e.g. Cameron et al., 2016). The success of programmes to introduce cleaner cookstoves depends on a number of factors including tailoring the stove design to suit local cooking techniques (Stanistreet et al. 2014; Zusman et al. 2014).

Energy cost savings associated with energy efficiency in buildings feature in many studies. This will have cascading effects through the rest of the economy, with trade-offs or synergies between social, economic and environmental impacts depending on how the money saved is spent. There is poor knowledge of the extent to which the 'rebound effect' can offset the actual energy savings resulting from increased energy efficiency. However, the rebound effect can be beneficial if it helps to reduce poverty or provide other wellbeing benefits (IEA, 2014). Energy efficiency can help reduce **fuel poverty** and thus increase **social equity** in both industrialised and industrialising countries. There is an emerging literature that considers which socio-economic groups benefit most from grant schemes.

Development. There is significant potential for new or retrofitted low carbon buildings to address climate change mitigation and adaptation at the same time as achieving other health and development goals such as improved sanitation and reduced exposure to pests (WHO, 2011a).

Social enterprises aimed at providing domestic renewable energy options to remote communities in industrialising countries, e.g. solar panels, lamps or phone rechargers, or cleaner cook-stoves, can improve equity, especially when women or other target groups are trained to sell, manufacture or install the products. Community engagement can increase the social co-benefits of interventions and can also increase the success rate by ensuring that the product matches the need of the local community (Popay, 2010).

Table 5 shows possible research gaps for the buildings sector. Those prioritised by the workshop delegates are shown in bold, with top priority being the need for quantified studies demonstrating the impacts of real interventions that combine climate change mitigation, adaptation and development aims in industrialising countries.

Table 5. Buildings: potential research gaps

Mitigation action	Impact	Gaps/ future directions
Residential buildings: insulation, efficient heating (heat pumps, fuel switch, efficient boilers, CHP, district heating, solar hot water) and low carbon design (e.g. passive solar, passive cooling, natural lighting and ventilation)	**Health and wellbeing benefits: comfort; indoor AQ (reduced mould, reduced CO and NOx from inefficient heaters); cost savings for households; Social equity; Energy security**	**Evaluation of the benefits in real life interventions.**
		Benefits of warmer homes for mental health.
		Improved methods to capture subjective benefits, for example relating to comfort levels.
		Social outcomes of neighbourhood-wide retrofitting programmes (e.g. social cohesion and impact on crime rates).
	Indoor AQ - Radon	Reducing radon build-up through better ventilation.
Non-residential buildings (as above)	Comfort and productivity	Productivity co-benefits in non-residential buildings, e.g. from better lighting, more comfortable temperatures, quieter appliances, less waste heat, lower maintenance costs.
Green infrastructure	AQ, health and wellbeing, microclimate, productivity	Potential GHG reductions and co-benefits from green infrastructure in, on and around buildings (green roofs, green walls, indoor plants, gardens, shade trees).
Low carbon building materials	**Material security, environmental impacts of resource extraction**	**Potential for sustainable building design to reduce other environmental impacts through using lower impact materials; integrating the evidence base on this into a co-benefit framework.**

Mitigation action	Impact	Gaps / Future directions
INDUSTRIALISING COUNTRIES		
Low carbon urban design and building retrofitting in industrialising countries	**Health and wellbeing benefits; sustainable development; social equity; energy security; indoor AQ (PM, black carbon, CO, NOx)**	**Quantified studies demonstrating impacts of real interventions that combine climate change mitigation, adaptation and development aims.** Community participation in building design – understanding its role and how to facilitate this.
Cook-stoves (replace polluting coal, kerosene or biomass stoves with cleaner gas, electric or biomass stoves)	**Health benefits from indoor AQ (PM, black carbon); socio-economic benefits; reduced deforestation**	**Role of community engagement in ensuring successful take-up of cleaner stoves.** Potential impact of increase of fuel costs (linked to climate change mitigation) on access to clean gas or electric stoves (recent work by IIASA).
Solar lighting (replacing kerosene lamps, a major source of black carbon)	Health benefits - respiratory, TB, eye problems, fires and accidents; energy access	Evaluation of health and socio-economic benefits of solar lighting in industrialising countries.
Solar refrigeration	Food security, health	Potential for solar refrigeration.

4.4 Industry

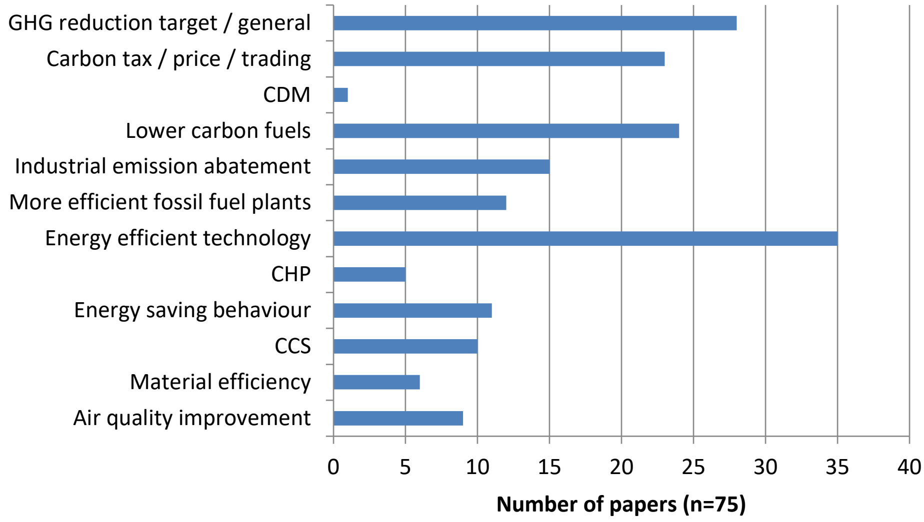
Main co-benefits of climate change mitigation in the industry sector

- **Improved energy efficiency in industry** offers major benefits for air quality, and there may be benefits for social equity because low income households tend to be over-represented in polluted industrial areas.
- **Reducing black carbon emissions** offers joint benefits for climate and air quality.
- **Resource efficiency and the circular economy** approach can yield major benefits for material, energy and water security, associated environmental benefits (reduced impacts of mining and processing raw materials), financial savings and increased competitiveness, and possible productivity benefits.
- **Use of more sustainable materials** with lower carbon footprints (e.g. sustainably sourced wood replacing steel or plastic) can have environmental co-benefits related to avoided extraction and processing of the less sustainable materials**.**

Potential adverse side-effects and means of overcoming them

- As for the power sector, **CCS carries an energy consumption penalty** (costs and energy security) and there are potential environmental impacts related to CO_2 storage and waste solvent disposal.

Figure 13 Mitigation actions for industry



Energy efficiency is the main mitigation approach identified in the co-benefit literature for the industry sector, but most studies report this in general terms, e.g. reduced fossil fuel consumption in the industry sector as a result of a carbon tax, and do not go into detail of the technical options deployed, which often involve major process changes rather than incremental efficiency improvements. The main co-benefits reported are air quality, energy cost savings and energy security.

Industrial emission abatement also features in the literature on reducing emissions of short-lived climate pollutants (black carbon and methane). This can use end-of-pipe filters or fuel switching, or simply focus on closing down old, polluting plants. It is usually implemented in response to air quality legislation rather than as a climate change mitigation action.

Material efficiency is largely neglected in the co-benefit literature, despite its potential to achieve large multiple environmental, social and economic benefits. Work by Julian Allwood's group at the University of Cambridge has developed estimates of the potential role of material efficiency in GHG abatement (e.g. Allwood et al., 2010), and Barrett and Scott (2012) estimate a modest potential for material efficiency to reduce UK GHG emissions by up to 8% (this ignores raw material production), but material efficiency rarely features in national climate change mitigation strategies, and there is no quantification of the associated co-benefits in terms of avoided material extraction and waste disposal (see also waste sector below). However, a material efficiency co-benefit assessment approach is currently being developed as part of the COMBI project (Teubler et al., 2015) and this could form a starting point for future assessments.

The review did not identify any literature on the potential to achieve co-benefits by the use of more sustainable materials in manufactured goods and in construction. Replacing metal or plastic with sustainably sourced wood could reduce GHG emissions from extraction and processing of the raw materials as well as sequestering carbon. This would also have socio-economic impacts (e.g. a shift in employment and economic activity from mining to forestry).

Table 6 shows potential research gaps in the industry sector. Those prioritised by the workshop delegates are shown in bold, with top priority being research on the distributional impacts of industrial emission reduction in terms of the location of air quality benefits.

Table 6. Industry: potential research gaps

Mitigation action	Impact	Gaps/ future directions
Industrial Process improvements	Multiple economic and environmental benefits	Quantifying the economic and environmental benefits of process improvements.
Emission reduction	**AQ**	**Distributional impacts, e.g. should investment be focused on polluting plants in highly populated areas? Analysis of benefits for different socio-economic groups and levels of engagement (national, regional, local).**
Circular economy / resource efficiency	**Multiple economic and environmental benefits**	**Material efficiency and water efficiency: bringing this into the co-benefit framework. (The water sector is not mentioned separately in co-benefit literature despite the growing importance of water security and the food-energy-water nexus).**
	Productivity	**Evaluating the productivity impacts of industrial resource efficiency, e.g. due to process improvements, higher quality product / lower rejection rate, lower consumption of water and materials, noise and vibration reduction, reduced maintenance needs, reduced accidents, time savings e.g. for waste disposal and material handling.**
Sustainable materials in construction and manufacturing (e.g. wood)	Air quality, water quality, biodiversity	Evaluation of co-benefits and socio-economic impacts.

4.5 Waste

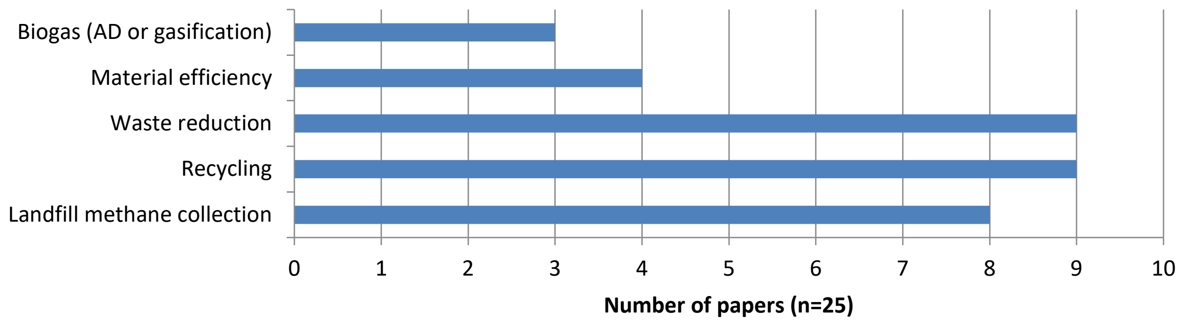
Main co-benefits of climate change mitigation in the waste sector

- **Waste minimisation, reuse and recycling (and the circular economy approach) have a very wide range of benefits:** reduced waste disposal impacts (land use, odour, visual impact, litter, vermin, water quality); avoided environmental and social impacts of raw material extraction and processing; cost savings; and increased material security.
- **Landfill gas recovery** leads to air quality benefits from reduced methane (an ozone precursor).
- **Anaerobic digestion** also leads to reduced methane emissions and reduced ammonia emissions in the case of farmyard manure / slurry.
- **There are potential employment benefits** from a shift away from a throwaway economy towards a 'repair and reuse' economy.

Potential adverse side-effects and means of overcoming them

- **'Energy from waste' plants** can reduce the imperative to reduce, reuse and recycle waste in preference to disposal or incineration.
- **Reduced material consumption** could have a negative impact on the extractive, manufacturing and retail sectors, although jobs will be generated in the repair, reuse, recycling and sharing economy sectors.

Figure 14 Mitigation actions for waste management



Waste avoidance, reuse and recycling (and the circular economy approach) provide multiple environmental, social and economic benefits but these are poorly represented in the co-benefits literature, although there is a separate waste management evidence base. Although the potential benefits of a circular or 'zero-waste' economy are widely discussed, there are barriers to achieving this in practice.

Re-use and recycling are also important in order to overcome the material security and associated toxic waste disposal impacts related to the **use of rare metals in low carbon technologies** such as wind turbines, solar panels and batteries.

Industrialising countries that do not have widespread waste collection systems can benefit from modern landfill sites with methane collection, and there are case studies of CDM support for this in India and Thailand (e.g. Puppim de Oliveira, 2013). Installation of landfill gas collection usually includes collection of leachate and covering of the waste, thus also reducing many of the other impacts of landfill (water pollution, litter, odour and vermin). However, modern landfill facilities are expensive but labour is relatively cheap, providing a motive for reduce-reuse-recycle. This also offers potential for 'green jobs', but there are also issues with acceptable conditions for workers in informal recycling. Worker co-operatives can help to ensure fair pay and safe working conditions.

Table 7 shows possible research gaps in the waste sector. Those prioritised by the workshop delegates are shown in bold, with top priority being research on opportunities for climate finance to encourage modern waste treatment plants in industrialising countries.

Table 7. Waste: potential research gaps

Mitigation action	Impact	Gaps/ future directions
General waste management		Tools and indicators for integrating waste management into a co-benefits framework.
Collection of methane from landfill or waste water treatment	**Water quality; GHG; health; energy cost savings**	**Opportunities for climate finance to encourage modern waste treatment plants in industrialising countries, with co-benefits for health, energy supply and water quality.**
Recycling, reuse, waste avoidance	**Multiple benefits (see below)**	**Recognising / evaluating the role of material efficiency as a climate change mitigation option with multiple co-benefits, and developing an assessment framework for these co-benefits.**
	Material security	Tools and indicators for quantifying material security benefits.
	Avoided impacts of resource extraction	Quantifying the avoided impacts of resource extraction (mining, processing, etc.) (linking LCA work with co-benefit framework).
	Sustainable development; Avoided impacts of waste disposal (pollution, odour, land use, visual impact)	**Role of carbon finance support for sustainable waste management in enabling engagement with industrialising countries.**
	Jobs; economic growth	**Employment impacts and economic benefits of a shift to a circular economy, including issues of job quality (especially in industrialising countries).**
Sharing economy and product life extension	Social and economic impacts	Socio-economic impacts, barriers and case studies of the ‘sharing economy’ and product life extension.

4.6 Agriculture, Forestry and Other Land Use (AFOLU)

Main co-benefits of climate change mitigation in the agriculture, forestry and land use sector

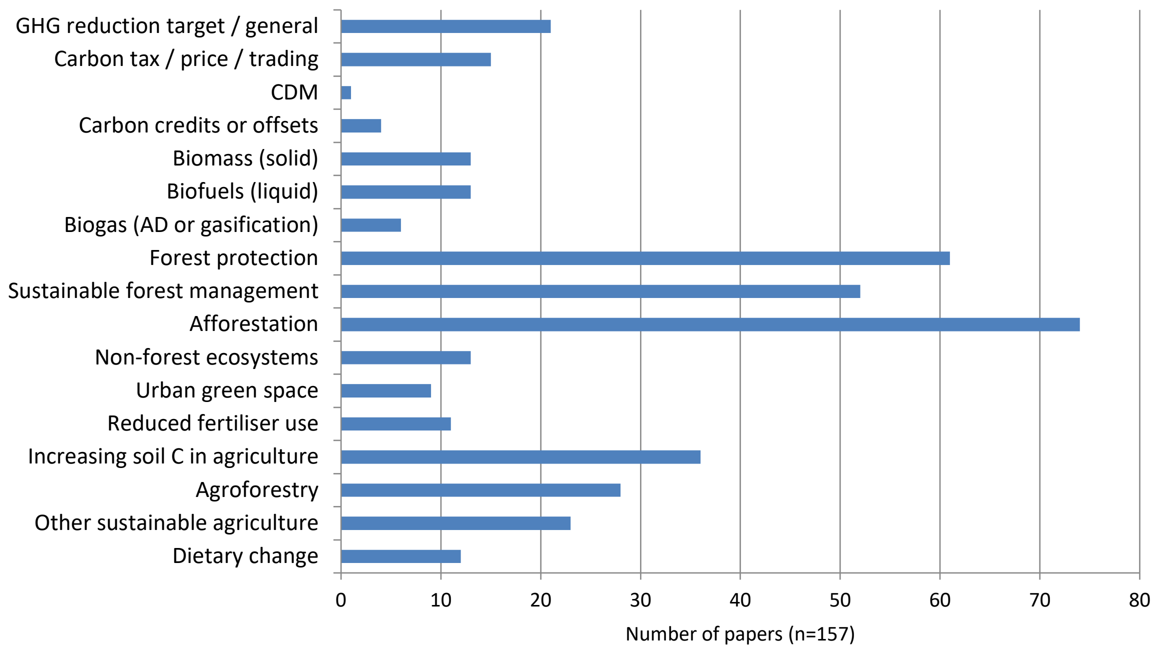
- **Afforestation, forest protection and sustainable forest management** can be promoted through traditional policy approaches (e.g. protected areas) and also novel ones involving incentives linked to the value of forest carbon stocks, such as REDD+ (Reducing emissions from deforestation and forest degradation, plus conservation, sustainable management of forests, and enhancement of forest carbon stocks) (UNFCCC, 2016). For well-designed schemes with safeguards, there can be large benefits for biodiversity and ecosystem services and there can also be benefits for local communities who depend on forest resources.
- **Carbon sequestration in agriculture**, by adding organic matter to the soil, reducing soil erosion or introducing agro-forestry, can have co-benefits for soil fertility, water retention (hence drought resistance), agricultural productivity and food security. Farmers need practical support to adopt new techniques.
- **Reduced fertiliser use,** e.g. through precision agriculture, has co-benefits for air and water quality by reducing emissions of nitrogen compounds, and also offers cost savings to farmers, but uptake by farmers can be slow.
- **Carbon storage in other ecosystems,** especially peatlands and wetlands, can be protected or enhanced/ restored via regulatory approaches (protected areas), payment for ecosystem services (PES), or collaborative management (e.g. between local communities, conservation organisations and water companies). Examples include catchment management approaches in Europe and North America, which offer substantial co-benefits for biodiversity, water quality and water supply, as well as coastal mangrove wetland ('blue carbon') projects in developing countries[4], which can offer major co-benefits for storm protection, biodiversity, fisheries and eco-tourism.
- **Green Infrastructure** such as urban parks, woodlands, green roofs and walls, offers a wide range of co-benefits. In industrialised countries the emphasis is often on health and wellbeing (from recreation, cultural and aesthetic value and, to some extent, pollution regulation), but there are also significant benefits for biodiversity and for climate adaptation in all countries (shade, cooling, flood protection).
- **Dietary change:** a shift to eating less animal produce, especially red meat from ruminants, can lead to a wide range of significant environmental benefits (reduced land use and thus reduced habitat loss; improved air quality from lower emissions of methane; improved water quality from lower use of fertilisers for improved pasture or feed crop production). There are also potentially very large health benefits associated with lower consumption of saturated fat and red meat, but these are uncertain and depend on the food(s) substituted for meat.

