Co-benefits and trade-offs of UK climate actions

A Systematic Rapid Evidence Assessment and rating of effects on climate adaptation and mitigation outcomes

29 March 2023

UK Government

CS-NOW

Climate services for a net zero resilient world

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About CS N0W

Commissioned by the UK Department for Energy Security and Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a four-year, £5 million research programme, that uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances scientific understanding of climate impacts, decarbonisation and climate action, and improves accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by Ricardo and includes research partners Tyndall Centre for Climate Change Research, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the Natural Environment Research Council (NERC), including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and University College London (UCL).

Contents

1. Executive summary

The aim of this work package was to build an understanding of the co-benefits and trade-offs between climate mitigation and adaptation in the United Kingdom (UK) to inform the Government's efforts to promote decarbonisation and resilience. Knowledge of co-benefits and trade-offs will aid the Government's identification of no/low regret actions (i.e. actions with little or no trade-offs for either adaptation or mitigation outcomes). To develop this understanding, we have:

1. Identified UK climate actions for assessment from the UK Net Zero Strategy and the Independent Assessment of UK Climate Risk: Advice to Government for the UK's Third Climate Change Risk Assessment (CCRA3).
2. Undertaken a systematic Rapid Evidence Assessment (REA) to identify and extract relevant evidence regarding UK climate actions from peer-reviewed literature and governmental reports.
3. Based on the evidence assembled by the REA, rated the effect of UK climate actions on UK mitigation and UK adaptation outcomes, and determined confidence in these ratings.
4. Based on the ratings of the effects of UK climate actions, identified key overall findings and caveats, and recommended which actions should be the subject of detailed case studies.
5. Developed case studies for two low/no-regret actions identified:
    - CA16: Soil conservation
    - CA5: Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017

In general, our assessment determined that the nature-based actions assessed have high co-benefits and no trade-offs in terms of the adaptation and mitigation outcomes assessed in this study. In particular, "Active habitat management to increase resilience" and "Soil conservation", which are actions included in the CCRA3, have substantial positive effects on climate adaptation and mitigation.

While most of the climate actions identified as having the highest co-benefits and no identified trade-offs are nature-based, other actions, such as “Passive cooling measures” (from the CCRA3) and “Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017” (from the UK’s Net Zero Strategy) also have large co-benefits and no identified trade-offs. However, both of the latter actions encompass nature-based solutions. Passive cooling measures includes urban greening/trees, and reducing emissions from public buildings can be achieved through use of green roofs.

On the other hand, some climate actions have high trade-offs. For instance, engineered removals have a high carbon sequestration potential, but our analysis showed potential negative impacts for adaptation around natural habitat and competition with farmland (BECCS), and a high energy penalty (DACCS). Climate actions based on increased electrification only have mitigation benefits if further decarbonisation of the grid is assumed, and otherwise potentially present substantial trade-offs. These include trade-offs for adaptation, including decreased adaptive capacity in the face of increasing extreme weather events that impact energy supply and demand.

Finally, while some actions were rated as having strong co-benefits and low or no trade-offs, these may vary over time. For example, while the action on “Suitable trees, crops, and livestock for future climate in appropriate locations” (CCRA3) has high co-benefits and no identified trade-offs, benefits for climate mitigation may only be delivered over time, especially regarding tree planting. In early stages a plantation may even lead to net carbon emissions, e.g., if planted on former pasture. Implementation of the action also needs to consider the increasing magnitude and frequency of extreme weather events, as well as incremental climate change, if it is not to lead to maladaptation.

2. What is behind this analysis?

The implications for both mitigation and adaptation of interventions intended either to mitigate or to adapt to expected climate change (hereinafter “climate actions”) are intertwined. If mitigation actions are designed without considering climate vulnerabilities and risks, they may be maladapted or lead to wider maladaptation (i.e., by compounding climate impacts). For example, increasing reliance on electricity (particularly from renewable sources) for energy supply to achieve mitigation goals may increase the risk of climate-related failure of the energy system from flooding or storms.

Similarly, if climate adaptation actions are selected without consideration for climate mitigation, they may increase greenhouse gas (GHG) emissions. For example, increasing the availability and use of air conditioning to reduce risks to human health and wellbeing from increased exposure to heat may increase energy use and, thereby, GHG emissions.

On the other hand, well-designed climate actions can be resilient to climate impacts, reduce climate vulnerabilities and risks more generally, and contribute to climate mitigation. For example, improving soil health through better farming practices may help to maintain agricultural productivity in a changing climate, while also increasing soil carbon stocks.

This work package aimed to build an understanding of the co-benefits and trade-offs between climate mitigation and adaptation in the UK to inform the Government's efforts to promote decarbonisation and resilience. Knowledge of co-benefits and trade-offs will aid the Government's identification of no/low regret actions (i.e. actions with little or no trade-offs for either adaptation or mitigation outcomes). To develop this understanding, we have:

1. Identified UK climate actions for assessment from the UK Net Zero Strategy and the Independent Assessment of UK Climate Risk: Advice to Government for the UK's Third Climate Change Risk Assessment (CCRA3).
2. Undertaken a systematic Rapid Evidence Assessment (REA) to identify and extract relevant evidence regarding UK climate actions from peer-reviewed literature and governmental reports.
3. Based on the evidence assembled by the REA, rated the effect of UK climate actions on UK mitigation and UK adaptation outcomes, and determined confidence in these ratings.
4. Identified key overall findings and caveats based on the ratings of the effects of UK climate actions, and consulted with the Project Steering Group to select actions which were the subject of detailed case studies.

These steps are briefly summarised below. This methodology, and the scope of the Assessment, is set out in detail in Appendix A.