[4] For examples and case studies, see the Blue carbon Portal at http://bluecarbonportal.org/

Potential adverse side-effects and means of overcoming them

- **Afforestation** schemes have sometimes led to replacement of natural forests or other ecosystems with monoculture plantations, leading to adverse biodiversity impacts, and some forest protection schemes have led to displacement or exclusion of forest dwellers or forest users. Safeguards to avoid these adverse impacts have been incorporated into the eligibility criteria for REDD+ finance.
- **Bioenergy feedstock cultivation** can result in adverse social and environmental side-effects, such as pressure on land and water resources and habitat loss, unless strict criteria are applied to ensure sustainability.
- **Dietary change** could result in adverse socio-economic impacts on rural communities, livestock farmers and the food industry**.**

Figure 15 Mitigation actions for agriculture, forestry and land use



Forest protection, afforestation and sustainable forest management (e.g. via REDD+)

Impacts of forest carbon projects could be either positive or negative, depending on the details of how they are implemented. Forests offer very significant co-benefits for biodiversity and also provide flood and erosion protection (e.g. Bradshaw et al., 2007), habitat for pollinating insects, air pollution removal and genetic resources (including medicinal plants), as well as having a high recreation, cultural and aesthetic value. There is also evidence that large forest areas such as the Amazon play a key role in maintaining rainfall in adjacent regions (e.g. van Noordwijk et al., 2015). In some cases, however, the potential for forest carbon payments has resulted in replacement of native ecosystems with monoculture plantations (which can reduce local water supply in arid regions), exclusion of local people from forests or 'land grabbing' where forest tenure passed to investors looking to profit from carbon payments.

The criteria for REDD+ payments therefore include social and environmental safeguards (the 'Cancun' safeguards), and effective monitoring and verification of these safeguards is essential to ensure delivery of co-benefits for biodiversity and equity / sustainable development / livelihoods, and to avoid adverse side effects. This in turn requires strong local governance and community participation. However, well-designed projects with effective monitoring and community participation tend to be more expensive, meaning that the carbon credits may not be attractive to potential purchasers. Although many buyers actively seek projects with verified co-benefits, they do not necessarily pay more per tonne for these projects (Goldstein, 2016). The additional costs involved in certification could therefore, in theory, limit the total area of forest that can be protected or enhanced via REDD+ finance. There is therefore a need for flexible and cost-effective monitoring approaches that can be adapted to assess social and environmental impacts in a range of different situations (e.g. see Latham et al. 2014 for guidance on assessing biodiversity).

Much of the research has focused on **mapping the correlation between forest carbon storage and biodiversity**. Some studies find good correlation, thus concluding that REDD+ can deliver benefits for both carbon and biodiversity (e.g. UNEP-WCMC, 2008), and some find otherwise – pointing out the need to conserve lower carbon forests (e.g. open woodland or savannah landscapes such as the Brazilian Cerrado) and other ecosystems of high biodiversity value, and restore degraded forests. A promising avenue of research is mapping potential high-carbon links between protected areas, to improve **connectivity** for wildlife (Jantz et al., 2014).

New initiatives are starting to address **GHG accounting at the whole landscape level**, building on the REALU (Reducing Emissions from All Land Use) approach developed by the World Agroforestry Centre (e.g. Vanderhaegen et al., 2015). This can help to avoid the problem of indirect land use change, where protecting a forest in one location might lead to a forest elsewhere being felled to make space for agriculture, for example. An example is the third phase of the World Bank's BioCarbon Fund: the Initiative for Sustainable Forest Landscapes (ISFL). New methodologies are being developed to account for GHG emissions across an entire jurisdictional region, including forest, agriculture and bioenergy planting. In theory, this could make it easier to realise co-benefits from sustainable agriculture and bioenergy schemes while avoiding adverse side-effects due to indirect land use change, but the approach has not yet been tested in practice. However, useful guidance has been developed regarding the tools and models that can contribute towards assessing GHG impacts and co-impacts (Bernard et al., 2011).

There is a large literature base but this review found **few quantitative estimates of co-benefits**, and some of these were only for the sale of sustainably harvested forest products. However, there are some modelling studies of biodiversity co-benefits, e.g. Strassburg et al. (2012) predicted that a carbon price of 25 US$/tonne CO_2 could reduce global species extinctions by 84%-93% compared to business as usual. It is hard to assess the degree of overlap of these biodiversity co-benefits with other ecosystem services such as pollination or flood protection (GCEC 2015). There is potential to link research on REDD+ with research on ecosystem service assessment in order to assess a wider range of co-benefits including flood and erosion protection, as well as trade-offs with food and biofuel production (e.g. Koh and Ghazoul, 2010). A recent survey of 144 forest carbon projects found that many offered co-benefits for biodiversity, water regulation and climate resilience, as well as social co-benefits such as clarification of land tenure, targeting of benefits on vulnerable groups and empowerment of women, but that better ways of measuring and reporting these benefits are needed in order to drive more investment (Goldstein 2016).

Agriculture

GHG mitigation techniques include agroforestry, contour hedge planting on erosion-prone slopes, use of cover crops, and incorporation of compost, manure, green manure or crop residues into the soil. These techniques all increase soil and/or biomass carbon sequestration while reducing soil erosion and improving soil fertility (especially for leguminous trees, shrubs or cover crops), infiltration and water-holding capacity. They thus contribute to food and water security, climate adaptation and livelihoods. In addition, agroforestry can provide an alternative source of income to farmers from sustainable harvesting of timber or fruit. Trees on farms can also provide shade, shelter and (if edible shrubs or fruit trees are used) forage for livestock, increasing animal welfare and also increasing milk yields (Broom et al., 2013).

There is considerable interest in these techniques in developing countries, where soil carbon sequestration is seen as a less contentious issue than forest carbon, but implementation barriers arise due to the high transaction costs of establishing these techniques and the time lag before farmers see a benefit in terms of increased crop yields. Funding and assistance is needed to overcome barriers to uptake by smallholder farmers, e.g. by providing loans for purchasing agroforestry saplings, or by demonstrating successful projects on nearby farms. There is also a need for more research on cost-effective methods for monitoring soil carbon sequestration. Quantitative estimates of the benefits in terms of increased crop production and reduced need for inorganic fertilisers are available for some projects, e.g. Braimoh (2012) and Prabhakar et al. (2013).

Precision agriculture can reduce the need for fertilisers; this technique is applicable both in developed and developing countries, and offers co-benefits for air and water quality through reduced emissions or runoff of nitrogen compounds, as well as cost savings for farmers. However, farmer uptake can be slow, and emerging research indicates that local demonstration projects are key to increasing uptake.

Bioenergy

Bioenergy is likely to play a major part in strategies to meet stringent climate targets, but it is associated with a range of important co-impacts which depend on the feedstock, fuel type and combustion technology. **First generation liquid biofuels** from starch or oil-based crops increase the global demand for agricultural land, water and fertilisers, thus potentially threatening food security and increasing food prices. This pressure on agricultural land may also drive deforestation, with major adverse impacts for biodiversity and ecosystem services. Some biofuels may not have significant GHG benefits, e.g. net emissions could be large and positive if peat forest is converted to biofuel crops. **Second generation biofuels** derived from woody crops such as Miscanthus grass or short rotation coppice can also drive indirect land use change, unless grown on marginal land. **Algal** biofuels avoid these problems to some extent but do still require a certain amount of land area and energy input, and are expensive and not yet available at a commercial scale.

Solid biomass for use in households, power stations or industry is generally derived from forests, waste or crop residues, and thus does not compete directly with food crops, but there may still be biodiversity impacts associated with removing wood from forests, or soil fertility (and soil carbon) impacts if crop residues are removed from fields. Purpose-grown woody crops such as short rotation coppice can drive indirect land use change. However, there is potential for some woody bioenergy crops to help restore degraded agricultural land, stabilising eroded soil and restoring fertility, and even providing biodiversity benefits under good management. The EU sustainable biofuels criteria aim to ensure that minimum GHG benefits are achieved and that biofuels are not planted on high biodiversity land, as well as providing additional incentives for biofuels with no additional land requirement (from algae, straw or forestry waste), and imposing an upper limit for biofuels in an attempt to limit indirect land use change. The land use impacts of bioenergy production are identified as a key priority area for future research in the SPLiCE study.

Air quality co-benefits of replacing fossil fuels with biofuels are small or even negative, depending on the fuel displaced. Solid biomass produces more particulate and NO_x emissions than gas, but less than coal and oil (Environmental Protection UK, 2013) so switching from gas to biomass could increase adverse health impacts in urban areas.

Despite these potential problems, the role of bioenergy is likely to increase in future, especially as bioenergy with CCS **(BECCS)** can act as a negative emissions technology. Production of bioenergy at a much larger scale is likely to pose major challenges for land, water, energy and fertiliser use (Smith et al., 2015b), as well as for biodiversity. However, liquid biofuels could play an important role in meeting climate targets for sectors where there are no alternative options, especially aviation.

Biogas has more beneficial impacts, depending on the source (providing that methane leakage is avoided). Household biogas from dung has taken off in China thanks to large scale subsidies, with large indoor AQ co-benefits from cook-stove replacement and (for biogas latrines) improved sanitation. However, there is a trade-off with the use of dung on fields for soil fertility and carbon sequestration (Lal, 2006).

Biochar offers the potential to sequester carbon as well as improving soil fertility, but production of feedstock is subject to the same constraints as solid biomass, and the climate impacts, co-benefits and trade-offs are still not definitively evaluated.

Non-forest ecosystem protection and restoration

Payment for ecosystem services (PES) has been used successfully to promote carbon sequestration as part of catchment restoration in the UK and USA. There is a potential to 'stack' payments for carbon sequestration and water quality, to achieve multiple benefits and facilitate greater uptake by farmers / landowners (Lankoski et al., 2015). In developing countries, there is a very significant potential to achieve multiple benefits for carbon sequestration, agriculture, biodiversity, ecosystem services and livelihoods by restoring degraded land, as with the large scale Loess Plateau restoration in China (Liu and Hiller, 2016).

Green Infrastructure (GI)

Benefits of urban GI (e.g. parks) for health and well-being are fairly well established in qualitative terms, although it is difficult to evaluate the benefits of individual schemes because of the difficulty in attributing any changes in physical activity or mental health in a local population to a specific green space improvement. GI offers multiple benefits for biodiversity and ecosystem services, including flood protection / stormwater management, microclimate regulation and (to some extent) air pollution removal, as well as social and economic benefits through making locations more attractive to residents, businesses and investors. There can be trade-offs, e.g. too much GI can lead to urban sprawl, which can increase GHG emissions from car travel. Also maintenance costs can be high (e.g. for tree pruning), though there can be benefits from converting parks from mown lawns to semi-natural areas. The new Green Infrastructure Innovation Programme funded by NERC is developing ways to assess and quantify some of these benefits and trade-offs.

Dietary change

Reduced consumption of animal produce (meat and dairy) can lead to large GHG and other social and environmental benefits (air and water quality from fertiliser use and methane emissions; land and water use; food security) and potentially very large health impacts from reduced intake of saturated fat (e.g. Scarborough et al., 2012; Milner et al., 2015), but these health benefits depend strongly on assumptions concerning the type of food substituted for animal produce. For example, econometric modelling by Briggs et al. (2013) predicted that a GHG tax on food in the UK could avert over 7000 deaths per year, due to reduced total calorie intake and reduced consumption of saturated fat, but a revenue-neutral tax that taxed high GHG foods while subsidising low GHG foods (including sugar) could increase calorie intake, increase obesity, and lead to over 2000 extra deaths per year. However, there is little information on how food consumption might change in the real world, or with supplementary policies to promote healthy, balanced diets (such as the recently announced UK sugar tax).

Although the potential health co-benefits of dietary change are linked to over-consumption of saturated fat in Western diets, this is also a growing problem in industrialising countries. There is emerging work in these regions, e.g. the Wellcome Trust funded work on low GHG diets in India (London School of Hygiene & Tropical Medicine, 2015).

The socio-economic impacts of dietary change could also be significant. For example, a GHG tax on food could have regressive effects in terms of food affordability, but could also have greater health benefits for lower income groups as they tend to suffer more from cardiovascular disease. There could also be adverse socio-economic and cultural side-effects for farming communities, which could possibly be reduced through appropriate re-investment of tax revenue (Briggs et al., 2013). Economic impacts on some sectors of the food industry could present political barriers to policy implementation. These effects are poorly studied.

Table 8 shows research gaps in the agriculture, forestry and land use sector. Those prioritised by the workshop delegates are shown in bold, with top priority being further research on the impacts of dietary change.

Table 8. Agriculture, Forestry and Land Use: potential research gaps

Mitigation action	Impact	Gaps/ future directions
REDD+ and other forest carbon payment schemes	Biodiversity	Further development of robust and cost-effective monitoring and verification systems for biodiversity assessment that can be widely applied in different contexts.
		Mapping forest carbon and biodiversity at finer scales, to include forest fragments, and targeting REDD+ at increasing connectivity.
	Socio-economic impacts	**Cost-effective monitoring arrangements for social safeguards to protect livelihoods, cultural value of forests and food security.**
	Ecosystem services	Integrated REDD+ assessments that take other ecosystem services (e.g. flood protection) into account as well as carbon and biodiversity.
		Better data on the value of forests for flood and erosion protection.
		Better quantitative data on air quality impacts of forests.
Non-forest ecosystems	**Biodiversity, cultural values, water security**	**Landscape approaches based on (Reducing Emissions from All Land Use): development of cost-effective MRV for co-impacts, and assessment of risks: e.g. would offering carbon finance for agriculture/ agroforestry lead to less value being placed on retaining natural forests?**
Soil carbon in agriculture; Agroforestry	Soil fertility, erosion, productivity / food security, water security, household financial benefits	Demonstration projects to overcome barriers: farmer uptake is greater when they can see successful schemes in nearby areas.
		Cost-effective MRV for soil carbon sequestration (strong interest in developing countries).
Reduced fertiliser use	Water and air quality; cost savings for farmers	Land sparing vs land sharing: balance between co-benefits and adverse side-effects for intensive agriculture vs low-input agriculture.
Payment for Ecosystem Services	Multiple benefits	Stacking of payments for multiple benefits, e.g. carbon sequestration and water quality.
Urban green infrastructure	**Multiple benefits for health, local economy, ecosystem services, biodiversity, social cohesion**	**Integrate the large evidence base on the multiple benefits of green infrastructure for health and wellbeing, ecosystem services and climate adaptation (e.g. flood protection, microclimate regulation) into a co-benefit framework.**
		Quantitative evidence of health benefits for specific interventions, e.g. a new or improved urban park.
Bioenergy	Biodiversity, food security, social	Criteria for sustainability of bioenergy production, and monitoring mechanisms.

Mitigation action	Impact	Gaps/ future directions
	impacts, flood management, soil fertility	Using woody bioenergy crops to restore degraded land.
Biogas from animal waste	Soil fertility, food security	Potential trade-offs between the use of biomass for energy (e.g. dung in domestic biogas plants) and its retention for soil fertility, food security and soil carbon sequestration. Potential for wider use of digestate as a soil improver to address these trade-offs.
Biochar	Soil fertility, food security / productivity	Evaluate effectiveness and environmental and social impacts.
Dietary change	**Health impacts of eating less meat**	**Potentially very large benefits but further work needed to clarify health impacts of eating less animal produce, which depend heavily on the foods substituted for meat.**

5 Cross-cutting themes and issues

In this section, themes and issues that cut across all sectors are discussed, starting with issues relating to the four main impact categories: economic, health, social capital and natural capital. The need for further development of the evidence base (methods, data and models) is then considered. Finally barriers to achieving co-benefits in practice are identified, together with potential options for overcoming these barriers. Research gaps related to these issues are summarised in Table 9.

5.1 Economy and employment

There is a substantial evidence base on the net **economic benefits** of climate change mitigation, well summarised by recent reports including the New Climate Economy (GCEC, 2014), IMF (Parry et al., 2014) and LSE (Green, 2015), as well as Stern (2015). These reports summarise the monetary value of a range of co-benefits including air quality, transport congestion, energy cost savings and energy security, with the New Climate Economy report incorporating co-benefit values into the Marginal Abatement Cost curve. For many mitigation options, the benefits outweigh the cost of climate change mitigation (depending on the discount rate chosen).

General equilibrium models tend to model climate change mitigation action as a carbon tax, which inevitably leads to a prediction of reduced economic growth rates. However, recent studies have argued that most models underestimate the benefits and over-estimate the costs of a low carbon transition (Mercure et al., 2013, Stern, 2013). An alternative approach using an econometric model of consumer behaviour instead of a general equilibrium model found that the small increase in costs of the energy system needed to meet UK climate targets would be outweighed by the benefits of economic restructuring, leading to reduced energy import costs and a net increase in employment and GDP (Pollitt et al., 2014).

The UNEP Green Economy report takes into account a wider range of costs and benefits, and predicts only a short term decline in growth rates followed by **stronger growth in the long term** (UNEP, 2011). If carbon tax revenues are recycled to reduce other taxes (e.g. taxes on labour and capital) there can be expansionary effects on the economy, especially if the tax starts low and increases gradually, thus sending a signal to shift investment to a low carbon pathway; only a small increase in BAU investment costs is required. However, there will be considerable restructuring which could lead to stranded assets in carbon-intensive sectors. There is qualitative and case-study based evidence that climate change mitigation has little effect on international competitiveness and that investment in low carbon technologies can stimulate growth and innovation (e.g. Dechezleprêtre and Sato, 2014; Rogge et al., 2015).

Net employment effects are less well studied, but most studies suggest that the net effect will be small, around +/- 1-2%, and is likely to be positive if carbon tax revenues are used to cut employment-related taxes, creating a 'double dividend' (GCEC, 2014; Blyth et al., 2015). However, structural changes will create winners and losers, and people in carbon-intensive sectors need support to retrain (ILO, 2010).

Energy security is a major driver for national governments, especially those heavily dependent on fuel imports, but this review found few quantified studies in the co-benefit literature (though see von Stechow et al., 2015, for a summary of studies in the wider climate policy literature). The new 24-indicator framework developed by Cox (2014) may help to improve quantification (see section 4.1). This could present an opportunity to demonstrate the significant co-benefits of climate action for energy security. An integrated approach to climate, air quality and energy security policy, rather than pursuing these goals separately, can offer significant synergies and cost savings (von Stechow et al., 2015).

The economic benefits of **resource efficiency** have been neglected, with a focus so far only on the benefits of energy savings. There is a considerable opportunity to achieve multiple co-benefits from a shift to a circular economy, including extending the life cycle of goods. Following on from this, behaviour change to reduce material consumption could be necessary to achieve the 1.5°C target, but the co-benefits of reduced material consumption are rarely discussed in the literature. In terms of emerging research: the Sustainable Consumption Institute at the University of Manchester is leading a programme of work to increase understanding of consumer behaviour relating to consumption; the Ellen MacArthur Foundation are leading work on the circular economy while the Centre for the Understanding of Sustainable Prosperity (led by the University of Surrey) is considering the economic, social, political and philosophical aspects of moving towards sustainable prosperity.

Reduced material consumption could have large environmental co-benefits but there could be adverse impacts on employment, economic growth and social equity, although a range of policy options could mitigate these impacts. This is an important topic for research within the economics community. Related emerging research includes work by Jackson and Victor (2015) which examines Piketty's hypothesis that declining growth rates can result in increased levels of inequality (Piketty, 2014). The outcomes suggest that inequality does not inevitably increase as growth is reduced, indeed there are situations where inequality is actually reduced or even eliminated (Jackson and Victor, 2015).