2.1 Identification of climate actions for assessment

Initial discussions with the Project Steering Group led to the identification of 39 potential climate actions for assessment. These comprised:

1. Actions primarily focused on mitigation drawn from the targets and ambitions of the UK's Net Zero Strategy and
2. Actions primarily focused on adaptation identified in the CCRA3 to address the priority risks identified in that document.

However, there was some overlap between the adaptation and mitigation actions and some appeared in both the Net Zero Strategy and CCRA3. Some actions that appeared to be targeted at mitigation were drawn from the CCRA3, and some actions that appeared to be targeted at adaptation were drawn from the Net Zero Strategy.

To further narrow the list of actions for assessment to fit within the timeframes of this study, the Project Steering Group requested that the assessment focus on those actions that are relevant to land use, the power sector, buildings, and other mitigation actions with potentially substantial adaptation benefits.

As agreed with the Project Steering Group, the resultant shortlist of 17 climate actions for assessment was:

1. Active habitat management to increase resilience
2. Improved water and nutrient management on agricultural and forested land
3. Support the restoration of at least 533,000 ha of peatland in the UK by 2050
4. Suitable trees, crops, and livestock for future climate in appropriate locations
5. Soil conservation (including soil monitoring and soil-friendly farming practices)
6. Increase tree planting rates from 13,660 hectares across the UK in 2020 to 30,000 hectares each year by the end of this Parliament
7. Achieve a minimum market capacity of 600,000 heat pumps per year by 2028

8. As many fuel poor homes as reasonably practicable to Band C by 2030, and as many homes to reach EPC Band C as possible by 2035, where practical, cost effective, and affordable
9. Passive cooling measures
10. Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017
11. By 2035 all our electricity will come from low carbon sources subject to security of supply
12. 40GW of offshore wind by 2030, including 1GW floating wind
13. 5GW of low carbon hydrogen production capacity by 2030
14. Achieve a final decision on whether to enable blending up to 20% hydrogen by volume into the Great Britain gas network by 2023, subject to successful completion of safety trials
15. The offshore oil and gas sector to have an absolute reduction in production emissions of 10% by 2025, 25% by 2027, and 50% by 2030 on the pathway to net zero by 2050
16. 100% of new cars and vans sold are zero emission by 2035, 100% of new HGV sold are zero emission, and 100% of new buses/coaches sold are zero emission
17. At least 5 MtCO2/yr of engineered removals by 2030

The descriptions of these actions, contained in the policy documents from which they are drawn, are set out in Appendix B.

2.2 Rapid Evidence Assessment

A systematic REA was undertaken to identify and extract relevant evidence from the peer-reviewed literature and governmental reports regarding UK climate actions from the UK's Net Zero Strategy and the CCRA3.

REAs use methods developed for full Systematic Reviews to ensure that they are systematic and transparent. For each climate action assessed, we have:

1. Identified relevant search terms and used them to scour the Web of Science and an agreed list of the UK Government's repositories.
2. Screened the results of these searches for relevant papers and reports.
3. Extracted evidence relevant to the climate action's effect on adaptation and mitigation outcomes (see Appendix C – evidence extraction spreadsheet).

At each stage we conducted a 10% blind peer review to ensure consistency in the screening and evidence extraction process.

References within this document are to the sources included in the evidence extraction workbook (Appendix C). The reference numbering in this document follows the numbering convention in that workbook, to provide readers with quick access to the further detail on each source.

2.3 Rating of climate actions

Based on the evidence assembled, the effects of each UK climate action on UK mitigation and UK adaptation outcomes were rated. The evidence and ratings are presented in the accompanying workbooks (Appendices C, D, and E).

From an adaptation perspective, we rated each climate action's effect on (1) sensitivity, (2) adaptive capacity, and (3) exposure to climate hazards[1] in seven key risk areas identified in the CCRA3:

1. Risks to the viability and diversity of terrestrial and freshwater habitats and species from multiple hazards.
2. Risks to soil health from increased flooding and drought.
3. Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions.
4. Risks to crops, livestock and commercial trees from multiple hazards.

1 See section 1.2 in Appendix A: Methodology for definitions of these terms.

5. Risks to supply of food, goods and vital services due to climate-related collapse of supply chains and distribution networks.
6. Risks to people and the economy from climate-related failure of the power system.
7. Risks to human health, wellbeing and productivity from increased exposure to heat in homes and other buildings.

Each of these three ratings was multiplied by the confidence rating (strength of evidence and level of agreement), without any weighting. This provides an overall rating of the action's effect on each risk area, as outlined in further detail in the body of this report.

From a climate mitigation perspective, we assessed each climate action's potential effect on (1) greenhouse gas emissions, (2) the rate of carbon uptake (carbon sequestration), and (3) the amount of carbon stored (carbon stocks). Again, each of these three ratings were multiplied by the confidence rating, without any weighting.

Due to the way overall ratings of each climate action's effects on adaptation and mitigation are calculated, greater absolute ratings may be due to a small effect with a high degree of confidence and/or a large effect but with lower confidence. Users wishing to understand the basis of each overall rating and the evidence behind it can view the individual ratings that make up each overall rating. Guidance on how to do so is provided in the next section, and in the Excel workbooks themselves (Appendices D and E).

3. How to use this analysis

3.1 How to use the ratings of all climate actions

The rating tables (Appendices D and E) provide the ratings of each climate action, along with a description of the basis for these ratings with references to the evidence. These workbooks enable policymakers to consider each climate action's co-benefits and trade-offs for climate adaptation and mitigation outcomes. When looking at the workbooks, we recommend that policymakers focus on the tabs labelled “Synthesis” in conjunction with the separate ratings sheets in the tabs labelled for each risk and mitigation outcome. The synthesis tables provide a qualitative rating of how strongly positive (darker green), or strongly negative (darker red) a given action’s outcome is for different adaptation and mitigation components.

The synthesis tables were used by this study to identify no/low-regret options, where cells are only white to green across a given action’s row. Any action with potential trade-offs has red cells in its row; the deeper the red, the greater the expectation of a trade-off.

The individual ratings that contribute to the synthesis tables are in each workbook’s separate risk area tabs and mitigation tab. In addition, clicking on any overall rating in the synthesis tables takes the user directly to the sheet and row containing the individual ratings making up that overall rating. The evidence underlying these ratings is summarised in narrative form alongside each individual rating and can be found in full in the Evidence Extraction sheets (Appendix C). The next section also summarises the key findings contained in these tables.

All ratings in the Appendix D workbook were based solely on evidence uncovered by our REA and take account of comments and quality assurance by expert reviewers. This workbook is particularly useful for highlighting gaps in the published or grey literature, i.e., cells identified as “no evidence”.

In the workbook in Appendix E, we filled these gaps by providing a rating based on expert judgment where “no evidence” was found of a climate action’s impact on climate mitigation in relation to carbon emissions, sequestration and/or stocks, or of its impact on climate adaptation for any of the seven climate risks.

Where there was ‘no evidence’ of a particular effect of a climate action in relation to a climate risk or mitigation element, we then considered whether, nevertheless, an effect could be expected. Where in our collective judgement no effect was expected, it was rated as a ‘true’ zero effect. However, where we did expect an effect, despite the lack of evidence, we provided a rating based on the project team’s expert judgment. We took account of comments and quality assurance from expert reviewers in finalising such judgements.

While the synthesis table in Appendix D contains conservative ratings that did not use expert judgement where there was a lack of evidence for expected effects, it may not fully reflect realities and may, therefore, mislead. Hence, policymakers may prefer to look at the synthesis table in Appendix E, which provides a fuller assessment upon which to base decisions. Nevertheless, we recommend that the two tables are used in combination, as together they:

1. Provide a full understanding of the drivers for/factors behind the co-benefits and trade-offs between climate mitigation and adaptation of each of the climate actions.
2. Identify research priorities, especially in relation to those climate actions where it would be reasonable to expect that they would affect climate adaptation and/or mitigation but where the REA did not find any evidence or identified contradictory evidence.

3.2 How to use the case studies

In addition to the ratings of all actions contained in the Excel workbooks, the following two actions were selected by the Project Steering Group for further analysis as case studies:

- CA16: Soil conservation
- CA5: Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017

Each of the case studies was designed for readers who wish to understand in greater detail, than is available in the Excel workbooks accompanying the Final Report, the findings of the assessment and their relevance for policymakers. These case studies, therefore, describe the methods that could be adopted when implementing the action and the effect of the climate action on each of the UK adaptation outcomes and UK mitigation outcomes that were within the scope of this assessment, associated caveats, and implications for policymakers. The case studies are available as stand-alone documents, incorporated in this report as Appendices G and H. Key findings across actions, as well as from the case studies, are incorporated into the following section.

4. Analysis and key findings

In general, our assessment determined that nature-based actions have high co-benefits and no trade-offs in terms of the adaptation and mitigation outcomes assessed in this study. In particular, “Active habitat management to increase resilience” and “Soil conservation”, which are actions included in the CCRA3, have substantial positive effects on climate adaptation and mitigation.

While most of the climate actions identified as having the highest co-benefits and no identified trade-offs are nature-based, other actions, such as “Passive cooling measures” (from the CCRA3) and “Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017” (from the UK’s Net Zero Strategy) also have large co-benefits and no identified trade-offs. However, both the latter actions encompass nature-based solutions. Passive cooling measures includes urban greening/trees, and reducing emissions from public buildings can be achieved through use of green roofs.

See Table 1, below, for a summary of the ratings of these low/no-regret actions.

On the other hand, some climate actions, such as engineered removals, have high potential trade-offs. For instance, engineered removals have a high carbon sequestration potential, but our analysis showed the potential for negative impacts for adaptation around natural habitat and competition with farmland (BECCS), and a high energy penalty (DACCS). Climate actions based on increased electrification have mitigation benefits if they are delivered alongside further decarbonisation of the grid. They otherwise present potentialtrade-offs for adaptation, including decreased adaptive capacity in the face of increasing extreme weather events that impact energy supply and demand.

See Table 2, below, for a summary of the ratings of climate actions with limited trade-offs, and Table 3, below, for a summary of the ratings of climate actions with clear trade-offs.

Table 1: Main low/no-regret climate actions

UK climate action	Risk 1 Overall score for effect on impact	Risk 2 Overall score for effect on impact	Risk 3 Overall score for effect on impact	Risk 4 Overall score for effect on impact	Risk 5 Overall score for effect on impact	Risk 6 Overall score for effect on impact	Risk 7 Overall score for effect on impact	Overall score for effect on emissions	Overall score for effect on sequestration	Overall score for effect on carbon stocks
CA3. Passive cooling measures	*1.0*	**0.0**	*2.0*	**0.0**	*2.0*	*4.0*	*6.0*	2.5	2.0	1.0
CA5. Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017.	*1.5*	**0.0**	*2.0*	**0.0**	**0.0**	*4.0*	*4.0*	7.5	1.0	1.0
CA11. Active habitat management to increase resilience	**6.3**	**5.3**	5.0	**2.3**	*1.0*	**0.0**	*1.5*	6.0	9.0	9.0
CA15. Suitable trees, crops, and livestock for future climate in appropriate locations	**3.8**	2.0	1.5	**1.7**	*2.0*	*2.0*	*2.0*	4.0	3.0	1.0
CA16. Soil conservation (including soil monitoring and soil-friendly farming practices)	3.0	6.0	0.8	3.8	2.8	**0.0**	**0.0**	5.0	6.0	9.0