5.2 Health

Climate change mitigation actions can provide substantial health benefits. The best quantified of these are the benefits related to improved **outdoor air quality**. Many studies focus on reduced exposure to particulate matter (PM) and NOx, partly because these pollutants are generally believed to be the main causes of pollution-related health impacts, and partly because to account for all pollutants separately might lead to double counting of health impacts. However, other pollutants studied include ozone (and methane and NOx as ozone precursors), SO_2, CO, NH_3 and, rarely, trace pollutants such as mercury, other metals and PAHs.

Indoor air quality has attracted increasing focus over the last few years, especially in the context of replacement of traditional cook-stoves with cleaner fuels, thus avoiding black carbon emissions which are a major cause of respiratory, cardiac and eye problems in industrialising countries. In industrialised countries there has also been concern over increased indoor air pollution associated with draught-proofing homes, i.e. build-up of radon or cigarette smoke, but this can be mitigated through better ventilation. The physical and mental health benefits of well-insulated homes with efficient cooling and heating systems far outweighs these potential adverse impacts (Wilkinson et al., 2009).

Although the health impacts associated with air quality are substantial, even greater benefits could result from **increased physical activity** associated with active travel, or provision of green space for recreation. However these benefits are less well quantified: it is difficult to capture the increase in activity resulting from a specific intervention such as construction of a cycle path, without extensive (and expensive) local surveys before and after the intervention (though research is being undertaken on this, e.g. the I-Connect project). Similarly, there are potentially very large health benefits from reduced consumption of animal produce, but the health impacts of consuming animal produce are still disputed, and there is a lack of data on what foods would replace meat in a low GHG diet.

Further health benefits could arise from climate change mitigation actions with **benefits for water quality**, such as reduced consumption of resources (avoiding oil spills, toxic mining pollution, and pollution from factories), reduced fertiliser use, or reduced disposal to landfill sites. However, these impacts are rarely studied. There is also comparatively little research on the adverse side-effects for health arising from certain low carbon energy supply options, including potential impacts on water quality from fracking and nuclear waste disposal, and impacts on air quality (NO_x and NH_3) from CCS.

The **health sector** is becoming more engaged with climate issues, and there is a growing recognition of the potential role of health practitioners in raising awareness both of the health impacts of climate change itself, and of the potential for health co-benefits (Adlong & Dietsch, 2015), as well as exploring climate change mitigation measures within the health sector itself (e.g. energy and resource efficiency). At the workshop it was suggested that the health sector, as a major consumer of energy and resources with extensive supply chains, could be used as a testing ground for research on co-benefits, e.g. for waste reduction initiatives. There are already active groups such as the Centre for Sustainable Healthcare working on sustainability in healthcare and the potential for 'green prescriptions' to encourage more active lifestyles. These networks could be used to facilitate research around the evaluation of real-life interventions in the health sector, e.g. related to active travel and green infrastructure.

5.3 Social capital

In general, the focus of research to date has been mainly on environmental (health) and economic impacts. However, social impacts are now receiving more attention, especially through the recognition that the **distribution of costs and benefits** is important. Climate change mitigation offers the opportunity to improve social equity for disadvantaged and minority groups (e.g. Mayne, 2016), so research is emerging on who benefits and when, including gender, race and socio-economic groupings. There is a need to understand who are the winners and losers from different mitigation actions. This can enable co-benefits to be maximised, e.g. by targeting air quality improvements on the most polluted areas (e.g. Boyce and Pastor, 2012), or by targeting home energy efficiency measures on vulnerable groups (Lidell et al., 2016; Sovacool, 2015), and it can also help to tackle implementation barriers (see Section 5.6).

There is also growing evidence on the role of **community engagement** and empowerment in identifying and delivering social and environmental co-benefits and avoiding adverse side-effects, especially for REDD+ (e.g. see Latham et al., 2014, p. 54) but also in other sectors such as urban design and cook-stove replacement. This may help to overcome political and institutional barriers to realising co-benefits. There could be a role for research into what is needed to facilitate successful community engagement.

Effective monitoring and verification is key to achieving social (and environmental) co-benefits in practice (e.g. for REDD+), and this requires good governance and adequate institutional capacity, but it can also result in high transaction costs that can make projects uneconomic (see Section 4.6).

5.4 Natural capital

Natural capital provides **ecosystem services** of benefit to humans, including air and water quality regulation, flood and erosion protection, pollination and pest control, as well as providing freshwater, food, timber and medicines (if extracted sustainably), and aesthetic and cultural benefits. **Nature-based solutions** are increasingly used for climate adaptation, e.g. coastal mangrove forests for storm surge protection, and urban green space for cooling and stormwater management. Increased woodland and forest cover in catchments upstream of urban areas could play an important role in flood protection, but this is poorly quantified. Biodiverse and healthy ecosystems are more resilient to future environmental change, ensuring that these services can be maintained into the future.

REDD+, sustainable agriculture and provision of **urban green infrastructure** all have obvious potential co-benefits for protecting and restoring ecosystems, although in the case of REDD+ these impacts are strongly dependent on the exact nature of the project. The potential adverse impacts of **bio-energy** production on natural capital are also well studied, although more research is still needed to establish the limits of sustainable production in the light of a growing reliance on BECCS as a negative emission technology, and to explore the circumstances in which bioenergy production could provide benefits for biodiversity.

The impacts of non-land use climate mitigation actions on natural capital are often neglected. Important co-benefits could arise from increased resource efficiency, due to the avoided need for raw material extraction and processing, leading to avoided habitat loss and improved soil and water quality. Similarly, measures to reduce transport demand could have significant benefits if they reduce the need for new road infrastructure, protecting crucial connectivity of wildlife habitats. However, mitigation actions that increase the demand for fossil fuel extraction (e.g. CCS or fracking) could have adverse impacts on air and water quality and habitats. Better assessment of these impacts is important in order to protect the long term health and resilience of ecosystems, so that they can continue to deliver essential services to humans into the future.

5.5 Extending the evidence base: methods, data and models

Certain co-benefits are now well established, especially the air quality benefits of reduced fossil fuel combustion and the health benefits associated with active travel and warmer homes. However, there is still a need to evaluate the impacts of a wider range of real world interventions (e.g. housing retrofitting or active travel infrastructure) in order to demonstrate co-benefits more convincingly in a range of different contexts. Compilation of case studies from around the world would also help to demonstrate these benefits; there are ongoing initiatives that could be harnessed as part of this (e.g. from the Asian Co-benefits partnership and C40 Cities network). For other impacts, such as the health benefits of dietary change, the evidence is less clear and further research is needed.

A range of tools and models are currently used to assess co-benefits and adverse side-effects: some of these are listed in Appendix B. These range from complex Integrated Assessment Models (IAMs) to a variety of simpler local or sectoral tools.

IAMs were originally developed to assess climate change impacts on GDP but many have been extended to include air quality and other co-impacts. In theory, they can be joined with other sectoral models to evaluate complex synergies and trade-offs between co-benefits and adverse side-effects, e.g. water-energy-food nexus research, although this is challenging in practice as models in different sectors may not be compatible.

IAMs are also limited by their focus on the economic perspective (GDP), which restricts their ability to capture wider impacts, e.g. energy security and social inclusion goals. As they model complex economic and natural systems, they are also highly dependent on a number of poorly known parameters. Schwanitz et al. (2015) analysed co-benefits using 11 integrated assessment models: four inter-temporal general equilibrium models (MESSAGE, MERGE-ETL, REMIND, and WITCH), three computational general equilibrium models (GEM-E3, IMACLIM, and WorldScan), and four partial equilibrium models (DNE21+, IMAGE, GCAM, and POLES), and finds that the spread of results across models is larger than across climate policy scenarios, suggesting that a multi-model analysis is necessary to identify robust results given the large uncertainties involved. However Pindyck (2015) goes further, suggesting that the uncertainty over key parameters means that IAMs are unsuitable for climate policy decisions and that simpler, expert-based, decision making processes should be used. This is part of a wider debate about whether (and the extent to which) certain impacts can be appropriately quantified (as discussed in section 3.3).

Although models can, in theory, be extended to capture a wider range of sectors, impacts and regions, in practice this entails the introduction of simplifying assumptions, so there is a trade-off between coverage and accuracy. There is therefore a role both for integrated models that can address a small number of co-impacts for multiple sectors and regions, and models that can focus in more detail on a single sector or region (von Stechow et al., 2015).

The data requirements, complexity and time demands of IAMs results in the need for smaller scale, more locally based models. These local models can also potentially capture broader benefits more easily and may be more appropriate engagement tools at, for example, the city level. There is a need to review the current availability of these tools and planned developments. Key resources and initiatives include the UNU-IAS Co-Benefits Evaluation tools (simple spreadsheet tools on transport, energy and waste aimed at city policymakers), the broadening of the WHO HEAT tool for assessing active travel co-benefits, the CD-Links project (quantifying the links between climate and development policies); the EU COMBI project, which is developing a graphical online tool to visualise the multiple impacts of energy efficiency; work in Sweden to develop a tool to enable businesses to quantify multiple benefits of energy efficiency[5], and work by the Asian Co-benefits Partnership to develop simpler assessment tools for policy makers in Asia (IGES, 2011). In the UK, there is a need for a health co-benefit assessment methodology which can be applied at the national level in a range of settings.

Much of the modelling literature focuses on scenarios consistent with limiting global temperature rise to 2^{o}C above pre-industrial levels. Following the Paris COP, there is a need to also address the implications of other targets including the 1.5^{o}C target and the associated long-term requirement for net zero emissions. This could build on emerging research that explores the impact of different emission pathways and timing of emission reductions on co-impacts (e.g. von Stechow et al. 2016 considers the impact of different mitigation pathways on the Sustainable Development Goals).

Finally, there is a very wide range of potentially relevant research outside the co-benefit literature, e.g. covering material efficiency, waste management, water security, sustainable buildings and international development. It would be useful to integrate some of this research within a co-benefit framework, e.g. to assess the potential role of material efficiency (alongside energy efficiency) in reducing greenhouse gas emissions, and quantify the co-benefits this would provide for air and water quality, resource security and productivity, building on work within the COMBI project (Teubler et al., 2015).

[5] Personal communication from Maja Dahlgren, Swedish Energy Agency and Linköping University

5.6 Barriers to achieving co-benefits

Although there is a growing evidence base on the potential to achieve co-benefits from climate mitigation, with many well-established win-win options, many barriers exist to achieving these benefits in practice. These include:

- Institutional barriers:
  - Government departments do not co-ordinate their goals and activities, either between policy areas (transport, energy, climate, environment, planning) or between levels (national, regional, local). For example, Bache et al. (2014) finds a failure to translate the headline UK target of an 80% cut in CO_2 emissions by 2050 into binding targets for each sector, or to provide specific targets, policy levers and resources at the local level.
  - Time and budget pressures lead to lack of co-ordination or abandonment of initiatives.
  - Standard project assessment techniques (e.g. cost-benefit analysis) do not take co-benefits into account.
- Political leadership
  - Lack of political commitment at the top level, or change of leader leads to abandonment or disruption of policies.
  - Political agenda dominated by short term economic growth imperative, to fit in with election cycles of 4-5 years.
  - Difficulty in working across national, regional and local levels, especially if leaders are from different political parties.
- Carbon lock in
  - Senior leaders become locked in to 'business as usual' policies.
  - Lobbying by vested interests in high-carbon sectors (Green, 2015).
  - Closed policy communities at the local level, dominated by those who prioritise economic growth above other goals, and excluding or suppressing those who support environmental goals (Bache et al., 2014).
- Public acceptability
  - Lack of acceptance for certain technologies, related to adverse side-effects (e.g. nuclear, wind, fracking, CCS, biofuels, REDD+) or to actual or perceived high investment costs.

Some of these barriers are related to the distribution of costs and benefits over time, between individuals and organisations, and geographically. For example, industry often carries the cost of mitigation actions, while wider communities reap the benefits. Conversely it is often true that the public bear the health costs and industry does not pay the full economic costs, for example of air pollution. Similarly, mitigation actions in one area may produce co-impacts in distant regions. There can also be time lags, with some mitigation investments (such as agro-forestry) only realising profits in the longer term. Information on who are the winners and losers is needed to present credible evidence for decision-making, and to tackle barriers related to lobbying by vested interest groups, or low public acceptance of certain policies or technologies. Identifying win-lose options, quantifying the impacts (and mitigating the adverse impacts) is thus important from a political point of view: better understanding of the consequences of a decision for different groups of stakeholders reduces the risk of unanticipated political impacts.

There is a need to raise awareness of co-benefits amongst the public and policymakers through dissemination of success stories, case studies and best practice, to create a positive vision of the potential benefits of a low-carbon world. Better communication of existing robust evidence is important (e.g. disseminating the findings of the New Climate Economy report), to dispel the widely held perception that climate action will have a negative impact on the economy.

To improve communication there is a need to understand the relevant decision-makers (usually non-experts, e.g. policymakers, business leaders or financial controllers) and what information they need to be able to make the right decisions. Attention should be paid to framing the information to highlight co-impacts relevant to the decision-maker, and recognising the need to inform both short term decisions and long term change. Communication should use simple, non-scientific terminology so that results can be readily understood by non-experts, and may need to be translated into different languages to reach an international audience.

Better communication of co-benefits can help to show other government departments that climate action can help them to meet their targets, e.g. for health, economy, energy security etc. For example, better understanding of co-benefits for productivity (e.g. through reduced congestion or increased industrial efficiency), innovation and competitiveness could help to engage key decision-makers in ministries of finance, energy and industry. The Stern Report received widespread attention by demonstrating the financial impacts of climate change, thus targeting the economics / business community. There will therefore be a need to evaluate co-benefits in monetary terms as far as possible, in order to reach these key policymakers, but it is important that impacts that cannot be monetised are not neglected. This means better ways of presenting both qualitative and quantitative measures to decision-makers are required, e.g. using simple visualisation tools that allow quantitative estimates to be ranked alongside qualitative estimates. Economic analysis should use a clear, comprehensive framework that covers a wide range of co-impacts, and should clearly identify impacts that cannot be monetised.

In summary, potential options for overcoming these barriers are listed below.

- **Targeted interdisciplinary research on winners, losers and barriers**, bringing in the social science, political science and behavioural research communities.
- **Role for a cross-cutting governmental group**, drawn from different departments plus some independent co-benefit experts, to facilitate dialogue and co-ordination between different departments.
- **Co-ordination between national and local policies,** with translation of headline targets into local and sectoral targets, specific attention to local policy levers, and greater interaction between national level policymakers and those involved in local implementation (see Bache et al., 2014).
- **Community participation** can help to ensure that opportunities to achieve wider social and environmental benefits are taken into account and potential adverse impacts are avoided in climate change mitigation strategies. This also contributes to the long term success of projects by increasing uptake (e.g. for active travel and cook-stoves) and local support (e.g. for forest carbon and urban design).
- **Raise awareness of co-benefits** and adverse side-effects amongst policy makers and the public, e.g. via success stories or robust evaluation of potential benefits.
- **Target communication at key policymakers** for example by emphasising the economic, financial, employment and productivity benefits to policymakers in finance and business.
- **Create more opportunities for dialogue** between policymakers and proponents of high co-benefit options, to counterbalance undue influence by those defending business-as-usual options that fail to achieve co-benefits or create adverse impacts.
- **Develop tools and indicators** for holistic assessment of climate and non-climate policies that take into account all co-benefits and adverse side-effects, so that co-impacts can be integrated into standard policy and project appraisal procedures, and into multi-criteria analysis frameworks for decision-makers. Indicators could be linked to the Sustainable Development Goals (SDGs), which

include some indicators relevant to co-benefits including well-being[6] and clean energy access[7] (Short lived climate pollutants (black carbon, methane and ozone) should be included.

5.7 Research gaps

Table 9 shows potential research gaps regarding cross-cutting themes and issues. Of these, the workshop delegates attached the highest priority to the inclusion of a wider range of co-benefits and adverse side-effects in economic models.

Table 9. Cross-cutting themes and issues: potential research gaps

	THEME	Gaps/ future directions
Extending the evidence base: methods, data and models	**Range of mitigation targets**	Co-benefits and adverse side-effects of mitigation actions that will be needed to limit global warming to a range of levels from 1.5 to 3ºC: e.g. co-benefits could increase for a 1.5ºC target but more technologies with adverse side-effects may be needed.
	Data	Extend and improve available datasets for estimating the magnitude of co-benefits and side-effects. Where are the greatest data gaps?
	Tools and Indicators	**What tools and indicators are available to enable policymakers to assess a wide range of co-benefits and adverse side-effects, and what further development is needed?**
	Economic models	**Inclusion of a wider range of co-benefits and adverse side-effects in economic models, alongside mitigation costs. What existing work is taking place, what further development is required?**
	Real life data and case studies	Real-life data from case studies of successful climate change mitigation actions that achieve co-benefits, and dissemination of case studies, best practice and success stories.
	Systems analysis	Use of systems analysis to explore complex synergies and trade-offs, e.g. water-energy-food nexus.
	Valuation	**Explore and test methods for combining quantitative and qualitative valuation approaches, to allow consideration of impacts that are hard to quantify**.
	Sectors	More in-depth studies of co-impacts related to the industry, non-residential buildings and waste management sectors.
Social capital	**Participatory approaches**	Use of participatory stakeholder approaches (MCA-based) to explore trade-offs between different impacts that cannot easily be monetised.
	Community engagement	How can community engagement be used to identify opportunities for local co-benefits, and ensure that adverse side-effects are avoided or mitigated?
	Distributional impacts	**Where are the impacts, and who is affected? How can we maximise the benefits, e.g. by targeting AQ improvements on the most polluted areas; aiming active travel at congested areas; and reaching people who could benefit most from dietary change?**
	Behaviour change	**How can behaviour change towards low-carbon lifestyles with multiple co-benefits be encouraged, and how can transient improvements after interventions be 'locked-in'? How can diffusion of sustainable behaviour be accelerated?**
Economic	**Consumption**	What are the social and economic implications of reduced material consumption?
	The rebound effect	What are the trade-offs between the economic, social and environmental benefits of resource efficiency measures, and do they matter? What policy options can lock in or magnify the benefits (e.g. by encouraging cost savings to be spent sustainably)?
Barriers	**Barriers to implementation**	Explore methodological, institutional and political barriers to integrating climate and non-climate policies, and means of overcoming these.
		Gaps between research and government awareness: how can valuation of co-benefits be included in impact assessments and appraisals? Are there barriers to appreciating the scale of costs, e.g. the large health benefits are often not accounted for in the same way as costs?
Other		Dynamic effects of changing innovation, costs and benefits over time.

[6] Sustainable Development Goal 3 – Ensure healthy lives and promote well-being for all at all ages

[7] Sustainable Development Goal 7 – Ensure Access to affordable, reliable, sustainable and modern energy for all

6 The international context: sustainable development

Increased international co-operation will be essential to limit global warming to well below 2 °C above pre-industrial levels, and this will involve engaging with countries that have different motives and capacities for climate action. For many emerging economies and low income countries[8], the priorities are climate adaptation, economic development and poverty reduction, rather than climate change mitigation. However, there are significant opportunities for international climate finance to be directed towards actions that achieve multiple benefits for mitigation, adaptation and development, while tackling urgent local problems related to air pollution, energy security and fuel import costs, waste management, transport and food security. For example, Day et al. (2015) used a simple estimation approach to indicate that the INDCs of China, India, South Africa and Chile could avoid thousands of premature deaths from air pollution and save billions of dollars in energy imports by 2030, and that these benefits could increase substantially if those countries move towards 100% renewable energy supply in line with the level of ambition needed to reach a 1.5°C target.