Table 2: Climate actions with (limited) trade-offs

UK climate action	Risk 1 Overall score for effect on impact	Risk 2 Overall score for effect on impact	Risk 3 Overall score for effect on impact	Risk 4 Overall score for effect on impact	Risk 5 Overall score for effect on impact	Risk 6 Overall score for effect on impact	Risk 7 Overall score for effect on impact	Overall score for effect on emissions	Overall score for effect on sequestration	Overall score for effect on carbon stocks
CA1. Achieve a minimum market capacity of 600,000 heat pumps per year by 2028.	*-1.5*	**0.0**	**0.0**	**0.0**	**0.0**	*2.0*	*1.0*	4.0	0.0	0.0
CA2. As many fuel poor homes as reasonably practicable to Band C by 2030, and as many homes to reach EPC Band C as possible by 2035, where practical, cost effective, and affordable.	*-1.5*	**0.0**	**0.0**	**0.0**	**0.0**	*2.0*	*-2.0*	6.0	0.0	0.0
CA7. Achieve a final decision on whether to enable blending up to 20% hydrogen by volume into the Great Britain gas network by 2023, subject to successful completion of safety trials.	*1.5*	*-1.0*	**0.0**	*-1.0*	**0.0**	1.3	**0.0**	6.0	0.0	0.0
CA17. Increase tree planting rates from 13,660 hectares across the UK in 2020 to 30,000 hectares each year by the end of this Parliament.	3.4	**4.2**	0.0	**1.3**	*-2.0*	*-1.0*	*2.0*	0.0	9.0	7.5
CA19. 40GW of offshore wind by 2030, including 1GW floating wind.	0.0	**0.0**	*1.0*	**0.0**	*-2.5*	*3.0*	**0.0**	9.0	0.0	0.0

Table 3: Climate actions with clear trade-offs

UK climate action	Risk 1 Overall score for effect on impact	Risk 2 Overall score for effect on impact	Risk 3 Overall score for effect on impact	Risk 4 Overall score for effect on impact	Risk 5 Overall score for effect on impact	Risk 6 Overall score for effect on impact	Risk 7 Overall score for effect on impact	Overall score for effect on emissions	Overall score for effect on sequestration	Overall score for effect on carbon stocks
CA6. 5GW of low carbon hydrogen production capacity by 2030.	2.0	-2.0	0.0	-2.0	-1.0	6.0	0.0	9.0	2.0	1.0
CA9. 100% of new cars and vans sold are zero emission by 2035, 100% of new HGV sold are zero emission, and 100% of new buses/coaches sold are zero emission	-1.5	0.0	-1.0	-1.0	-2.5	6.0	0.0	6.0	0.0	0.0
CA10. At least 5 MtCO2/yr of engineered removals by 2030.	-2.0	1.5	-2.0	-9.0	-6.0	-4.0	2.0	0.0	9.0	0.0
CA18. By 2035 all our electricity will come from low carbon sources subject to security of supply.	-1.9	-2.0	-1.0	-2.0	-6.0	0.0	1.0	9.0	-1.0	0.0

Finally, while some actions were rated as having strong co-benefits and low or no trade-offs, these may vary over time. For example, while the action on “Suitable trees, crops, and livestock for future climate in appropriate locations” (CCRA3) has high co-benefits and no identified trade-offs, benefits for climate mitigation may only be delivered over time, especially regarding tree planting. In early stages a plantation may even lead to net carbon emissions, e.g., if planted on former pasture. Implementation of the action also needs to consider the increasing magnitude and frequency of extreme weather events as well as incremental climate change if it is not to lead to maladaptation.

More detail on key findings regarding specific actions identified as no/low-regret options, or as having important trade-offs requiring further consideration, is provided below. Further detail on these findings, and the sources relied on, are provided in the annexes.

4.1 CA11: Active habitat management to increase resilience – a low/no regret natural resources-based action

Active habitat management strategies improve or create habitat, leading to wider ecological benefits. Our analysis showed that this action is a no regret action, with clear positive outcomes and no obvious trade-offs among the adaptation and mitigation outcomes assessed in this study. Although it is an activity more directly targeted at increasing resilience (and thus adaptation outcomes), it has important co-benefits for climate mitigation as well.

On adaptation to climate change, strong benefits relate to CCRA3 Risks 1, 2, and 3. Active habitat management has clear positive outcomes on the viability and biodiversity of ecosystems (Risk 1): for example, restoration activities, ecosystem engineering, and rewilding. In addition, there is evidence that improved habitat management can enhance the resilience of soils to flooding and aridity through flood control and ecosystem engineering (Risk 2). Finally, the preservation and restoration of existing natural habitats can reduce risks to carbon stores (Risk 3).

Active habitat management includes a plethora of different actions. Most support emissions reduction (e.g., natural regeneration of forests, pastureland conversion), increase carbon sequestration capacity (e.g., agroforestry, wetland restoration, afforestation) and/or restore carbon stocks (e.g., peatlands management).

However, there are also some caveats relevant to the adaptation and mitigation outcomes of this action. First, uncertainty arises where a significant degree of long-term management is required. Second, some practices have specific stipulations. Agroforestry is a mostly theoretical research subject, and its integration into practice has not been studied over the long term, especially in temperate areas. If nature-based solutions with low biodiversity value, such as non-native monocultures, are encouraged, then the impact on adaptation outcomes could be limited. Habitat restoration can lead to trade-offs if the right species are not selected. In addition, there can be risks such as competition with food production.

4.2 CA16: Soil conservation – a low/no regret natural resources-based action

Soil conservation includes measures such as no-till agriculture and use of legumes in pasture rather than application of inorganic fertilisers. These activities can lead to pollution reduction, GHG emissions abatement, and increases in soil carbon, as well as contributing to successful adaptation. Our analysis showed that this action is a no regret action, with clear positive outcomes and no apparent trade-offs among the adaptation and mitigation outcomes assessed in this study.

Soil conservation practices, such as regenerative agriculture (e.g., reduced tillage, integration of crop residues into the soil, and intercropping) and improved grazing, can reduce emissions from agricultural land. In addition, regenerative agriculture strategies have a positive effect on carbon sequestration. They can also enhance carbon stocks in agricultural soils, with related co-benefits on soil fertility and crop production.

Soil conservation also has broad benefits across CCRA3 risks, especially risks 1, 2, and 4. Many soil conservation strategies can reduce soil loss and improve soil quality, with positive effects on flood and drought control (Risk 2). Cover crops and permanent vegetation reduce the need for chemical fertilisers, improving water quality and decreasing N losses (Risk 1). Finally, practices like the use of cover crops and no/reduced tillage can increase the resilience of agricultural crops to climate hazards (Risk 4).

Caveats with this action involve the need to use multiple soil conservation strategies together to achieve the positive effects on the adaptation and mitigation outcomes identified above. There is also uncertainty regarding the timeframes for these potential effects. Although positive effects can be observed over time for many soil conservation strategies, soil sinks may saturate after 10-100 years depending on the soil conservation option applied. This calls for appropriate management, depending on soil type and climate zone, to preserve carbon stocks.

For further details, see the case study prepared for this action in Appendix G.

4.3 CA5: Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017 – a low/no-regret action for the built environment

To reduce the impact public sector buildings have on total UK emissions, measures such as low carbon heating, energy efficient retrofitting, and integration of renewable energy systems are needed. These can also have adaptation benefits. Our analysis showed that climate action 5 is a no-regret action, with clear positive outcomes and no obvious trade-offs among the adaptation and mitigation outcomes assessed in this study.

The evidence on this action highlights a reduction of GHG emissions following implementation of energy efficiency measures and/or integration of rooftop solar PV in public buildings. Passive cooling measures such as green roofs can also be deployed, with positive effects on carbon sequestration.

On climate adaptation, notable effects were identified for CCRA3 risks 6 and 7. Energy efficiency measures reduce the burden on the power system, thus mitigating the risks from its climate-related failure (risk 6). In addition, energy efficiency strategies in public buildings often include mechanical cooling systems, which lead to more stable indoor temperatures, reducing exposure to overheating (risk 7).

However, it must be noted that the magnitude of the effects presented above depends on the local geographical and energetical (electricity mix) conditions.

For further details, see the case study prepared for this action in Appendix H.

4.4 CA3: Passive cooling measures – a low-regret action for the built environment, with caveats

Passive cooling measures, such as green cover, natural ventilation and better shading, address overheating in buildings and indoor thermal comfort. Alongside these adaptation benefits, they can also reduce energy demand, thus contributing to climate mitigation. Our analysis showed that climate action 3 is a low-regret action, although it presents important caveats that need to be addressed.

All passive cooling measures, on average, reduce energy consumption for cooling (especially during summer). As these practices can substitute for mechanical cooling, the effect on carbon emissions is generally positive. In addition, green infrastructure and green roofs lead to an increase in carbon sequestration.

The benefits for climate adaptation mainly relate to CCRA3 risks 6 and 7. Passive cooling measures reduce overheating and exposure to subsequent health issues (risk 7). By reducing the energy needs of the building infrastructure, climate action 3 can also mitigate the risks from climate-related failure of the electricity system (risk 6).

However, possible negative effects on carbon emissions during winter were identified, as lower indoor temperatures increase the need for heating. Implementation alongside insulation also reduces the efficiency of passive cooling during summer, potentially requiring mechanical ventilation. The evidence also showed that passive cooling measures are more efficient if implemented together.

4.5 CA15: Suitable trees, crops, and livestock for future climate in appropriate locations – a low-regret natural resources-based action with caveats

Strategies to replace or introduce suitable trees, crops, and livestock in appropriate locations are key to adapt to the inevitable changes in climate. Our analysis showed they can also contribute to climate change mitigation. Wide ranging co-benefits and limited trade-offs explain why climate action 15 is a low-regret action in terms of the adaptation and mitigation outcomes assessed in this study. However, the action presents some caveats that need to be addressed.

Although there is only limited direct evidence of the benefits of this action on carbon stocks, there are clearer indications of the positive outcomes on emissions reduction and carbon sequestration. Practices such as the use of legumes in pasture, tannin containing forage legumes, or improved genetic material in grassland sheep systems can reduce carbon emissions. Generally, introducing suitable crops, trees, and livestock in appropriate locations also increases carbon sequestration.

The effect on adaptation mainly concerns CCRA3 risks 1, 3, and 4. Using appropriate species for the climate and location reduces the exposure to hazards that would otherwise threaten biodiversity and ecosystems (risk 1). Some practices, such as appropriate forage, can lower mortality of both forage and livestock and reduce soil erosion (risk 3). Finally, climate action 15 radically decreases the risks to crops, livestock, and commercial trees from climate hazards (risk 4).

The main caveats with this action relate to uncertainty and the need for further research. There is limited evidence regarding the use of some tree species, and a lack of information concerning the timeframe for trees' mitigation effects. In addition, further research is needed regarding the resilience of different species of crops, trees, and livestock to the broad range of potential future extreme climate events.