To achieve these multiple benefits, and to avoid adverse side-effects, it would be useful to develop tools and indicators that enable co-impacts to be explicitly incorporated into the criteria for climate finance mechanisms such as the International Climate Fund, including promising but neglected options such as soil carbon sequestration and low-carbon urban design. This could build on the framework developed for the SD Tool, a 'tick-box' style online reporting aid to enable CDM projects to report co-benefits,[9] and ongoing work by UNEP to develop a tool for assessing the sustainable development impacts of NAMAs (Nationally Appropriate Mitigation Actions) (Olsen et al., 2015). There is an opportunity for countries that are not yet locked in to high carbon infrastructure to become centres of low carbon learning for the rest of the world; appropriate use of climate finance and targeted engagement could support this.

The MAPS Programme (Mitigation Action Plans and Scenarios)[10] is an important developing country initiative to explore links between mitigation and development. It uses participatory stakeholder approaches to define realistic mitigation scenarios, which feed into general equilibrium models (linked to bottom-up sector models) that examine the social and economic impacts of mitigation policy. MAPS originated with the Energy Research Centre in South Africa, and projects have been run in Peru, Brazil, Colombia and Chile, with plans to extend to a number of African countries (Cohen et al., 2015). Parallel activities are taking place in India, including development of a multi-criteria analysis approach for developing mitigation policy with co-benefits (e.g. Dubash et al., 2013). Rennkamp and Boulle (2015) found that practitioners trying to conduct co-benefit assessments in developing countries needed hands-on support from international researchers familiar with the methodology, and that academic researchers could also benefit from closer links with those trying to apply the co-benefit concept in practice. The CD-Links project (www.cd-links.org), which started in 2015, also aims to assess the synergies between mitigation and development.

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[8] Research in emerging economies including China, India, Indonesia, Brazil and South Africa can be funded via ODA's Newton Fund, whereas low income countries receive funding from DFID.

[9] For examples of reports generated with the SD Tool see http://cdmcobenefits.unfccc.int/Pages/SD-Reports.aspx

[10] There is an extensive list of relevant publications, only some of which have been included in our database, at http://www.mapsprogramme.org/category/publications/papers/.

6.1 China

China's INDC submission states a commitment to reducing GHGs, and sees this as an opportunity to progress to a green, low-carbon, resource-efficient development pathway, leading to 'multiple wins in terms of economic development, social progress and combating climate change'. The co-benefits of climate mitigation are therefore implicitly recognised, though not explicitly mentioned. The submission presents ambitious targets for energy efficiency and low-carbon energy in 2030 as well as commitments to optimised urban design, public transport and active travel infrastructure, 50% green buildings in new development, and a shift towards a circular economy, including extending the life span of buildings. There are comprehensive land use mitigation and adaptation plans including afforestation, partly to combat desertification and protect from disasters, as well as restoration of wetlands and grasslands, and zero growth in fertiliser and pesticide use by 2030. There is also a focus on lifestyles, with a commitment to 'advocate moderate consumption, encourage the use of low-carbon products and curb extravagance and waste'.

There is a very large evidence base focusing on the power (26 papers), industry (23), buildings (19) and transport (14) sectors, with only 6 papers on AFOLU and one on waste. Of the 54 papers reviewed, 45 focus on air quality co-benefits, driven by the severe pollution in Chinese cities. This literature is more often framed in terms of air quality as a climate mitigation co-benefit (35 papers), rather than the other way around (14 papers). Indoor air quality associated with cookstoves is also a major concern, and has led to a successful rural biogas stove programme. Most of the evidence base (43 papers) is classed as strong quantitative evidence, being mainly modelling studies, and there is consensus that air quality benefits can substantially offset the cost of climate mitigation in China. The Climate Cost study estimated that reduced fine particle pollution could increase life expectancy by 19 months in China by 2050 under a global mitigation scenario designed meet a 2ºC target, and ozone related mortality could fall by 22,000 cases per year. As well as human health, there is evidence of significant benefits from reduced ozone damage to crops. For example, Aunan et al. (2007) found that China can reduce GHG emissions by 17% with no welfare loss, because of the benefits of PM and NOx reduction for health and crop yields. However, Bollen et al. (2009) found that if AQ is the only concern, local air pollution control policies appear to be typically cheaper than indirect action via climate mitigation.

Energy security was mentioned by seven papers and energy savings by three, perhaps reflecting that these might not be major concerns in China at present, with its large coal reserves and rapid deployment of nuclear and renewable energy. Only four papers mentioned employment and five mentioned social equity or sustainable development. Dai et al. (2016) predicted that large scale renewable energy development could have major economic benefits for China, creating 4 million jobs and $1 trillion of benefits for other economic sectors by 2050.

Hardly any of the papers reviewed mentioned other types of co-benefit. Only one or two mentioned biodiversity, soil erosion, food security or flood protection, although there is a large evidence base in the ecosystem services literature on the use of vegetation to combat erosion, flooding and desertification (e.g. on the massive 'Grain for green' programme to plant trees on steep erosion-prone slopes, and on the impressive restoration of the Loess Plateau documented in Liu and Hiller 2016). There might be scope to bring these 'missing' ecosystem-related co-benefits into the climate mitigation framework.

Only four papers mentioned adverse side-effects, including the financial impact of a carbon tax, the water security impacts of biofuels and nuclear energy, and the impact of household biogas on agricultural production (less use of dung as a fertiliser).

6.2 India

India has adopted a 'co-benefit approach' defined as being to 'promote our development objectives while also yielding co-benefits for addressing climate change effectively' (Dubash et al., 2013; Doll et al., 2015). India's INDC submission does not refer explicitly to co-benefits but stresses the country's main goals of poverty reduction and sustainable development, including access to clean energy, as well as the urgent need to adapt to climate change in view of the vulnerability of both urban and rural populations (and livestock) to floods, droughts and temperature instability. The INDC lists a comprehensive range of existing actions including improving energy efficiency, uptake of nuclear and renewable energy, enhancing forest cover, promoting agroforestry and implementing sustainable waste management, and puts forward ambitious targets to scale up these activities provided that international funding is made available. There is also a focus on equity, lifestyles and consumption behaviour, with an expectation that developed countries will reduce their consumption levels in order to create 'development space' to allow developing countries to grow. India also commits to 'put forward and further propagate a healthy and sustainable way of living based on traditions and values of conservation and moderation.'

Papers reviewed (41) covered a range of sectors including transport (19 papers), power (16), buildings (13), AFOLU (9), industry (6) and waste management (4). The strong interest in the transport sector may reflect the fact that transport energy demand is predicted to grow from 1.5 EJ in 2005 to 13.3 EJ in 2050 and 30.9 EJ in 2090 as a result of rapid urbanisation, and the share of air travel could grow from 10% of total travel (vkm) in 2005 to 30% in 2050 (Chaturvedi and Shukla, 2014). Energy security is a major concern, with these authors predicting that import dependency will grow from over 70 % in 2015 to almost 90 % in 2035 for oil requirements, from 24 % to 61 % for coal and from almost zero to 46 % for gas, causing the fuel import bill to increase by a factor of 2.5, from US$ 110 Bn in 2015 to US$ 290 Bn in 2035 (2010 prices). However, energy efficiency together with a carbon tax could cut the import bill by US$ 33 Bn in 2035, mainly through reduced oil imports.

Both indoor and outdoor air quality are major issues: Delhi, Patna, Gwalior and Raipur are the most polluted cities in the world, and 33 other Indian cities appear in the list of the 100 most polluted cities ranked by $PM_{2.5}$ concentrations (Dhar and Shukla, 2015). Over 700 million people lack access to clean cooking fuels, and use of traditional biomass causes one million deaths annually (Cohen et al., 2015). Inefficient use of traditional biomass means that the buildings sector consumed almost half of the total final energy in 2005 (Chaturvedi and Shukla, 2014). However, only three of the 41 papers reviewed on India explicitly addressed cookstoves (although many of the 22 papers mentioning cookstoves had a global focus). This may reflect an expectation that traditional biomass will be displaced by cleaner fuels as incomes grow, without the need for specific air quality or climate measures (Chaturvedi and Shukla, 2014).

Indian and South African researchers are working on the use of stakeholder-led MCDA to take co-benefits into account in decisions on climate and energy policy, with the advantage that both quantitative and qualitative indicators can be compared (Cohen et al., 2015; Rennkamp and Boulle, 2015; Dubash et al., 2013; Khosla et al., 2015). However, there is scope to improve modelling of co-benefits in India. Dubash et al. (2015) review seven recent (2013 or later) energy and climate modelling studies for India and find that assessment of co-benefits such as air, land and water quality is at an early stage: only two of the studies consider local environmental impacts, and they are not presented in the model outcomes.

6.3 Indonesia

Similarly to India, the INDC submission stresses the need for poverty reduction and adaptation, with reference to the SDGs. Deforestation is the major issue: 63% of GHG emissions are due to land use change and forest fires, with only 19% being from fossil fuels. Mitigation focuses on forest protection and a ban on peatland conversion, with an emphasis on stakeholder participation (including indigenous communities, vulnerable groups and women) and landscape-level planning. Indonesia is highly vulnerable to climate impacts including floods, droughts, landslides and sea-level rise, and the submission stresses the need for adaptation and ecosystem restoration to protect food, water and energy security. There is a focus on capacity building for climate adaptation. Targets for increased renewable energy use and sustainable waste management are mentioned briefly.

Only 16 papers were found that referred explicitly to Indonesia, although a number of the papers referring to developing countries in general are also relevant (mainly on the topic of REDD+). Ten of these papers focused on forests and land use, with two covering the transport sector, one each on power and waste, one addressing industry, transport, buildings and waste (Puppim de Oliveira, 2013), and one categorised as no specific sector (the IMF study of nationally beneficial carbon pricing by Parry et al., 2014). This low number of papers, especially outside land use, represents a major research gap considering that Indonesia is the fourth most populous country in the world. Transport is a particular problem: demand in cities is growing rapidly yet public transport, walking and cycling face major barriers due to urban sprawl and lack of infrastructure (Permana, 2015; Dirgahayani, 2013).

The papers on forest carbon illustrate the complexity of this sector, with Cacho et al. (2014) and Tata et al. (2014) finding that there are trade-offs between forest protection and local livelihoods, as farming or oil palm cultivation can provide more jobs and higher incomes than REDD+. Beaudrot et al. (2015) and Murray et al. (2015) find that prioritizing carbon storage alone will not necessarily meet biodiversity conservation goals. Thuy et al. (2014) find that more information is needed on synergies between the role of forests for mitigation and adaptation.

6.4 Brazil

In Brazil, and elsewhere in Latin America, GHG emissions from land use change exceed those from fossil fuels. The INDC submission notes the need to reduce poverty and improve housing and sanitation, and proposes a strategy based around forest protection, restoration, sustainable agriculture and a large increase in bioenergy and other renewable energy, as well as energy efficiency in industry and transport.

The INDC was informed by the IES-Brasil initiative[11] which was established in 2013, in collaboration with the MAPS programme. This is exploring how to create climate change mitigation policies that will maximise social and economic development. A participatory process involving the government, the private sector, academia and civil society is being used to create mitigation scenarios up to 2050, as input to a general equilibrium model, IMACLIM-Brasil. Unusually, this model goes beyond an analysis of macroeconomic impacts to encompass social issues such as poverty and income distribution (Cohen et al., 2015; Rennkamp and Boulle, 2015).

Of the 18 papers reviewed for Brazil, 13 focus on land use, including REDD+ and other tools to reduce deforestation, which is driven by conversion of forest to agricultural use, illegal deforestation, subsistence farmers and infrastructure development. One or two deal with non-forest ecosystems: wetlands (which cover 20% of Brazil) and restoration of degraded pasture. Five papers deal with transport, and only one or two with other sectors.

[11] http://www.mapsprogramme.org/category/projects/brazil-projects/

6.5 South Africa

South Africa's priorities as set out in its INDC submission are poverty reduction, equality, sustainable development and energy security. It is heavily dependent on coal, both for power and for liquid fuels. The INDC envisages increased investment in renewable energy projects, stating that 'Current analysis of investments in renewable energy projects shows that these have a positive impact on the economy'. Other measures include CCS for coal plants, hybrid and electric vehicles, energy efficiency and land restoration. South Africa is working closely with India, Brazil and other countries as part of the MAPS programme, discussed above, which grew from a national initiative to develop stakeholder-driven modelling scenarios.

The review only identified eight papers that covered South Africa. These included one paper each for power, buildings, industry and land use (the potential for REDD+), with the rest being multiple sectors. Given the large potential for co-benefits in South Africa, for example from a shift to renewable energy to solve energy access and sustainable development problems, this represents a sizeable research gap.

6.6 Middle East

No evidence was found for countries in the Middle East in the co-benefit literature, even though a separate search was conducted by an Arabic speaker, except that Saudi Arabia is covered in the IMF carbon price modelling study (Parry et al., 2014). However, it is notable that the INDC of Saudi Arabia states in the second paragraph:

> *'The Kingdom will engage in actions and plans in pursuit of economic diversification that have co-benefits in the form of greenhouse gas (GHG) emission avoidances and adaptation to the impacts of climate change, as well as reducing the impacts of response measures. This will help the Kingdom to achieve its sustainable development objectives.'*

Thus it seems that the primary focus of Saudi Arabia, in common with other countries, is on development and adaptation, including diversification away from a dependence on oil exports, and GHG mitigation is viewed as a co-benefit that might arise from these activities. Vulnerability to climate change is recognised, especially through water scarcity, heat waves, sandstorms and sea-level rise which threatens infrastructure sited on the coastal strip. However, the relatively small GHG reduction below BAU promised in the INDC is dependent on a '*robust contribution of oil revenues to the national economy',* with a promise that this oil revenue will be invested in high-technology sectors, including renewable energy, energy efficiency and CCS. The alternative, should export revenues decline, is presented as domestic use of oil and gas in heavy industry, which would increase national GHG emissions further.

The INDC also presents a range of adaptation activities that have mitigation co-benefits, including planting of coastal mangrove forests for storm surge protection, use of 'green barriers' to control encroachment of sand dunes, restoration of degraded ecosystems with benefits for soil fertility, wildlife and livestock, and restoration of coral reefs, which has benefits for tourism and 'blue carbon'.

6.7 Africa and other continents/countries

In various countries in Africa and South America there have been many studies of REDD+, most of which flag the potential for both positive and negative impacts for biodiversity and local communities, and the importance of effective safeguards.

For Africa, where degraded soils and drought threaten food security, there are many studies on the potential of sustainable agriculture (sometimes termed 'climate-smart agriculture') to provide multiple benefits for adaptation, mitigation and development. This includes studies on the potential for incorporating more organic matter into the soil (e.g. through addition of compost, manure, crop residue or cover crops) to enhance soil carbon sequestration and reduce the need for inorganic fertilisers at the same time as increasing soil fertility and water storage capacity. Agro-forestry can also enhance soil fertility (especially if leguminous trees are planted in strips within crops), as well as protecting against soil erosion and potentially providing an additional source of food, fodder or fuelwood.

Studies on improved cookstoves are common across Africa, Latin America and Asia, showing large co-benefits for health from improved indoor air quality. There are also a number of studies on the benefits of local renewable energy technologies, including solar lighting, for improved energy access and associated socio-economic benefits.

6.8 Research gaps

A key recommendation is to work directly with selected international partners, perhaps through case studies at the city level, to identify and promote uptake of climate change mitigation options with multiple co-benefits for development and adaptation, including developing appraisal tools and exploring options for targeting climate finance on mitigation actions with maximum co-benefits.

Table 10. International engagement: potential research gaps

THEME	Gaps/ future directions
Oil-exporting regions	How can the economic and social co-benefits of climate change mitigation be maximised and adverse side-effects minimised in oil-exporting regions?
Countries	**How to engage with countries such as South Africa, Brazil, Indonesia, Saudi Arabia where little co-benefit literature has been identified so far. Is this a case of limited literature or difficulties in access?**
Sustainable development	**How can consideration of adaptation and development co-benefits be incorporated into climate finance mechanisms?**
	How can institutional capacity be built to enable measuring, reporting and verification of these co-benefits without excessive transaction costs?
Urban design	**How can sustainable urban design with multiple co-benefits be encouraged? What tools and indicators do planners need? What regulatory frameworks are needed?**

7 Research capability

This section identifies existing research capability in the UK and overseas. It identifies centres of expertise based on the outcomes of the literature review and call for evidence, and identifies existing networks that could be used to facilitate future research on co-benefits. The need for both improved datasets and more real life case studies emerged as key themes in this scoping study, so existing capabilities in these areas are also considered.

7.1 Centres of expertise

International centres of expertise for research on co-benefits are listed in Appendix B.

Examples of some centres of expertise for particular research areas that have emerged from our literature review and call for evidence are listed below, for the UK and internationally. These lists are not exhaustive — they indicate some examples of where publications on certain topics clustered around particular institutions, but it needs to be recognised that there will be other important centres not listed here, as well as individual significant researchers and important papers published elsewhere.

Air quality: As air quality is the most widely studied co-benefit, many centres of expertise exist. IIASA in Austria probably ranks as the main global centre of expertise on co-benefits in general, with studies dating from around 2009, mainly using the GAINS and MESSAGE models for assessing the air quality and energy security impacts of climate change mitigation policy. IIASA also produced the Global Energy Assessment, as well as working on the ClimateCost modelling study of global AQ co-benefits. Tsinghua University and Fudan University have conducted many studies in China, including studies of specific industrial sectors (iron and steel, cement and ammonia; see Ma et al., 2015; Ma and Chen, 2015; Tan et al., 2015); and buildings (e.g. Jiang et al., 2013). The Centre for Policy Research in India works on modelling of energy security an air quality co-benefits, and the National Institute for Environmental Studies of Japan (NIES) conducts studies in other Asian countries including China, India and Thailand, as well as Japan (e.g. Mittal et al., 2015; Dong et al., 2015; Ma et al., 2013). CICERO in Norway also works on air quality issues in China. Other international centres include the University of California (Berkeley).

Centres of expertise in the UK include King's College London, Imperial College London, University of East Anglia, University of Leeds and the Met Office (Met Office, 2015). The Cambridge Centre for Climate Change Mitigation Research (C4MR) has carried out studies of the AQ benefits of low carbon transport in developing countries such as Thailand and Mexico[12]. The Universities of Surrey and Cambridge and Imperial College London are working on the EPSRC-funded MAGIC project (Managing Air for Green Inner Cities), which is using advanced fluid dynamics and energy analysis to reduce energy use and improve air quality.

Economic co-benefits: This is a well-developed research field, with international research by Resources for the Future in the US[13] and the Basque Centre for Climate Change[14], among others. The UK holds a strong position in international research on policy linking the environment and the economy, with well-known examples such as the Stern Review (Stern, 2006)[15] and other research performed by the London School of Economic and Political Science (LSE), including modelling of green growth and green jobs at the Grantham Research Institute (e.g. Bowen and Kuralbayeva, 2015), and the work of the LSE Cities research centre. Much relevant work is being undertaken under the auspices of the ESRC Centre for Climate Change Economics and Policy (CCCEP), run by LSE and the University of Leeds. LSHTM with Copenhagen University has done work on the economic aspects of health co-benefits (Jensen et al., 2013).