4.6 CA10: At least 5 MtCO2/yr of engineered removals by 2030 – an action with clear trade-offs

Carbon removal technologies, such as bioenergy with carbon capture and sequestration (BECCS) and direct air carbon capture and storage (DACCS), are key components of the UK Net Zero Strategy. They present notable positive effects on carbon sequestration. However, our analysis showed several trade-offs with respect to climate adaptation, especially around natural habitat and competition with farmland.

The BECCS supply chain is characterised by extensive land use and global transport of bio-energy crops. DACCS has a high energy penalty and important energy requirements. These effects could be mitigated by transitioning to low-carbon electricity systems, but further research on this is required. Most evidence shows a positive effect on carbon sequestration. BECCS and DACCS can remove large levels of CO_2 from the atmosphere, contributing to global mitigation efforts.

The outcomes on climate adaptation for flood mitigation (risk 2) and reducing overheating (risk 7) are positive. BECCS may compete with agriculture and farmland for bio-energy crops, with negative effects on food supply and food security (risks 4 and 5). In addition, if energy supply does not keep pace with demand, the high energy penalty of (mainly) DACCS may increase the risks from climate-related failure of the power system in case of widespread integration (risk 6). This risk can be reduced by ensuring a stable supply of (low-carbon, resilient) energy.

The effects of BECCS on transport emissions and competition with agriculture are highly dependent on the provenance of crops. In addition, sustainable production of bio-energy crops could mitigate possible negative effects on biodiversity, carbon emissions, and food supply.

4.7 Caveats

Some of the climate actions assessed encompass a range of different measures or may be implemented in several different ways. Where there is evidence that the manner of implementation can affect the magnitude or even the direction of the climate action's effect on climate adaptation and/or mitigation, this has been noted in the caveats column within the Excel workbooks. In these cases, the rating reflects the most likely way that the climate action will be implemented based on its description in the UK Net Zero Strategy and/or CCRA3.

Our main use of the Excel workbooks was to identify low/no regret climate actions regarding adaptation and mitigation outcomes. Such climate actions are easily identified from the synthesis sheets in Appendices D and E, as all cells are shaded green across their row (see also Tables 1, 2, and 3 in Section 4, above).

It is important to note that the evidence base for this assessment was largely qualitative. It has therefore not been possible to assign specific numerical values/ranges to the ratings of the effects of the climate actions on climate adaptation and mitigation. For example, when assigning a rating for GHG emissions, it would theoretically be possible to identify an emissions range (in MtCO2/yr) associated with each potential rating on the -3 to +3 scale.

However, in practice, we found that the literature often lacked this level of specificity, and where provided, estimates varied greatly and were heavily caveated and context dependent. In addition, some climate actions were insufficiently defined (e.g., lacking specific targets or measurable results, or encompassing a range of different ways in which they could be implemented), thereby hindering quantitative evaluation of their likely effect.

Users should avoid calculating an overall rating of an action's effect on climate adaptation or mitigation by summing all individual ratings of the action's effect on aspects of adaptation or mitigation. Especially for mitigation, this could imply double counting: for instance, carbon sequestration benefits may accrue quickly but then tail off (e.g., as trees mature). During sequestration, some carbon may be transferred to stocks, which may continue to build as net sequestration declines. Both mitigation outcomes would therefore be rated positively but are happening over different timescales and should not be summed. For adaptation, and across actions, a common metric would be required to allow summation. Such a common currency does not currently exist, and its development would be fraught with difficulty as most metrics relevant to adaptation will not be easily quantified.

As the study focused on identifying co-benefits and trade-offs, the most important aspect was understanding the direction of the effect, rather than quantifying its magnitude. This enabled an understanding of which actions had higher co-benefits and low/no trade-offs relative to other actions, even if quantifying the magnitude of these effects was not always possible.

Thus, further refinement would be required to enable direct comparison across actions (in terms of quantitative effects on adaptation and/or mitigation outcomes), which was beyond the scope of this exercise. Refinements could include:

1. Clearer specification of some actions, e.g., only some have clear, specific targets. But as noted in the underlying spreadsheets, even actions with a clear target specification (e.g., amount of trees planted, number of heat pumps) will have varied impacts depending on how they are implemented, what 'types' (e.g., species, models) are used, and where they are placed. This makes quantifying the environmental cost-benefit of a given action uncertain. Quantifying the range of responses may help communicate this uncertainty.

2. A need to extract quantitative estimations of change engendered by each action in a common metric (where this is possible), which will be further enabled by clear specification of the actions.

Due to the time available for this study, it was focused on the key risks identified in the CCRA3 and did not consider the longer list of risks identified there. In addition, key climate risks will change over time, requiring updated analysis.

4.8 Further research needs

This study has identified several areas where further research is needed to expand knowledge and improve understanding of the co-benefits and trade-offs between climate mitigation and adaptation in the UK. Such areas include:

1. Conducting syntheses of additional case studies to inform policymakers. These may regard other low/no-regret actions, climate actions with (limited) trade-offs, or climate actions with clear trade-offs.
2. Filling the remaining knowledge gaps regarding each of the climate actions and their outcomes for climate mitigation and adaptation.
3. Assessing the further 20 climate actions that were initially excluded (those identified from the UK Net Zero Strategy and the CCRA3).
4. Evaluating other co-benefits and trade-offs of climate actions. For instance, with respect to biodiversity and ecosystem services in the UK and elsewhere. In addition, further research could cover co-benefits and trade-offs between climate actions regarding the scope, scale and speed at which they might be implemented (e.g., nationally, locally, spatially).
5. Considering the eighth CCRA risk (i.e., multiple risks to the UK from climate change impacts overseas). This means observing interactions between climate adaptation and climate mitigation actions and outcomes in the UK and elsewhere.