Buildings: IEA, LSHTM, UCL, Taiyuan University of Technology, Oxford Brookes University and the Netherlands Environmental Assessment Agency were identified as key areas of expertise. The IEA have undertaken a recent synthesis study on energy efficiency with particular relevance to buildings (OECD & IEA, 2014) while the LSHTM and UCL have undertaken extensive work on co-benefits and health associated with buildings such as indoor air pollution improvement from better cook-stoves, reduced thermal stress, improved indoor environment from avoided cold, damp and mould and problems with radon build-up (Wilkinson et al., 2009). A number of US Universities (Yale University, UC Berkeley, University of British Columbia, University of Minnesota) are currently undertaking research on indoor air quality improvements through alternative cook-stove technologies.

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[12] http://www.4cmr.group.cam.ac.uk/research/projects/hhr/human-health-risk

[13] http://www.rff.org/home

[14] http://www.bc3research.org/index.php

[15] http://webarchive.nationalarchives.gov.uk/20100407172811/http://www.hm-treasury.gov.uk/stern_review_report.htm

Transport: Centres of expertise on co-benefits related to new vehicle technologies can be found at MIT, IIASA and Tsinghua University, and expertise on co-benefits of active travel can be found at the University of Cambridge, University of Oxford, SUSTRANS, LSHTM, the MTI and University of Wisconsin in the US (e.g. Rodier et al., 2014), and New Zealand (e.g. Shaw et al., 2014).

Industry: Work on energy efficiency in industry is widespread globally. Work on material efficiency and the circular economy is undertaken in the UK by WRAP and by Julian Allwood's group at the University of Cambridge, and by the Wuppertal Institute in the Netherlands (e.g. see D4.1 of the COMBI project, Teubler et al., 2015).

Consumption: The Sustainable Consumption Institute at the University of Manchester has a comprehensive programme of research on consumer behaviour. The Ellen MacArthur Foundation are leading work on the circular economy while the Centre for the Understanding of Sustainable Prosperity (led by the University of Surrey) is investigating the links between consumption and the economy.

Food: Centres of expertise related to impact of dietary change include the Oxford Martin Programme on the Future of Food and LCIRAH/LSHTM,[16] [17] [18] and L'Institut National de la Recherché Agronomique (INRA) in France.[19]

AFOLU: Research on the impacts of REDD+ is carried out by the Tyndall Centre for Climate Change Research and the University of Cambridge in the UK[20,21] and globally the UNEP-WCMC, who work with developing countries to map and assess the potential for REDD+ co-benefits, and the Forestry and Forest Products Research Institute (FFPRI).[22] Land-use models include the GLOBIO3 model, the result of an international research project made up of the UNEP-WCMC, UNEP, GRID-Arendal and the Netherlands Environmental Assessment Agency to analyse the human impacts on biodiversity,[23] and the GLOBIOM model at IIASA, which has been applied in various countries. Pete Smith at the University of Aberdeen leads a centre of expertise on carbon storage in soil and GHG emissions from agriculture, and CIFOR lead work on sustainable agriculture and forestry, including agroforestry.

7.2 Networks

The call for evidence and the workshop revealed an active, highly engaged research community, although there are currently no formal networks to link researchers studying co-benefits in different sectors and from different disciplines. Stronger networking opportunities could enable better integration of fields such as waste management, material efficiency, water security and land use into the co-benefit framework, as well as being crucial for the development of holistic assessment methods and models.

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[16] http://www.oxfordmartin.ox.ac.uk/people/479

[17] http://www.oxfordmartin.ox.ac.uk/people/528

[18] http://www.lcirah.ac.uk/

[19] http://www.inra.fr/en/Scientists-Students

[20] http://www.tyndall.ac.uk/redd-law-project-legal-frameworks-land-development-and-conservation

[21] http://www.4cmr.group.cam.ac.uk/research/projects/reddpluslawproject

[22] https://www.ffpri.affrc.go.jp/redd-rdc/en/

[23] http://www.globio.info/what-is-globio/history-of-globio

During the course of this project an extensive group of researchers have been identified who could form a new co-benefit network, including those invited to the workshop and those who responded to the call for evidence. There are existing research networks in related fields that could also be drawn on. These include:

- The Urban Climate Change Research Network (UCCRN) a consortium of over 600 individuals working with analysis of climate change adaptation and mitigation from an urban perspective. The research network was founded in 2007 during the C40 Large Cities Climate Summit by an initial group of 100 researchers from 60 cities and has developed research on co-benefits of city-scale climate change mitigation strategies (Rosenzweig et al., 2011).
- C40 Cities is a network of more than 80 of the world's megacities that are taking action to reduce GHG emissions. The network regularly publishes research and case studies related to economic and social co-benefits of city-scale climate action, as well as running a number of separate networks covering urban sectors such as buildings, transport and energy.[24]
- The Food Climate Research Network (FCRN), an interdisciplinary and international network researching issues related to food and climate. Among other work, the FCRN has published work on sustainable healthy diets, links between animal efficiency and animal welfare, and China's food system.
- The Asian Co-benefits Partnership (ACP) launched in 2010 following the International Forum for a Sustainable Asia and the Pacific in Hayama, Japan to improve stakeholder cooperation and knowledge management on co-benefits in Asia.[25] The ACP has had a fundamental role in the development of co-benefits research from an Asian context through the development of reports, white papers, tools & toolkits, factsheets, and case studies.
- The research funded by the Wellcome Trust under their Health and Sustainability funding stream and in future the Our Planet Our Health funding programme includes work relevant to co-benefits e.g. on sustainable cities and diets/food systems, involving a range of institutions including LSHTM, UCL, Universidad Federal da Bahia, Brazil, Public Health Foundation of India and Harvard School of Public Health.

Other relevant networks include the Green Infrastructure Network, the Ecosystem Knowledge Network, the ARCC (adaptation research), the IEA Multiple Benefits network, the researchers engaging with the WHO on the development of new co-benefit modelling tools, and the CD-Links (climate and development) consortium.

7.3 Case studies and datasets

Private and public sector organisations and networks, as well as academic institutions produce case studies on co-benefits and adverse side effects of climate change mitigation. One such organisation building on the growing importance of cities in climate change mitigation (Betsill & Bulkeley, 2007), is the C40 Cities Climate Leadership Group. C40 Cities are in the process of identifying a number of case study cities to test and take forward a protocol with regards to data collection for use in co-benefits analysis and this research will be completed towards the end of 2016.

As mentioned above, the Asian Co-benefits Partnership is also in the process of developing a set of case studies illustrating co-benefits for cities in Asia. A case study published by ACP investigates the opportunities

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[24] http://www.c40.org/networks

[25] http://www.cobenefit.org/about/

to reduce the production of GHGs and other air pollutants such as black carbon, organic carbon and ozone through techniques such as improved brick making, improved transport efficiency, fuel switching, expanding use of renewable energy such as solar heaters and alternative agricultural practices to open field burning.[26] The World Health Organisation has also developed case studies of co-benefits in the housing and transport sectors.[27]

An extensive digest of research on air quality co-benefits is provided by the Climate and Clean Air Coalition. This currently holds over 700 items and is searchable by pollutant, geographic area or topic: for example, there are 187 items on cookstoves.

The development of databases and datasets underpins quantitative assessment of co-effects and the lack of good datasets is one of the key challenges facing modellers. Modelling of co-impacts may use either purpose built or publically available datasets. These span a wide range of sectors. Examples identified in the literature review include prefecture-level economic and emission data (Zhang & Wang, 2011), meat consumption habits (Aston et al., 2012), protected areas (Jantz et al., 2014), point sources of GHGs and air pollution (Boyce & Pastor, 2012), thermal retrofit measures (Ahern et al., 2013), and travel habits (de Nazelle et al., 2010).

8 Conclusions and recommendations

This scoping study found a large evidence base demonstrating that the co-benefits of climate change mitigation action are substantial, and that the value of these co-benefits can often outweigh the cost of the mitigation action. Taking co-impacts into account emphasises the importance of demand-side measures, which offer a wide range of co-benefits and few adverse side-effects. Many supply-side low carbon energy measures also offer significant co-benefits, e.g. for air quality and energy security, but certain technologies do have some adverse side-effects, which can sometimes be reduced through careful design or improved technology. Mitigation options in the land use sector, such as forest carbon and bioenergy, offer the potential for either co-benefits or adverse side-effects, depending on the extent to which social and environmental safeguards are implemented.

Decision-makers need to balance co-impacts with the role of different mitigation actions in meeting climate targets. More ambitious deployment of demand-side measures may help to meet stringent climate targets and can also, to some extent, reduce the need for supply side measures and negative emission technologies, and thus reduce their adverse impacts. In particular, there are opportunities to extend the current focus on energy efficiency to include material and water efficiency and sustainable consumption. However, the effective uptake of demand-side measures faces social, political and economic barriers, and depends on a much better understanding of consumer behaviour. This gives rise to a need to go beyond the traditional focus on engineering solutions, to bring in more interdisciplinary research.

Similarly, more research is needed on land use mitigation options, which will play a significant role in meeting stringent climate targets, especially as afforestation, soil carbon sequestration and BECCS can act as negative emission technologies. It is important to understand the constraints on deploying these options and how to maximise their co-benefits and minimise their potential adverse side-effects. There are also opportunities to gain multiple benefits from intelligent use of green infrastructure and nature-based solutions as cost-

[26] http://www.cobenefit.org/publications/images/ACP%20Factsheet%20No.4_Black%20Carbon.pdf

[27] http://www.who.int/sustainable-development/transport/case-studies/en/ and http://www.who.int/sustainable-development/housing/case-studies/en/

effective alternatives or complements to traditional grey infrastructure. Again, this research will require co-operation between different disciplines and different government departments.

A co-benefit approach offers good potential for engaging with industrialising countries, by supporting climate mitigation options that have co-benefits for development (e.g. transport, housing, air quality, waste, health) and climate adaptation (e.g. soil carbon sequestration; trees for flood protection and micro-climate regulation). More emphasis on supply-side measures may be appropriate in the international context, where consumption levels are much lower, and there is a need to avoid carbon lock-in by 'leapfrogging' to efficient, low carbon infrastructure.

The main recommendations for the future development of DECC's research programme are summarised below, first regarding UK climate policy (section 8.1) and then regarding the potential for the UK to engage with other countries (section 8.2). There is considerable overlap between these two areas as many recommendations apply equally to the UK and international context. Section 8.3 presents recommendations regarding development of tools and models, and section 8.4 summarises opportunities for maximising engagement with the research, policy and practice communities. Key research priorities are listed in section 8.5. These research priorities span a wide range of sectors and disciplines, and therefore require co-ordinated and co-operative action by DECC and other government departments, and sometimes also by international partners or funding agencies, as already noted in Table 1 in the summary.

8.1 Research recommendations: UK policy

Impacts of climate mitigation can be divided into four groups:

1. well characterised co-benefits, where future effort should focus on implementation, demonstration and dissemination;
2. impacts that require further research to improve understanding;
3. known adverse side-effects where research is required on potential mitigation options; and
4. impacts that are rarely assessed and need to be brought into a co-benefit framework.

8.1.1 Well characterised co-benefits

Areas where co-benefits are reasonably well understood include:

- air quality benefits of burning less fossil fuel (gaps remain for agricultural emissions and SLCPs);
- benefits of active travel for physical activity, congestion, noise, accidents and energy security;
- physical and mental health benefits, cost savings and energy security benefits of warm homes.

These co-benefits are well established and have generally been quantified in a number of robust studies, though this quantification is often highly dependent on the range of possible assumptions. However, they are not always achieved in practice, due to lack of awareness and other implementation barriers. Research should therefore focus on implementation, demonstration and dissemination, as well as on maximising the benefits through closer attention to distributional impacts.

- **Demonstration projects:** funding and evaluating real life demonstration projects (including active travel and low carbon buildings), and evaluating the co-benefits achieved in practice including where possible comparator sites making use of natural or designed experiments (see Shaw et al., 2014 for a detailed assessment of research needs for transport studies).
- **Case studies:** compiling examples of success stories and lessons learned from around the world, and disseminating to the public and policymakers.

- **Simple tools:** developing a portfolio of simple tools to enable policymakers to assess the potential benefits of new projects (building on existing tools such as HEAT), and to clearly present both qualitative and quantitative measures to decision-makers.
- **Behaviour change:** funding social and behavioural science research to understand how to encourage lasting behaviour change (for active travel, dietary change and energy saving behaviour), both through voluntary change and through identifying opportunities for creating an enabling environment (e.g. public procurement, taxation policy, investment in public transport).
- **Distributional impacts:** who benefits from different mitigation actions and how can the co-benefits be maximised, e.g. by focusing air quality improvements in the most polluted areas, by targeting retrofitting programmes on households or neighbourhoods vulnerable to fuel poverty, and by targeting active travel or dietary change interventions where health improvements are needed?
- **Barriers:** funding interdisciplinary social, political and behavioural science research to address barriers to integrated policies (e.g. through improved co-ordination between departments and between local / regional / national government; through quantifying the impacts on winners and losers of mitigation actions).
- **Finance**: assess how consideration of co-benefits and adverse side-effects can be incorporated into financing and investment opportunities for climate change mitigation policies or measures.

8.1.2 Less well understood impacts

The following important areas have complex positive and/or negative impacts where further research is required to improve understanding.

- **Dietary change**: potential benefits for climate, health and the environment are substantial, but more research is needed to understand the full implications of a low GHG emission diet, including what foods are substituted for red meat, the distribution of health benefits, and the wider socio-economic impacts on employment, rural economies, the food industry and global trade.
- **Aviation and shipping**: what are the potential co-benefits and adverse side-effects of climate change mitigation options for aviation and shipping, including demand reduction, modal shift (for aviation), fuel switching (including to biofuels), energy efficiency and (for shipping) speed reduction?
- **Integrated urban policies:** The effects of a range of policies implemented in an integrated way at the city level including in transport, land use, built environment and other sectors on co-benefits and local economy/employment.
- **Productivity co-benefits**: there could be significant economic co-benefits from resource efficiency in non-residential buildings (e.g. from better lighting, more comfortable temperatures, quieter appliances, less waste heat and lower maintenance costs) and in industry (e.g. due to process improvements, higher quality product / lower rejection rate, lower consumption of water and materials, noise and vibration reduction, reduced maintenance needs, reduced accidents, time savings for waste disposal and material handling). These co-benefits could be important for leveraging additional support for climate action in the business community.
- **Climate targets:** What are the co-benefits and adverse side-effects of changes that will be needed to meet a range of climate targets, including the 1.5°C target?
- **Rebound effect:** how can wider policies (e.g. taxation) be used to maximise the co-benefits of resource efficiency measures, i.e. by discouraging expenditure (of energy cost savings) on energy-intensive goods and services?
- **Employment and economic development/growth:** There is strong evidence on the potential for certain economic co-benefits, such as the benefits from improved air quality (reduced health service costs and less time off work), but other benefits, such as the impacts on innovation and

competitiveness, are less well characterised. Employment impacts of most mitigation actions are also likely to be highly variable, with winners and losers in different sectors. Further work in these areas may help to overcome commonly held myths about the potential adverse impacts of climate action on the economy and employment.

- **Social impacts and community participation:** There is uncertainty over the social impacts of many climate mitigation actions, e.g. the impact of active travel or green infrastructure on community cohesion. Research should also address the opportunity for community participation to enhance co-benefits and help to avoid adverse side-effects.

8.1.3 Known adverse side-effects

Most energy supply options have some degree of adverse side-effects, with the net impact often depending on the counterfactual, i.e. the option being replaced. In some cases, it may be possible to mitigate these adverse impacts, e.g. through better siting or more community consultation over the location of wind turbines. Mitigation may depend on development of improved future technologies, e.g. modular nuclear power generation technologies with lower accident risks, or improved carbon capture technologies that reduce process energy requirements and solvent waste production. Some impacts may be hard or impossible to mitigate, e.g. dealing with long term disposal of nuclear waste, or the impacts of nuclear fuel mining, and reducing the risk of CO_2 leakage from underground storage and pipeline transport. In some cases, mitigation may be possible but may lead to increased costs, e.g. ensuring social and environmental safeguards for REDD+, or to reduced supply, e.g. restricting bioenergy production to sustainable sources such as forestry waste.

The following are known adverse side-effects: research should focus on the extent of these impacts and whether mitigation of these impacts is possible.

- **Bioenergy:** Research has already highlighted the potential adverse side-effects of bioenergy feedstock production for land use, biodiversity, water use, water quality, soil fertility and food security, as well as the need to take into account additional greenhouse gas emissions associated with, for example, conversion of peatland to biofuel production. Even for relatively sustainable biofuels such as forestry or crop waste, there are trade-offs with biodiversity and soil fertility. In the context of the increased attention on BECCS as a means to keep temperature rise well below 2°C, further research is needed to establish the circumstances in which bioenergy feedstock is sustainable, the quantity that can be produced sustainably, potential conflicts with biodiversity goals such as the Convention on Biological Diversity (CBD) requirement for no net habitat loss, and how to ensure that social and environmental safeguards for biofuel production are widely respected.
- **Nuclear energy:** The impacts of radioactive waste, routine discharges to air and water, accident risks and geo-security implications in various countries are still poorly quantified. Better information on the extent to which new nuclear technologies (i.e. modular designs) can mitigate the impacts is required. The choice of an appropriate discount rate for assessing long term impacts (and the case for a zero rate) needs further consideration in the context of ethics and social justice.
- **CCS:** As CCS is viewed as a critical technology for achieving climate targets, especially regarding the role of BECCS as a commonly suggested negative emissions technology for dealing with potential overshoot, research is needed to address the risks associated with transport and long term storage of CO_2, the impact on emissions to air, impacts associated with production, use and disposal of toxic amine solvent and upstream impacts associated with additional fuel production due to the energy penalty. How far can alternative CCS technologies mitigate any adverse impacts?
- **Wind power:** Research is needed on the potential impact of community engagement and careful siting on the public acceptability of wind farms, which is currently a major barrier in the UK.

8.1.4 Rarely assessed as co-benefits

The following areas are rarely assessed as co-benefits, although research does exist in the wider literature. Studies are needed to quantify the benefits and integrate them into assessments of climate change mitigation action.

- **Resource efficiency / circular economy / consumption:** Energy efficiency is familiar, but material efficiency is rarely considered as a climate change mitigation action, although it offers huge potential co-benefits and few adverse impacts. Quantifying these benefits will require integrating life-cycle assessments, waste management and circular economy literature into a co-benefit framework (building on the approach being developed in the COMBI project, Teubler et al., 2015). As for energy efficiency, research is needed to address the rebound effect and the use of a wider policy framework (e.g. eco-taxes) to tackle this. Stringent climate targets are also likely to require reduced material consumption; this faces economic, political and social barriers, and will require increased research on consumption behaviour. Research should also address the potentially important socio-economic impacts, e.g. on economic growth and employment, especially through starting a dialogue between conventional economists and ecological economists.
- **Water sector / water security:** Similarly, water efficiency has received little attention in the context of climate action. This is also extremely important in the international context, for climate adaptation.
- **Sustainable building design:** This has the potential to reduce other environmental impacts through using lower impact materials; the evidence base on this needs assessing within a co-benefit framework.
- **Natural capital, ecosystem services and green infrastructure:** The large evidence base on the multiple benefits of green infrastructure for health and wellbeing, ecosystem services and climate adaptation (e.g. flood protection, microclimate regulation) needs integrating into a co-benefit framework. Better data is needed on the role of forests for flood protection and air quality regulation.

8.2 Research recommendations: International engagement

Co-benefits are already a major driver of climate action in many industrialising countries (see section 6, and there is potential to strengthen this by facilitating the uptake of mitigation options that offer multiple co-benefits for mitigation, adaptation and development. Demonstrating the near-term benefits of climate action for development and climate adaptation could motivate the adoption of larger INDCs. Specific research is needed on the following topics.

- **Urban design:** well-designed urban developments can address multiple problems, e.g. public health / sanitation; poor quality housing; air pollution; lack of mobility; climate adaptation (passive cooling; sustainable drainage). Qualitative and quantitative assessment tools are needed so that planners can optimise across all co-benefits and the co-benefits can be incorporated into climate finance mechanisms. Research should also address how community participation in urban design can maximise co-benefits.
- **Small scale renewable energy** (including solar lighting and refrigeration): there are significant co-benefits for enhanced energy access and social equity, but not all schemes succeed; research is needed on the role of social enterprises in maximising these co-benefits, and on critical success factors such as community engagement.
- **Cookstoves:** Cookstove replacement projects have major health, social and environmental co-benefits, but not all projects succeed. Research needs to address the reasons for this and the role of community participation in ensuring successful outcomes. Further research may be needed (building

on ongoing studies) to address the potential conflict when replacing carbon-neutral biomass with gas or electric stoves, including the potential adverse impact of increased fuel costs (linked to climate change mitigation) on access to clean gas or electric stoves.

- **Sustainable waste management (circular economy) and modern waste treatment plants:** These offer co-benefits for health/ sanitation, energy supply (landfill gas / biogas) and water quality, which can incentivise uptake. Research is needed to evaluate the impacts, including the implications for employment and job quality (regarding the informal recycling sector).
- **Travel choices:** Motivation for active travel is different in industrialising countries, as many people lack access to a car, and obesity is less prevalent. Fear of crime may also be a genuine barrier, but safe and efficient public transport can improve social equity, mobility and community cohesion. Research needs to address these social factors including options for improving the safety of active travel and public transport.
- **REDD+ and bioenergy:** Cost-effective monitoring arrangements are urgently needed to ensure effective social and environmental safeguards for REDD+ and bioenergy feedstock production. Integrated REDD+ assessments are needed, taking other ecosystem services (e.g. flood protection) into account as well as carbon storage and biodiversity. Participatory governance can play a key role in delivering social and environmental co-benefits: demonstrations and evaluations of this approach are required.
- **Soil carbon sequestration and agroforestry:** There is considerable interest, but there is uncertainty over quantification of soil carbon storage over time, and cost-effective monitoring and verification is needed to enable the use of climate finance. Behavioural research is needed to understand farmer uptake and dis-engagement, as ongoing management is required to maintain or increase soil carbon. Local demonstration projects and participatory research are key to ensuring uptake.
- **REALU:** Reducing Emissions from All Land Use takes all land use into account, not just forests, to try to avoid indirect land use change and loss of lower-carbon ecosystems such as open forests and grasslands. This is a key topic, especially in the light of the likely future demand for BECCS and afforestation as negative emissions technologies. Research should address the feasibility of a REALU approach including the potential risks: e.g. would offering carbon finance for soil carbon sequestration in agriculture lead to additional conversion of forests to agriculture?
- **Specific research and case studies for particular countries and regions:** Research gaps have been identified, especially the Middle East, as well as Brazil, South Africa and Indonesia.

8.3 Tools, methods and models needed both in UK and internationally

A range of tools and models exist, but further development is needed to ensure that a wider range of co-benefits and adverse impacts can be assessed. Various research needs have been identified.

1. **Simple tools** (e.g. checklists, matrices, decision trees or spreadsheet models) for decision-makers to use for evaluating co-benefits and adverse impacts, to allow them to explore policy options that have multiple benefits across different sectors and to avoid unintended adverse consequences. For example, this could include tools to enable planners to evaluate different urban design options, or co-impacts could be integrated into 'carbon calculator' tools such as the 2050 Calculator to enable the co-impacts of different mitigation strategies to be visualised by policymakers or the public, alongside the direct benefits and costs of mitigation. The challenge in developing simple tools is the trade-off between accuracy (e.g. the need to take into account interactions between sectors), transparency and ease of use.
2. Inclusion of a **wider range of co-impacts into economic analysis tools** (e.g. macroeconomic models, cost-benefit analysis and cost-effectiveness analysis frameworks), linking together sectors such as

climate, energy, health, air quality, transport, land use and economy, so that co-benefits can be taken into account in decision-making in other sectors.

3. **Integrated models** to address synergies and trade-offs between impacts in complex systems, e.g. the food-energy-water-land nexus, and the long term impacts of changes in one sector or country on other sectors or countries. Examples include the socio-economic impacts of replacing concrete and metal with wood, or replacing meat with non-meat foods. New methodological approaches may be needed, e.g. micro-simulation modelling for health co-benefits.
4. **Extension of co-benefit assessment approaches** to include sectors and impacts that are often excluded, especially material efficiency / waste management, water security and land use / ecosystem services / agricultural productivity.
5. **Multi-criteria decision analysis tools** and participatory stakeholder approaches for taking into account impacts that are hard to quantify or monetise, and evaluating complex trade-offs.

Recommendations include a review of available tools and models and establishing a modellers' forum to explore further integration of models across sectors. This could link into existing modelling initiatives such as the COMBI project work on developing assessment and visualisation methods for energy efficiency co-benefits, and the ongoing development of the WHO HEAT tool for assessing active travel co-benefits.

To address conflicts and trade-offs in complex areas such as the food-water-land-energy nexus, there is a need to trial the wider use of participatory stakeholder approaches. Stakeholder participation can also be useful when developing realistic scenarios for input to models, following the approach of the MAPS project. Finally, the cost-effectiveness of research can be increased through systematic reviews of existing research and greater emphasis on the maintenance, update and development of existing tools, models and datasets, to keep the research relevant and useful for future decision making.

8.4 Engagement levers: cities, health, networks and interdisciplinary approaches

The cost-effectiveness of research can be enhanced by targeting 'engagement levers' where impact can be maximised. Although national and regional governments set the policy framework, cities and local level Government often lead the way in implementation (Watts et al., p. 41). There is large potential for cities to achieve multiple benefits from integrated planning of housing, transport, green infrastructure etc., with the added incentive that these benefits are local and immediate. Local planners and policymakers could benefit from simple tools and information on the multiple co-benefits of climate change mitigation for adaptation and development. There is a good opportunity to work with city networks (e.g. Smart cities, C40 cities, Mayors Adapt) to raise awareness of potential co-benefits, develop and test simple planning and visualisation tools, compile case studies and evaluate the impacts of real life interventions.

The health sector also offers a good opportunity to raise awareness of co-benefits and evaluate real life demonstration projects (see section 5.2).

Co-benefit research is extensive but fragmented, and there are opportunities to enhance cost-effectiveness by creating a new network of researchers, policymakers and practitioners, building on contacts identified during this project as well as existing networks (see section 7.2). There is also an increasing need to involve social, political and behavioural scientists more closely with climate change mitigation research and to incorporate social science insights into models, for example regarding understanding of practice and behaviour, community engagement, distributional effects and barriers. This could be encouraged via a cross-research council programme of interdisciplinary research on co-benefits and adverse side-effects.

8.5 Priority recommendations

This section presents priority recommendations for future research.

1. Model development

Quantification of co-impacts remains challenging. There are many existing tools and models for assessing co-impacts (28 are listed in Appendix B) but no overview of these tools or co-ordination of model development activities was identified. There is a need for:

- Simple tools (e.g. checklists, matrices, decision trees or spreadsheet models) for decision-makers to use for visualising and evaluating co-benefits and adverse impacts, to allow them to explore policy options that have multiple benefits across different sectors and to avoid unintended adverse consequences.
- Inclusion of a wider range of co-impacts into economic analysis tools (e.g. macroeconomic models, cost-benefit analysis and cost-effectiveness analysis frameworks), linking together sectors such as climate, energy, health, air quality, transport, land use and economy, so that co-benefits can be taken into account in decision-making in other sectors.
- Integrated models to address synergies and trade-offs between impacts in complex systems, e.g. the food-energy-water-land nexus, and the long term impacts of changes in one sector or country on other sectors or countries.
- Extension of co-benefit assessment approaches to include sectors and impacts that are often excluded, especially material efficiency / waste management; water security; land use / ecosystem services / agricultural productivity and the upstream impacts of avoided fuel production.
- Multi-criteria decision analysis tools and participatory stakeholder approaches for taking into account impacts that are hard to quantify or monetise, and evaluating complex trade-offs.

To address these research gaps, it is recommended that:

a. **a review of available tools and models** is commissioned, including their data requirements, to identify the research needs;
b. **the establishment of a modellers' forum is encouraged** to explore development of simple assessment tools and further integration of models across sectors. This could build on ongoing work under C40 Cities, the development of the WHO Heat tool and IGES work on simple assessment tools. One aim should be to develop assessment tools to enable inclusion of co-benefits in climate finance project evaluations, including areas such as sustainable urban design and waste management.

2. Co-benefit research network

Co-benefit research is extensive but fragmented. The call for evidence and the workshop revealed an active, highly engaged research community, although there are currently no formal networks to link researchers studying co-benefits in different sectors and from different disciplines. Stronger networking opportunities could enable better integration of fields such as waste management, material efficiency, water security and land use into the co-benefit framework, as well as being crucial for the development of holistic assessment methods and models. There are opportunities to enhance cost-effectiveness by creating a new network of researchers, policymakers and practitioners, building on contacts identified during this project as well as existing networks This could be focused around a central website and case study database provided by researchers. It would provide DECC with access to latest evidence, and could target researchers in priority countries for which there are research gaps.

3. Compile case studies

Policymakers have limited knowledge and understanding of co-benefits and adverse side-effects, and this is a major barrier to incorporating co-impacts into policy and practice. To tackle this, there would be great value in compiling a set of co-benefit case studies drawn from around the world, illustrating best practice and lessons learned, to form an evidence base to demonstrate the value of co-benefits. This would raise awareness and facilitate engagement with key stakeholders and policymakers. There are opportunities to partner with the ongoing case study initiatives of the Asian Co-benefits Partnership and C40 Cities. Case studies could include key topics of importance for priority countries, including urban design, waste management, sustainable transport, agroforestry and climate adaptation. Priority countries such as the Middle East and South Africa could be targeted, but some may need support for case study data collection.

4. Real-world demonstration projects

Linked to the case studies of existing initiatives, there is a need for new demonstration projects involving comparator sites, especially for active travel and urban design. This could be linked to ongoing model development initiatives, through design of the projects to improve understanding of real life processes and impacts, provide data to inform model parameters, and test new assessment methods. The projects could also be targeted towards the need for more interdisciplinary research (see next point), including better understanding of social barriers, and of how benefits can be more widely distributed.

5. Interdisciplinary research to study behaviour change, distributional effects and barriers

Interdisciplinary research bringing together social, political and behavioural scientists and economists with climate science and policy is urgently needed to address several major research gaps:

- The significant untapped potential for cutting GHG emissions through behaviour change, which could also achieve major co-benefits with few adverse side-effects.
- The lack of understanding of the distributional impacts of climate change mitigation action.
- The need to overcome political, social and institutional barriers to achieving co-benefits.
- The potential role of community engagement in maximising co-benefits and avoiding adverse side-effects, and the potential benefits of climate action for community cohesion.

This could be encouraged via a cross-research council programme of interdisciplinary research on co-benefits and adverse side-effects, perhaps based around the Global Challenges RUK programme. This could address the following priority topics:

- **Dietary change**: Evaluation of the potential co-impacts of low GHG diets, taking into account the health impacts of food substitution and wider socio-economic impacts on the food and farming industry and rural communities.
- **Active travel**: Understanding travel behaviour and how to maximise health co-benefits by ensuring broader uptake of walking and cycling by different socio-economic groups.
- **Barriers:** understanding and addressing political, institutional, social and economic barriers to achieving co-benefits and avoiding adverse side-effects.
- **Distributional impacts** of low carbon technology, e.g. electric vehicles.
- **Co-impacts related to aviation and shipping:** e.g. impacts of reducing air travel demand on noise, air quality, socio-economic and wellbeing; impacts of reduced shipping speeds; impacts of increased energy efficiency or low carbon fuels (including biofuels).

6. Impact of different climate targets on co-impacts

More stringent targets, including the 1.5°C target, are likely to require a different mix of mitigation options and will therefore have different co-impacts. Many co-benefits are likely to increase, but there is also a risk that certain adverse side-effects could increase. Further understanding of these potential co-impacts is urgently needed to inform decisions on the optimum technology mix, and to plan appropriate measures to avoid or reduce adverse side-effects. Research priorities include:

- **CCS:** impacts of CO_2 storage and risk of leakage; impacts of solvent use and disposal; air quality impacts (SO_2 and PM could decrease; NO_x and NH_3 could increase); impacts of increased upstream fuel production as a result of the 25% energy penalty; potential for alternative CCS designs to reduce any adverse impacts.
- **Nuclear energy:** impacts of waste disposal; accident risks; geosecurity (e.g. terrorist activity using illegally obtained radioactive material); impacts of uranium mining and fuel production; choice of appropriate discount rate; potential for new technology (small modular reactors) to reduce adverse impacts.
- **BECCs** (bioenergy with carbon capture and storage, a negative emissions technology): impacts of increased biomass production on biodiversity and water quality (from fertiliser and pesticide use); further work on demand for water, land, fertilisers and energy; potential for carefully managed sustainable biomass production to restore degraded land or provide biodiversity benefits.

7. Extending REDD+ to other ecosystems using a landscape approach

As attention is increasingly focused on the role of bioenergy, BECCS and afforestation to meet challenging climate targets, it is important to consider the impact of expansion of bioenergy crops and afforestation on other land uses, including agriculture and natural ecosystems such as heathlands, grasslands and wetlands. New initiatives such as the Initiative for Sustainable Forested Landscapes take a whole landscape approach to carbon sequestration, building on the REALU approach (reducing emissions from all land use). By offering climate finance for agricultural techniques that add organic matter to the soil, thus improving fertility and water retention, this could provide large co-benefits for development, food security and climate adaptation that are of particular interest to developing countries. However more research is needed to support this approach, including how to measure and monitor soil carbon sequestration cost-effectively over time, exploring methods of assessing trade-offs between competing land uses, and assessing the risk that it could lead to additional conversion of natural forests to agriculture or agroforestry.

8. Cost-effective MRV for land use climate mitigation options

REDD+ and its extension to other ecosystems offers tremendous potential to achieve co-benefits for biodiversity, ecosystem services and local communities, but this is dependent on effective enforcement of the social and environmental safeguards that have been developed. Similarly, there is a need to enforce safeguards to ensure that bioenergy feedstock production is sustainable. However, monitoring and verifying these safeguards can be expensive and the cost can limit the uptake of these important GHG mitigation options. Research could address the development of more cost-effective MRV options, including further work on the use of remote sensing, and also the use of participatory governance and community involvement. There is also potential to maximise biodiversity co-benefits and minimise adverse impacts by focusing on maintaining and enhancing habitat connectivity when identifying new locations for REDD+ or bioenergy plantings.

9. Multiple benefits from green infrastructure and sustainable agriculture

Green infrastructure can provide multiple benefits for climate mitigation and adaptation, biodiversity and ecosystem services, including flood protection, and can offer a cost-effective alternative or complement to grey infrastructure, e.g. for flood protection or water supply. There is a large evidence base which could be brought into a co-benefit framework to provide additional motivation for climate action. Similarly, sustainable agriculture (soil carbon sequestration, precision fertiliser use and agroforestry) can enhance agricultural production while providing benefits for soil protection, biodiversity and flood protection, but farmers need support to understand the potential benefits.

10. Resource efficiency / circular economy / reduced consumption

Resource efficiency – not just energy but also water and materials – offers huge untapped potential to provide both GHG reduction and co-benefits. Around 60% of all GHG emissions are associated with production, manufacture, distribution and retail of food and consumer goods, extraction of raw materials, and construction of housing and other infrastructure. Reducing the waste of materials, water and embodied energy through a shift towards a circular economy approach can drive innovation, increase competitiveness and avoid the upstream environmental impacts on air and water quality and habitat loss associated with quarrying, mining, smelting and manufacturing. In addition, dematerialising the economy through In addition, dematerialising the economy through alternative consumption patterns which act to decouple economic activity from unsustainable resource use will contribute significantly towards meeting challenging climate targets, but this faces significant social, political and economic barriers. Research priorities are to:

- Quantify potential co-benefits: economic benefits (resource cost savings; productivity); resource security (energy, water and materials); AQ; land use; water quality; biodiversity, drawing on life cycle assessment approaches and input-output analysis.
- Investigate social, political, and economic barriers to new, more resource-efficient business models and alternative consumption patterns, and means of overcoming these, e.g. through more studies of consumer behaviour and the potential to shift towards 'sharing economy' innovations based on hiring or leasing goods rather than individual ownership.
- Investigate the wider socio-economic impacts of reduced material consumption, including impacts on employment and growth, by initiating a dialogue between conventional and ecological economists.
- Investigate the potential co-benefits of sustainable waste management and water security for engaging with priority countries.

11. Economic development and employment

Climate change mitigation has important potential co-impacts for economic development, innovation, competitiveness and employment but although the evidence base is growing, these are still not well characterised. Employment impacts are rarely assessed as net changes, taking account of winners and losers in different sectors. Further work in these areas may help to overcome commonly held myths about the potential adverse impacts of climate action on the economy. Research could address:

- Net **employment** and **economic** benefits (ex-post interventions) of climate change mitigation technology.
- **Innovation co-benefits** of low carbon technology and resource efficiency.
- **Productivity co-benefits** in non-residential buildings and industry (e.g. due to process improvements, increased comfort).