Appendix A: Methodology

1. Introduction

The implications for both mitigation and adaptation of interventions intended either to mitigate or to adapt to expected climate change (hereinafter “climate actions”) are intertwined. If mitigation actions are designed without considering climate vulnerabilities and risks, they may be maladapted or lead to wider maladaptation (i.e., by compounding climate impacts). For example, increasing reliance on electricity (particularly from renewable sources) for energy supply to achieve mitigation goals may increase the risk of climate-related failure of the energy system, as a result of flooding or storms.

Similarly, if climate adaptation actions are selected without consideration for climate mitigation, they may increase greenhouse gas (GHG) emissions. For example, increasing the availability and use of air conditioning to reduce risks to human health and wellbeing from increased exposure to heat may increase energy use and, thereby, GHG emissions.

On the other hand, well-designed climate actions can be resilient to climate impacts, reduce climate vulnerabilities and risks more generally, and contribute to climate mitigation. For example, improving soil health through better farming practices may help to maintain agricultural productivity in a changing climate, while also increasing soil carbon stocks.

This work package aims to build an understanding of the co-benefits and trade-offs between climate mitigation and adaptation in the UK to inform the Government’s efforts to promote decarbonisation and resilience. Knowledge of co-benefits and trade-offs will aid the Government’s identification of no/low regret decisions. To develop this understanding, we have:

1. Identified UK climate actions for assessment (Section 2).
2. Undertaken a Rapid Evidence Assessment (REA) to identify and extract relevant evidence regarding UK climate actions from peer-reviewed literature and governmental reports (Section 3). REAs use methods developed for full Systematic Reviews to ensure that they are systematic and transparent.

3. Based on the evidence assembled by the REA, rated the effect of UK climate actions on UK mitigation and UK adaptation outcomes, and determined confidence in these ratings (Section 4).
4. Based on the ratings of the effects of UK climate actions, identified key overall findings and caveats, and determined which actions we recommend should be the subject of detailed case studies (Section 5).

It is essential that the products of this work package are relevant to policymakers. Throughout this process we have, therefore, invited the Department for Energy Security and Net Zero (DESNZ), the Department for Environment, Food and Rural Affairs (Defra), and the Climate Change Committee (CCC) to comment.

In addition, to ensure consistency and high quality, team members have conducted a 10% blind QA of other team member's work at each stage of the process. Our research director (Robert Nicholls (Tyndall)) and expert advisors (Paula Harrison (UKCEH), Julia Tomei (UCL), Jeremy Blackford (NERC-PML), Rachel Warren (Tyndall)) have also quality assured the outputs at each stage.

1.1 Scope and scale of the assessment

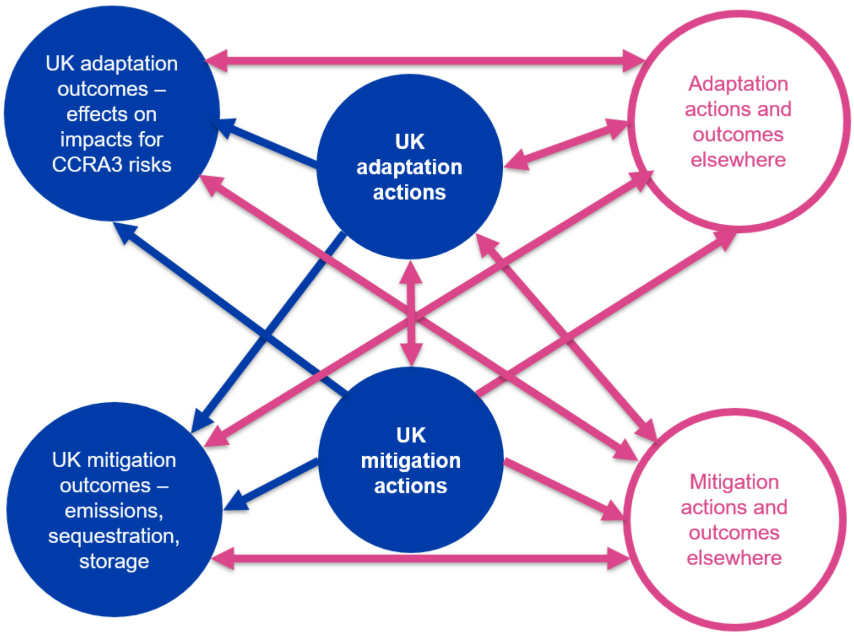
The scope and scale of the assessment was determined with care to ensure that it could be completed systematically within the time and resources available.

This work package focuses on the effect of UK climate actions on UK adaptation and UK mitigation outcomes, not on other UK climate actions (Figure 1, below). While the effects of UK climate actions on other UK climate actions are beyond the scope of this study, it is important that consideration is given to how implementation of a given action affects the ability to implement other actions (e.g., trade-offs in land use, where the same piece of land cannot be used for two different climate actions). It is recommended that such interactions between different climate actions should be the subject of a separate study.

The focus of this work package is on co-benefits and trade-offs among adaptation and mitigation outcomes from climate actions within the UK. Therefore, the effect of adaptation and mitigation actions and outcomes elsewhere on UK climate actions and UK outcomes is outside this study's scope, as is the impact of UK climate actions on adaptation and mitigation actions and outcomes elsewhere (Figure 1). Each climate action was assessed at a UK scale.

In addition, this assessment has not systematically considered lifecycle effects. Many of these would be outside of the geographical scope of this assessment (e.g., emissions involved in manufacturing of heat pumps overseas for use in the UK are outside of the geographical scope of this assessment). Due to the challenges of determining which lifecycle effects would be within or outside of the geographical scope of this study, the limited evidence on the topic for most actions, and the limited timeframe and resources available, these effects were generally excluded. However, where life cycle evidence was specifically uncovered, this was detailed in the evidence extraction spreadsheet (Appendix C).