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Appendix A: Key evidence

Reference	Key evidence for	Evidence
Aaheim et al. (1999), Climate Change and Local Pollution Effects - An Integrated Approach, Mitigation and Adaptation Strategies for Global Change 4: 61-81	Health; Methodology	A proposed 5 year programme to save 7.65% of Hungary's energy consumption (mainly through awareness) could save 1.3 MtC, worth $25M/y, with air quality co-benefits for health worth US$648 M/y and energy cost savings of US$ 373 M/y, for expenditure of US$ 66M/y
Akhtar et al. (2013), GLIMPSE: A rapid decision framework for energy and environmental policy, Environmental Science and Technology 47:1201112011-12019	Health; Methodology	Capping CO_2 at 50% of 2005 levels in 2050 decreases health impacts from SO_2 and organic carbon to 80% of baseline in 2030, and offsets the reduction of the sulphate cooling effect that stems from AQ measures alone.
Anenberg et al. (2012), Global air quality and health co-benefits of mitigating near-term climate change through methane and black carbon emission controls, Environmental Health Perspectives 120:831-839	Health	Fully implementing 14 black carbon and methane emission control measures could reduce global population-weighted average surface concentrations of $PM_{2.5}$ and ozone by 23–34% and 7–17% respectively and avoid 0.6–4.4 and 0.04–0.52 million annual premature deaths globally in 2030. More than 80% of the health benefits are estimated to occur in Asia and 98% are due to the black carbon mitigation measures.
Aunan et al. (2007), Benefits and costs to China of a climate policy, Environment and Development Economics 12:471-497	International (China); Health	China could reduce its CO_2 emissions by 17.5% below the baseline in 2010 without suffering a welfare loss, because PM and NO_x reductions improve health and agricultural yields.
Bache et al. (2014), Symbolic Meta-Policy: (Not) Tackling Climate Change in the Transport Sector, Political Studies 63 (4): 830-851	Barriers	Headline UK government targets for reducing climate change have not been translated into action on the ground in the transport sector, because of a lack of measures to ensure implementation by other government departments and local authorities.
Bollen et al. (2009), Co-Benefits of Climate Change Mitigation Policies: Literature Review and New Results, OECD Economics Department Working Papers, OECD Publishing	Methodology; Health	A 50% GHG cut relative to 2005 levels in 2050 reduces the number of premature deaths caused by air pollution by 20% to 40% in 2050 (depending on regions) relative to a business as usual scenario. Co-benefits could range between 0.7% of GDP in the European Union to 4.5% in China in 2050.
Bollen et al. (2010), An integrated assessment of climate change, air pollution, and energy security policy, Energy Policy 38: 4021–4030	Health; Energy security	Integrating climate, air pollution and energy security policy achieves large synergies: it can cut global oil demand by 24%, thus avoiding oil depletion by 2100; it is the only scenario that meets a 3°C target; and it can reduce the number of premature deaths

Reference	Key evidence for	Evidence
		from chronic exposure to air pollution by 14,000 annually in Europe and over 3 million per year globally.
Briggs et al. (2013), Assessing the impact on chronic disease of incorporating the societal cost of greenhouse gases into the price of food: an econometric and comparative risk assessment modelling study, BMJ Open 3(10):e003543	Health	A tax of £2.72/tCO_{2e}/100 g product applied to all food and drink groups with above average GHG emissions generates £2.02 billion in revenue, cuts GHG emissions by 18,683 ktCO_{2e}/year (7% of global emissions from food produced for UK consumption) and results in 7770 deaths averted each year. However a revenue neutral tax (with low-GHG foods subsidised) is predicted to lead to a 1% increase in total calorie intake, a 5% increase in sugar consumption and 2685 extra deaths per year.
Bryan et al. (2013), Can agriculture support climate change adaptation, greenhouse gas mitigation and rural livelihoods? Insights from Kenya. Climatic Change 118:151-165	Economic benefits; International (Kenya); Social welfare	For 28 combinations of 4 packages of soil fertility measures applied in 7 agricultural zone/ soil type contexts, the net revenue from maize yield was positive in 25 cases, ranging up to US$ 1947/ha. For 14 scenarios of improved livestock feeding, revenues from milk production increased in 11 cases and methane emissions per litre of milk were always lower.
Chateau et al. (2011), Employment Impacts of Climate Change Mitigation Policies in OECD: A General-Equilibrium Perspective, OECD Environment Working Papers No. 32.	Economic benefits; Employment	An emission trading scheme aimed at achieving a 50% cut in GHGs by 2050 relative to 1990 in OECD countries and a 25% cut from BAU by non-OECD leads to a slight reduction in the pace of economic growth, but even in the worst case growth from 2013 to 2030 is only reduced from 44% to 41%, and this becomes a positive increase if the double dividend is modelled. (Co-benefits for health are not included).
Chaturvedi and Shukla (2014), Role of energy efficiency in climate change mitigation policy for India: Assessment of co-benefits and opportunities within an integrated assessment modeling framework, Climatic Change 123:597-609	Economic benefits; Energy security; Health; International (India)	Energy efficient technology is predicted to cut the fuel import bill for India by US$ 5 Bn in 2015 and US$ 33 Bn in 2035, mainly due to reduced oil imports, and cut the cost of investing in electricity generation by US$ 1-3 trillion between 2010 and 2090 (2010 prices). When a carbon tax is added at a level aimed at stabilising radiative forcing at 2.6 W/m2 by 2090, emissions of black carbon, CO, NO_x and SO_2 fall by 70-80%.
Clarke et al. (2014), Assessing Transformation Pathways, In Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, eds. O. Edenhofer et al. Cambridge, UK: Cambridge University Press, 413–510.	Economic benefits; Energy security; Health; International (Global)	Table 6.7 presents a qualitative assessment of the direction of impact of all co-impacts. This is broadly in agreement with Table 2 of this report, although the table is much more detailed. The authors conclude that the potential for co-benefits clearly outweighs that of adverse side-effects in the case of energy end-use mitigation measures (transport, buildings and industry), whereas the evidence suggests this may not be the case for all supply-side and AFOLU measures.

Reference	Key evidence for	Evidence
Cohen et al. (2015), Incorporating co-impacts into climate mitigation planning: Experiences from Latin America, MAPS	International (Latin America)	The MAPS programme has trialled co-benefit assessment approaches in South Africa, India, Brazil, Peru, Chile and Colombia, using macro-economic CGE models with stakeholder-derived mitigation scenarios, as well as developing a MCDA approach that can compare quantitative and qualitative information in a rigorous and structured framework.
COMBI, Calculating and Operationalising the Multiple Benefits of Energy Efficiency in Europe	Methodology; Economic benefits; Employment; Energy security; Health; Social welfare	This project (March 2015-Feb 2018) aims to develop an online tool for quantifying the multiple benefits of energy efficiency for air quality, health, comfort, productivity, energy costs, fuel poverty, energy security, resource use, employment and GDP, and incorporating these benefits into decision-making frameworks. It has already produced a number of useful literature reviews summarising co-benefits and assessing the challenges of quantifying and modelling co-benefits. http://combi-project.eu/downloads/
Cox (2014), Assessing the future security of the UK electricity system in a low-carbon context, Draft report, Science Policy Research Unit, University of Sussex	Energy security	Proposes a set of indicators and metrics for assessing energy security in terms of affordability, availability (long term), reliability (short term) and sustainability.
Crawford-Brown et al (2013), Climate change air toxic co-reduction in the context of macroeconomic modelling. Journal of Environmental Management 125:1-6.	Health; International	PM health benefits of global GHG reduction result in global annual cost savings of slightly more than $10 bn, when uniform GHG reduction measures across all sectors of the economy form the basis for climate policy, or $2.2 bn if only Annex I nations reduce emissions.
Dai et al. (2016), Green growth: The economic impacts of large-scale renewable energy development in China, Applied Energy 162:435-449	Economic benefits; Employment; International (China)	If the share of RE in China reaches 56% in the total primary energy in 2050, then non-fossil power sectors will become a mainstay industry with value added accounting for 3.4% of GDP, a share comparable to other sectors such as agriculture (2.5%), iron and steel (3.3%), and construction (2.1%). This will stimulate output worth $1.18 trillion from other RE related upstream industries and create 4.12 million jobs in 2050, as well as substantially reducing emissions of CO_2, NO_x and SO_2.
DAMVAD Analytics (2015), The Co-Benefits of Sustainable City Projects, C40 Cities Report	Economic benefits; Health; International; Mthodology.	Case studies of co-benefits in cities, including bus rapid transit in Bogotá and Istanbul; congestion taxes in Stockholm and London; LED Street lighting projects in Sydney and Los Angeles; community green space Copenhagen and eco-roofs in Portland. A wide range of co-benefits are assesses and monetised where possible. For example, the present value of the first 20 years of the bus rapid transit was estimated at $3.8 billion

Reference	Key evidence for	Evidence
		in Bogotá, with a benefit-cost ratio of 1.6 and an internal rate of return of 23%, and $20 billion in Istanbul, with a benefit-cost ratio of 2.8 and an internal rate of return of 23%, dominated by travel time savings in both cases.
Day et al. (2015), Assessing the missed benefits of countries' national contributions: Quantifying potential co-benefits, New Climate Institute	Economic benefits; Employment; Energy security; Health	The INDCs of the EU, US, China, Canada, Japan, India, Chile and South Africa yield total savings of over US$ 50 billion on energy imports, avoid 150,000 early deaths from air pollution and create around 150,000 extra jobs. These benefits would increase significantly if the countries adopted a target of 100% renewable energy by 2050, consistent with a 1.5-2°C target, giving energy costs savings of US$ 765 billion, avoiding 2.6 million deaths and creating 3.8 million jobs. Note that this uses a simple method and the results are first-order indications of the magnitude of potential benefits.
Dhar and Shukla (2015), Low carbon scenarios for transport in India: Co-benefits analysis, Energy Policy 81: 186-198	Energy security; International (India)	Sustainable transport policies deliver improved energy security (cumulative oil demand lower by 3100 Mtoe), improved air quality ($PM_{2.5}$ emissions never exceed the existing levels) and the cumulative CO_2 emissions are 13 billion tonnes lower.
Dowling and Russ (2012) The benefit from reduced energy import bills and the importance of energy prices in GHG reduction scenarios. Energy Economics 34:S429-S435	Energy security; International	Asian economies will benefit from reduced energy import bills, due to reduced fossil fuel use as well as lower global energy prices, if they reduce GHG emissions by 50% (compared to 1990) in line with a 2°C target. Europe saves almost $600 billion per year by 2050, and a cumulative total of over $9.8 trillion from today to 2050. China saves almost $1 trillion per year by 2050 and almost $12 trillion cumulatively, and India saves $453 billion in 2050 and $4.8 trillion cumulatively from 2010 to 2050.
Driscoll et al. (2014) US power plant carbon standards and clean air and health co-benefits. Nature Climate Change 5:535-540.	Health	A scenario to achieve a 35% reduction in CO_2 emissions from 2005 levels by 2020, similar to the US EPA's Clean Power Plan target of 30% by 2030, will cut SO_2 by 27% and NOx by 22%, reduce PM and ozone concentrations in all states, and avoid 3,500 premature deaths per year by 2020. This scenario, which adopts a flexible approach including demand-side efficiency and switching from coal to gas, achieves larger benefits than two alternative scenarios that rely on retrofitting existing coal-fired power plants either with more efficient boilers or CCS.
Dubash et al. (2013), Indian climate change policy: Exploring a co-benefits based approach, Economic and Political Weekly 48:47-61	Barriers; Methodology	Presents a MCA methodology for operationalising a co-benefits approach to climate policy formulation, based on examining trade-offs across multiple objectives of policy, such as growth, inclusion and environment.

Reference	Key evidence for	Evidence
Feliciano et al. (2014), Climate change mitigation options in the rural land use sector: Stakeholders' perspectives on barriers, enablers and the role of policy in North East Scotland, Environmental Science & Policy 44: 26-38	Barriers	A survey and workshops with farmers in Scotland assessed barriers to the uptake of a range of GHG mitigation measures, and suggested means of overcoming them including emphasising the co-benefits (reduced fertiliser costs, improved productivity), providing incentives, and providing demonstration schemes on nearby farms.
Ferroukhi et al. (2016), Renewable energy benefits: measuring the economics, IRENA	Employment; Energy security; International (Global); Social welfare	Analysis using the E3ME tool showed that doubling the share of renewables in the global energy mix would increase global GDP in 2030 by 0.6 to 1.1%, equivalent to US$ 0.7 to 1.3 trillion.
Friel et al. (2009), Public health benefits of strategies to reduce greenhouse-gas emissions: food and agriculture, Lancet 374:2016e25.	Barriers; Health	A 30% reduction in livestock production, combined with technological improvements, is needed to meet UK CCC targets to reduce GHG emissions by 50% in 2030 and 80% in 2050. This would decrease the burden of ischaemic heart disease by about 15% in the UK (equivalent to 2850 DALYs/million population/year) and 16% in São Paulo city (equivalent to 2180 DALYs/million population/year).
GCEC (2014), Better Growth Better Climate: The New Climate Economy Report, Global Commission on Economy and Climate, World Resources Institute	Barriers; Economic benefits; Employment; Energy security; Health; International; Methodology	Better urban design could reduce urban infrastructure capital requirements by more than US$ 3 trillion over the next 15 years. Restoring just 12% of the world's degraded agricultural land could feed 200 million people by 2030, while also strengthening climate resilience and reducing emissions.
Green (2015), Nationally self-interested climate change mitigation: a unified conceptual framework, Grantham Research Institute on Climate Change and the Environment Working Paper No. 199	Barriers; Methodology	Based on a review of major recent studies, this paper argues that most of the mitigation action needed to decarbonise the global economy this century is likely to be nationally net-beneficial, and therefore nationally self-interested. The paper makes the case that this should be the default assumption, shifting the burden of proving that action is nationally net-costly onto those who wish to make that claim. The barriers to mitigation action are mainly related to domestic interests, institutions and ideas formed in the fossil fuel age, i.e. carbon lock-in and the vested interests of a small number of powerful actors. A new conceptual framework is presented that recognises that some mitigation actions become nationally net-beneficial when they are implemented simultaneously or sequentially with other complementary actions (such as removal of fossil fuel subsidies), or reinforced by parallel actions taken by

Reference	Key evidence for	Evidence
		other states, or when knowledge spillover effects are taken into account. A few mitigation actions (such as stringent reductions in energy-intensive sectors) will not have net national co-benefits, but these actions are still likely to be justified when the direct global benefits of climate mitigation are taken into account.
Haines (2012), Health benefits of a low carbon economy, Public Health 126:S33-S39	Health	Health co-benefits such as reduced pollution and increased physical activity could offset part, and in some cases all, of the increased costs of mitigating action. (Review of the four 2009 Lancet papers, Woodcock et al., Friel et al., Markandya et al. and Wilkinson et al., which are also listed separately here).
Holland et al. (2011) Ancillary Air Quality Benefits. The Reduction in Air Quality Impacts and Associated Economic Benefits of Mitigation Policy: Summary Results of EC RTD Climate Cost Project	Economic benefits; Health	Under a 2°C climate stabilisation scenario, the EU27 gains 480,000 life years annually by 2050, worth €44-95 bn/y; equivalent to €24/t CO_2 abated. The average life expectancy gain is estimated at 19 months in China and nearly 30 months in India by 2050, compared to the baseline, and ozone related mortality would also be reduced by more than 75 thousand cases per year across the two countries
Howden-Chapman and Chapman (2012), Health co-benefits from housing-related policies, Current Opinion in Environmental Sustainability 4: 414-419	Barriers; Health	An evaluation of the health, energy and employment benefits of 47,000 uninsulated and poorly heated houses retrofitted by the New Zealand government found a benefit-to cost ratio of almost 4:1.
IEA (2014), Capturing the Multiple Benefits of Energy Efficiency, IEA report ISBN: 978 92 64 22072 0	Economic benefits; Employment; Energy security; Health	Energy efficiency provides multiple benefits but suffers a lack of investment compared to supply side technologies. Analysis of GDP changes due to large-scale energy efficiency policies show positive outcomes with economic growth ranging from 0.25% to 1.1% per year. The potential for job creation ranges from 8 to 27 job years per € 1 million invested in energy efficiency. Including health improvements from warmer buildings in analysis can result in cost: benefit ratios of 4:1. Mental health benefits can be half of the physical health benefits. Industrial productivity and operational benefits can be up to 2.5 times (250%) the value of energy savings.
Khosla et al. (2015), Towards methodologies for multiple objective-based energy and climate policy, Economic & Policy weekly 49: 49-59	Methodology	The paper presents a multi-criteria decision analysis (MCDA) approach for evaluating co-benefits and trade-offs, and illustrates this with two examples for India: cookstove replacement and building energy efficiency.
Küster and Blondel (2013) Calculating the economic benefits of cycling in EU-27, European Cyclists Federation	Health; Economic benefits	The annual economic benefit of cycling in the EU-27 from reduced fuel costs, noise, congestion and pollution and increased activity is at least € 205 bn, with health

Reference	Key evidence for	Evidence
		contributing 80% of this. There are also wider social and economic benefits, plus contributions of €18M a year from tourism and €45M a year from the bicycle industry.
Markandya et al. 2009, Public health benefits of strategies to reduce greenhouse-gas emissions: low-carbon electricity generation, The Lancet 374:2006-2015	Health	Decarbonising electricity production in line with a target to cut total CO_2 emissions by 50% by 2050 globally compared with 1990 would reduce $PM_{2.5}$ and deaths caused by it in the EU, China and India, with the greatest effect in India (where the health benefits of $46 per t CO_2 reduced exceed the mitigation costs of $42 per t CO_2) and the smallest in the EU (where electricity production is cleaner and mitigation costs higher).
McCollum et al. (2013), Climate policies can help resolve energy security and air pollution challenges, Climatic Change 119:479-494	Energy security; Health	Under stringent climate policy scenarios that give a 70% chance of staying within the 2°C limit, globally-aggregated DALYs can be reduced by as much as 23 million by 2030 relative to a baseline scenario that assumes current and planned air pollution policies are enacted, or by as much as 32 million if there is no further tightening of regulations. Low-carbon technologies and energy-efficiency improvements can also help to further the energy security goals of individual countries and regions by promoting a more dependable, resilient, and diversified energy portfolio. The cost savings of these climate policy synergies are potentially enormous: $100–600 billion annually by 2030 in reduced pollution control and energy security expenditures (0.1–0.7 % of GDP).
Milner et al. (2015), Health effects of adopting low greenhouse gas emission diets in the UK, BMJ Open 5:e007364.	Health	If the average UK dietary intake were optimised to comply with the WHO recommendations, an incidental reduction of 17% in GHG emissions is estimated. Such a dietary pattern would be broadly similar to the current UK average. The model suggests that it would save almost 7 million years of life lost prematurely in the UK over the next 30 years and increase average life expectancy by over 8 months. Diets that result in additional GHG emission reductions could achieve further net health benefits. For emission reductions greater than 40%, improvements in some health outcomes may decrease and acceptability will diminish.
OECD (2012), The jobs potential of a shift towards a low-carbon economy, OECD	Employment	The overall employment impacts of a shift to a low carbon economy are likely to be small, because around 90% of total CO_2 emissions are attributable to 10 industries that account for just 16% of total employment. Impacts will vary by country: the share of employment in the most polluting industries ranges from around 10% in Denmark up to nearly 30% in Poland. The challenges are to foster a smooth reallocation of workers from losing to winning firms, and to ensure that workers obtain the new mix of job skills that will be required as production patterns become progressively cleaner. Recycling carbon tax revenues so as to lower the tax wedge on labour income can

Reference	Key evidence for	Evidence
		reduce the risk that the structural change required by mitigation policies will lower employment rates. A double-dividend can sometimes be achieved, with gains in both environmental outcomes and employment.
Parry et al. (2014), How Much Carbon Pricing is in Countries' Own Interests? The Critical Role of Co-Benefits, IMF working paper WP/14/174	Economic benefits; Health	For the top 20 CO_2 emitting countries, level at which carbon pricing has net benefits, (i.e. the point at which the value of the co-benefits exceeds the carbon price) averaged $57.5 per tonne of CO_2 in 2010. This mainly reflected the value of health benefits from reduced use of coal in power plants plus reduced pollution, congestion and accidents in the transport sector. This level of carbon pricing would reduce CO_2 emissions from the top twenty emitters by 13.5%. However, co-benefits vary dramatically across countries (e.g., with population exposure to pollution) and differentiated pricing of CO_2 emissions therefore yields higher net benefits (by 23 percent) than uniform pricing. The benefits depend on productive use of revenue from pricing.
Pollitt et al. (2014) The economics of climate change policy in the UK: An analysis of the impact of low-carbon policies on households, businesses and the macro-economy. Cambridge Econometrics.	Economic benefits	Meeting the reduction in greenhouse gas emissions set out in the first four UK carbon budgets will result in slightly higher costs but will also change the structure of the economy, with net benefits for the UK. Modelling suggests a net 1.1% increase in GDP by 2030, the creation of an additional 190,000 jobs and higher real disposable incomes (£565 per household per year), relative to a counterfactual scenario where no action is taken to mitigate the effects of climate change. There would also be benefits for energy security and avoided health care costs due to air quality improvements.
Rafaj et al. (2013), Co-benefits of post 2012 global climate mitigation policies, Mitigation and Adaptation Strategies for Global Change 18:801-824	Economic benefits; Health	Policies to meet a 2^{o}C target can reduce the current loss of life expectancy due to PM concentrations in China (40 months) by 50 % in 2030. An annual cost saving of 35 billion Euros is estimated for the EU. Decrease of ozone concentrations estimated for the climate scenario might save nearly 20,000 cases of premature death per year. There are also significant reductions in acidification and eutrophication of ecosystems.
Scarborough et al. (2012), Modelling the health impact of environmentally sustainable dietary scenarios in the UK., Eur J Clin Nutr 66(6):710–715	Health	Scenario 1 (50% reduction in meat and dairy replaced by fruit, vegetables and cereals; 19% reduction in GHG emissions) resulted in 36,910 deaths delayed or averted per year. Scenario 2 (75% reduction in cow and sheep meat replaced by pigs and poultry; 9% reduction in GHG emissions) resulted in 1999 deaths delayed or averted. Scenario 3 (50% reduction in pigs and poultry replaced with fruit, vegetables and cereals; 3% reduction in GHG emissions) resulted in 9297 deaths delayed or averted.

Reference	Key evidence for	Evidence
Ščasný et al. (2015), Quantifying the Ancillary Benefits of the Representative Concentration Pathways on Air Quality in Europe, Environmental and Resource Economics 62:383-415	Economic benefits	The mitigation scenario compatible with a 2°C target (RCP 2.6) reduces total pollution costs in Europe by 84%. Improved human health accounts for about 90% of ancillary benefits, reduced biodiversity loss for about 6% and reduced impacts on buildings for about 3%. Agricultural productivity changes very little. Emissions of heavy metals decline in both scenarios but they cause very low economic damage and their contribution to total ancillary benefits is negligible.
Schucht et al. (2015) Moving towards ambitious climate policies: Monetised health benefits from improved air quality could offset mitigation costs in Europe. Environmental Science and Policy 50:252-269	Health; Economic benefits	A move towards stringent climate policies on a global scale to meet a 2°C target would reduce health impacts (68% decrease in life years lost from the exposure to $PM_{2.5}$ and 85% decrease in premature deaths from ozone in 2050 in the mitigation scenario relative to the reference scenario) and air pollution costs (by 77%) in Europe, offsetting at least 85% of the additional cost of climate policy in this region.
Shaw et al. (2014), Health co-benefits of climate change mitigation policies in the transport sector, Nature Climate Change 4:427-433	Health	This is a systematic review of the evidence on the impact of 'real life' transport policies on health and CO_2 emissions. Modelling studies show that policies that encourage walking and cycling may increase population physical activity and decrease air pollution, thus reducing the burden of conditions such as some cancers, diabetes, heart disease and dementia, and that the balance of positive health effects will substantially outweigh the harm due to the increased number of deaths caused by injury. However, only 22 observational studies were found, covering 11 interventions in 4 countries, mainly for personalised travel plans with modest improvements in cycling and walking rates. The quality was generally low. Urgent action is needed to provide more robust evidence for policies, e.g. concerning the impact of interventions on health inequalities.
Shrestha and Pradhan (2010), Co-benefits of CO_2 emission reduction in a developing country, Energy Policy 38:2586-2597	Energy security; Health; International (Thailand)	MARKAL modelling for Thailand shows that a 30% CO_2 emission reduction target for 2050 would cut SO_2 emissions by 43% and reduce cumulative energy imports for 2005-2050 by 26,000 PJ compared to the baseline, as well as diversifying the primary energy supply system towards lower use of coal and higher use of natural gas, biomass and nuclear fuels.
Smith et al. (2015a), Health and environmental co-benefits and conflicts of actions to meet UK carbon targets, Climate Policy	Economic benefits; Health	This article presents the first quantitative review of the wider impacts on health and the environment likely to arise from action to meet the UK's legally binding carbon budgets, based on the CCC's Medium Abatement Scenario. It was not possible to quantify all impacts, but for those that were monetized the co-benefits of climate action (i.e. excluding climate benefits) significantly outweigh the negative impacts,

Reference	Key evidence for	Evidence
		with a net present value of more than £85 billion from 2008 to 2030. Substantial benefits arise from reduced congestion, pollution, noise, and road accidents as a result of avoided journeys. There is also a large health benefit as a result of increased exercise from walking and cycling instead of driving.
Sovacool (2015), Fuel poverty, affordability, and energy justice in England: Policy insights from the Warm Front Program, Energy 93 (1): 361-371	Barriers; Social welfare; Health	This reviews evidence on the benefits of the "Warm Front" (WF) program, which upgraded the energy efficiency of 2.3 million "fuel poor" British homes. From 2000 to 2013, WF interventions cut CO_2 emissions per home by 1.5 tons per year, displaced £610.56 in annual energy costs and increased the average annual income per customer by £1894.79: every £1 invested saved £1 to £36.3 in energy costs over a 20 year period. WF increased daytime living room temperatures by an average of 0.58–2.83 C, reduced the amount of energy needed to maintain warmth by 5–10 percent, improved air quality in the home with less detectable dust and mould, and increased the proportion of households reporting being "thermally comfortable" from 36.4 percent to 78.7 percent. This reduced morbidity and mortality associated with fuel poverty and lessened the risk of chronic medical conditions such as cardiovascular and cerebrovascular diseases, diabetes, respiratory and renal diseases, Parkinson's disease, Alzheimer's disease, and epilepsy.
Strassburg et al. (2012), Impacts of incentives to reduce emissions from deforestation on global species extinctions. Nature Climate Change 2:350-355.	Biodiversity	A carbon price scenario of US$ 7/tonne CO_2 would prevent between 51% and 55% of the global extinctions as a result of habitat loss projected up to 2100 under business-as-usual, whereas a price of US$ 25/tonne CO_2 could reduce extinctions by 84%-93% while saving up to 4.3GT CO_2.
Suerkemper et al. (2015), Benefits of energy efficiency policies in Thailand: an ex-ante evaluation of the energy efficiency action plan, Energy Efficiency 9 (1): 187-210	Economic benefits; Employment; Energy security; International (Thailand)	Ex-ante evaluation of the 20-year Energy Efficiency Action Plan (EEAP) in Thailand, aimed at reducing energy intensity by 25% in 2030 compared to 2010, by cutting energy consumption by 20 % (38 Mtoe), shows that the plan may cut energy expenditure by 37.7 billion EUR by 2030, significantly reduce GHG emissions, cut Thailand's energy import costs and generate private investment in energy efficiency of about 5 billion EUR annually in 2030, which in turn may lead to about 300,000 new jobs.
UNEP (2011), Towards a Green Economy: Pathways to sustainable development and poverty eradication, UNEP	Economic benefits; Employment	A green investment scenario of 2% of global GDP delivers long-term growth over 2011-2050 that exceeds the optimistic business as usual case after 5-10 years, while avoiding the effects of climate change, greater water scarcity, and the loss of

Reference	Key evidence for	Evidence
		ecosystem services. It also creates green jobs that exceed jobs lost, and reduces global poverty by protecting natural capital.
Urge-Vorsatz et al. (2014), Measuring the co-benefits of climate change mitigation, Annual Review of Environment and Resources 39:549-582	Methodology	Co-benefits rarely enter quantitative decision-support frameworks, often because the methodologies for their integration are lacking or not known. This review fills in this gap by providing comprehensive methodological guidance on the quantification of co-impacts and their integration into climate-related decision making based on the literature. Examples show that co-benefits can amount to as much as 50% to 350% of direct energy benefits from technology-based investments in energy efficiency and renewable energy.
Von Stechow et al. (2015) Integrating Global Climate Change Mitigation Goals with Other Sustainability Objectives: A Synthesis. Annual Review of Environment and Resources 40:363-394	Methodology; Economic benefits; Energy security; Health; International (Global)	Builds on the synthesis of co-impacts in the IPCC's 5th Assessment Report (Clarke et al., 2014) to illustrate the challenges of assessing multiple co-impacts and presenting the information in a form that can be visualised by decision-makers. There are trade-offs between accuracy and coverage, with the need to simplify the approach in order to include more co-impacts, more countries and monetisation of impacts. Also contains a useful summary of air quality and energy security co-impacts.
West et al. (2013), Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health, Nature Climate Change 3:885-889	Economic benefits; Health	Modelling of the co-benefits of reduced PM and ozone pollution shows that global GHG mitigation avoids 0.5±0.2, 1.3±0.5 and 2.2±0.8 million premature deaths in 2030, 2050 and 2100, compared to a reference scenario. Global average marginal co-benefits of avoided mortality are US$ 50–380 per tonne of CO_2, which exceed marginal abatement costs in 2030 and 2050, and are within the low range of costs in 2100. East Asian co-benefits are 10–70 times the marginal cost in 2030. Air quality and health co-benefits, especially as they are mainly local and near-term, provide strong additional motivation for transitioning to a low-carbon future.
WHO (2011a) Health in the Green Economy: Health co-benefits of climate change mitigation – Housing sector. WHO, Geneva, Switzerland	Health; International	Very comprehensive qualitative study: evidence for reduction of heart disease, strokes, injuries, asthma and other respiratory diseases and increased wellbeing and mental health through building retrofit measures. Also covers cookstove benefits; improved sanitation; urban design for accessibility to local services; and green space.
WHO (2011b) Health in the Green Economy: Health co-benefits of climate change mitigation – Transport sector. WHO, Geneva, Switzerland	Health; International	Very comprehensive qualitative study: urges a much greater emphasis on urban design, active travel and public transport, as these strategies have much greater co-benefits than energy efficient or alternative fuel vehicles. There may be other

Reference	Key evidence for	Evidence
		cascading benefits for social welfare, including greater urban vitality and economic productivity.
Wilkinson et al. (2009), Public health benefits of strategies to reduce greenhouse-gas emissions: household energy, The Lancet 374:1917-1929	Health; International (India)	Hypothetical strategies to improve energy efficiency in UK housing stock and to introduce 150 million low-emission household cookstoves in India could yield benefits of 850 fewer disability-adjusted life-years (DALYs), and a saving of 0.6 MtCO_2 per million population in 1 year in the UK, and 12,500 fewer DALYs and a saving of 0.1–0.2 Mt CO_{2e} per million population in 1 year in India
Woodcock et al. (2009), Public health benefits of strategies to reduce greenhouse-gas emissions: urban land transport, Lancet 374:1930e43.	Health	Cutting CO_2 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 one year) than from the increased use of lower-emission motor vehicles (160 DALYs in London, and 1696 in Delhi). However, a 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 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. Therefore measures to reduce accident risk and make walking and cycling more attractive are crucial.

Appendix B: Research capacity

Table 11 lists centres of expertise, based on the affiliations of authors of the 994 papers retrieved by the main Scopus search[28]. Table 12 lists models mentioned by papers reviewed.

Table 11. Centres of expertise, ranked by number of papers retrieved in the main Scopus search

Affiliation	Number of papers
International Institute for Applied Systems Analysis (IIASA), Laxenburg	31
Tsinghua University	22
National Institute for Environmental Studies of Japan (NIES)	22
University of Cambridge	19
Australian National University	17
UC Berkeley	17
London School of Hygiene & Tropical Medicine (LSHTM)	16
UCL	15
University of Leeds	14
Imperial College London	14
University of East Anglia	13
The University of British Columbia	13
University of Oxford	13
University of Queensland	13
World Agroforestry Centre	13
Wageningen University and Research Centre	12
United States Environmental Protection Agency	12
Cicero Senter for klimaforskning	12
United Nations University	12
Indian Institute of Management Ahmedabad	12
Center for International Forestry Research (CIFOR), West Java	12
Netherlands Environmental Assessment Agency	11
Lawrence Berkeley National Laboratory	11
Sirindhorn International Institute of Technology, Thammasat University	11
Commonwealth Scientific and Industrial Research Organization	11
Ohio State University	10
Asian Institute of Technology Thailand	10
Universitetet i Oslo	10
Eidgenossische Technische Hochschule Zurich	10
Shenyang Institute of Applied Ecology Chinese Academy of Sciences	10
BC3 Basque Centre for Climate Change	10

[28]This ranking includes around 110 papers that were later rejected as not relevant after screening of abstracts

Table 12. Examples of models used for assessing co-impacts of climate change mitigation actions

Model	Description	References	Centres
AIM/ENDUSE Asia–Pacific Integrated Assessment	Computational general equilibrium model for Asia.	Dong et al. 2015; Shukla and Dhar 2015; Tan et al. 2015 Mittal et al. 2015; Xu and Masui 2009	NIES; Indian Institute of Management, Ahmedabad; Asian Institute of Technology
BEPAM Biofuel and Environmental Policy Analysis Model	Partial equilibrium, open economy, dynamic model of the fuel and agricultural sectors of the US.	Chen et al. 2014	University of Illinois
DIETRON	Analyses the role of diet in health. This model is being expanded to include physical activity.	Scarborough et al. 2012; Briggs et al. 2013	University of Oxford.
DNE21+	Partial equilibrium model.	Schwanitz et al. 2015	
E3ME	Macro-econometric E3 (Energy-Environment-Economy) model. Used for a number of studies demonstrating employment and GDP benefits of climate targets.	Barker et al. 2015; Pollitt et al. 2015	Cambridge Econometrics
ENV-Linkages	Computational General Equilibrium model.	Chateau et al. 2011; OECD 2012	OECD
EPIC Environmental Policy Integrated Climate model.	Models effect of farming measures such as no-till, green fallow, buffer strips and reduced fertiliser use on soil erosion, N and P runoff, and GHGs. Used in PES studies.	Lankoski et al. 2015, Kurkalova et al. 2004	Developed by USDA Agricultural Research Service
GAINS Greenhouse Gas and Air Pollution Interactions and Synergies.	Integrated assessment model developed by IIASA. Versions for Europe, India and China are publicly available and are used by other research teams.	Zhang et al. 2015a,b; Dong et al. 2015; Liu et al. 2013; Rafaj et al. 2013; ApSimon et al. 2009; Markandya et al. 2009	IIASA
GCAM	Partial equilibrium model.	Shukla and Dhar, 2015	Indian Institute of Management, Ahmedabad
GEM-E3	Computational general equilibrium model.	Schwanitz et al. 2015	
GLIMPSE GEOS-Chem LIDORT Integrated with MARKAL for the Purpose of Scenario Exploration	Decision model for climate change and human health impacts of energy systems. Fast, reduced form integration of MARKAL model of U.S. energy system with benefit assessment modeling.	Akhtar et al. 2013	University of Michigan
GLOBIO 3 Global Biodiversity model for policy support	Assesses impact of human activities on biodiversity; has been used to assess impacts of bio-energy. Takes input from IMAGE.		Netherlands Environmental Assessment Agency, UNEP WCMC, GRID-Arendal
GLOBIOM Global Biosphere Management Model	A global recursive dynamic partial equilibrium model to assess competition for land use between agriculture, bioenergy, and forestry.	Dowling and Russ 2012	IIASA

Model	Description	References	Centres
Haiku	Partial equilibrium electricity market model that solves for investment and operation of the electricity system in 22 linked regions of the continental United States.	Burtraw et al. 2003; 2015; Bloyd et al. 2002	Resources for the Future; University of California Berkeley
HEAT Health Economic Assessment Tool for Cyclists	Free online tool used to assess physical activity benefits of active transport. Methodology being extended to address air pollution co-benefits.	WHO 2011; Kuster and Blondel 2013	Developed by WHO and applied by European Cyclists Federation and others
IMACLIM	Computational general equilibrium model.	Schwanitz et al. 2015	
IMAGE Integrated Model to Assess the Global Environment	Partial equilibrium model; simulates impact of human activities on biodiversity, environment and human wellbeing.		Netherlands Environmental Assessment Agency
MARKAL Market al.location model	Energy system market al.location model that underpins a number of other models (e.g. TIMES, TIAM)	Dhar and Shukla 2015; Tan et al. 2015; Shrestha and Shakya 2012	Indian Institute of Management, Ahmedabad; Tsinghua University; Asian Institute of Technology
MCA	Multi-criteria analysis.	Dubash et al. 2013; UNEP 2011c	Centre for Policy Research, New Delhi, India; UNEP
MDM-E3	Macro-econometric model of the UK economy, energy system and environment	Pollitt et al. 2014	Cambridge Econometrics
MERGE-ETL	Inter-temporal general equilibrium model.	Bollen et al. 2009b,c	Netherlands Environmental Assessment Agency
MESSAGE	Inter-temporal general equilibrium model used to generate the IPCC's Representative Concentration pathways. Linked to MAGICC (climate change scenario model), MACRO (macroeconomic model of energy demand), GLOBIOM (land use model) and GAINS (AQ model) for integrated assessments.	Schucht et al. 2015; McCollum et al. 2013	IIASA
MIT IGSM-CAM	Massachusetts Institute of Technology Integrated Global System Model linked to the Community Atmosphere Model.	Garcia-Menendez et al. 2015	MIT
POLES Prospective Outlook on Long-term Energy Systems.	Partial equilibrium model for global energy supply, demand and prices. Used to assess benefits of reduced energy bills.	Dowling and Russ 2012	Developed by Enerdata, European Commission's JRC IPTS and University of Grenoble-CNRS.
REMIND	Inter-temporal general equilibrium model.	Schwanitz et al. 2015	
SCRIBE Strategies for Carbon Reduction In the Built Environment	An energy efficiency model for the UK housing stock, assessing health impacts. Uses CONTAM, a validated airflow and pollutant transport building physics tool.	Shrubsole et al., 2015	UCL and LSHTM
SIMPLE	Model of global agricultural trade and land use, used to link adaptation investments, yield growth rates, land conversion rates, and land use emissions.	Lobell et al. 2013	Stanford University
TIMES	A bottom-up energy system optimisation model.	Ma et al., 2015; Krook et al. 2011	Developed by the IEA; applied by various

Model	Description	References	Centres
The Integrated MARKAL-EFOM System			researchers including Tsinghua University
WITCH	Inter-temporal general equilibrium model.	Ščasný et al. 2015a, b	Charles University in Prague
WorldScan	Computational general equilibrium model. Covering the entire world and seven EU countries, WorldScan simulates economic growth in a neo-classical recursive dynamic framework, including emissions and abatement of greenhouse gases (CO_2, N_2O and CH_4) and air pollutants (SO_2, NOx, NH_3 and $PM_{2.5}$).	Bollen et al. 2009a; Bollen and Brink, 2014; Bollen 2015	Netherlands Environmental Assessment Agency

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