Figure 1: Scope of assessment (*Solid dark blue in scope. White/pink out of scope.*)



The potential co-benefits and trade-offs of all climate actions will be considered:

1. For mitigation, in relation to their effects on GHG emissions, carbon sequestration, and carbon stocks.
2. For adaptation, in relation to their effects on climate sensitivities and adaptive capacities and thereby climate vulnerabilities, and the exposure of climate

vulnerabilities to climate-related hazards and thereby climate impacts regarding the seven climate risks identified in the CCRA3 that are relevant to this assessment:[2]

a) Risks to the viability and diversity of terrestrial and freshwater habitats and species from multiple hazards.

b) Risks to soil health from increased flooding and drought.

c) Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions.

d) Risks to crops, livestock and commercial trees from multiple hazards.

e) Risks to supply of food, goods and vital services due to climate-related collapse of supply chains and distribution networks.

f) Risks to people and the economy from climate-related failure of the power system.

g) Risks to human health, wellbeing and productivity from increased exposure to heat in homes and other buildings.

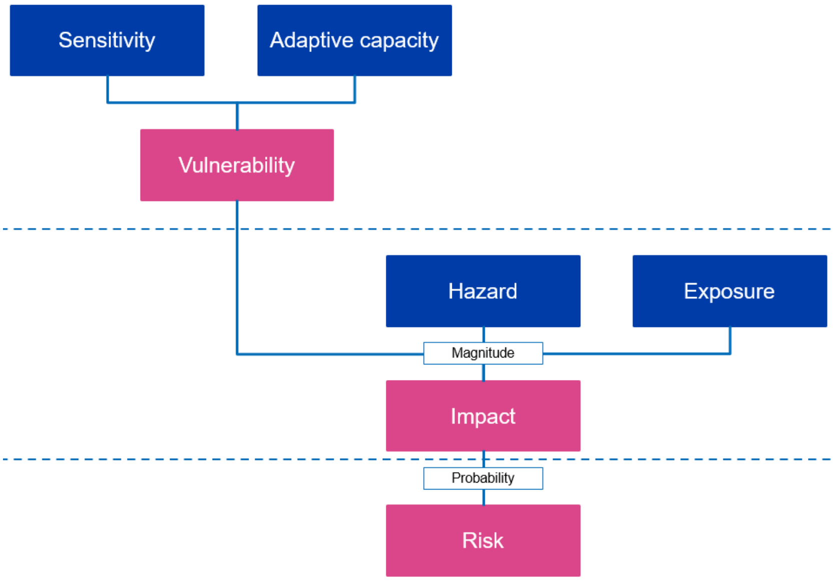
1.2 Definition of terms

1.2.1 Adaptation

For adaptation, definitions of key terms and their interactions from the Intergovernmental Panel on Climate Change (IPCC) Fifth (AR5) and Sixth (AR6-SR15) Assessment Reports have been used (see Figure 2, below), as also used in the CCRA3.

[2] One of the CCRA3 priority risks, “Multiple risks to the UK from climate change impacts overseas”, were identified as being out of scope, due to the agreed focus of this study on the effect of UK climate actions on UK adaptation and mitigation outcomes, rather than overseas impacts.

Figure 2: Impact chain flow diagram



These terms are outlined below.

Sensitivity: "The degree to which a system or species is affected, either adversely or beneficially, by climate variability or change."

Adaptive capacity: "The ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences." Table 4 below outlines the elements of adaptive capacity.

Table 4: Elements of adaptive capacity

Element	Definition
Economic resources	Expresses as the economic assets, capital resources, financial means, of a system/asset, determining its level of adaptive capacity. *Example: Finance may be available to support farmers in adopting water saving technology, but not in purchasing climate-resilient crops*
Institutions	Institutional support is available in the form of policies, regulations, strong governance system with clear accountability, etc *Example: Policies may exist to ensure the sustainable use of groundwater resources so that crops may be less sensitive to droughts*

Technology	Availability, access to and ability to develop technology at various levels (i.e., from local to national) in the sector (e.g., warning systems, protective structures, crop breeding and irrigation, settlement and relocation or redesign, flood control measures) *Example: technology may be available to support drip-irrigation systems, but not to support cattle breeding practices*
Information and skills	Sufficient knowledge and knowledge system exists to address the sensitivities identified (either direct or indirect sensitivities), there is a solid scientific understanding of the problems and information is available and understood. *Example: sufficient knowledge may be available to predict future climate hazards, but communication devices may not be available to all farmers*
Infrastructure	Presence of infrastructure to retreat, accommodate changing needs. *Example: farms' infrastructures are robust enough to withstand damages from extreme events if need be.*
Equity	Access to resources is equitably distributed *Example: technology may only be available to some farmers*

Vulnerability: "The propensity or predisposition to be adversely affected."

Exposure: "The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected."

Hazard: "The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources."

Impact: "Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system."

Risk: "Risk is often used to refer to the potential for adverse consequences of a climate-related hazard, or of adaptation or mitigation responses to such a hazard, on lives, livelihoods, health and well-being, ecosystems and species, economic, social and cultural assets, services (including ecosystem services), and infrastructure. Risk results from the interaction of vulnerability (of the affected system), its exposure over time (to the hazard), as well as the (climate-related) hazard and the likelihood of its occurrence."

Adaptation: "The process of adjustment to actual or expected climate and its effects"

Regarding Figure 2 above, adaptation:

a) Reduces vulnerabilities by reducing climate sensitivities and/or increasing adaptive capacities

b) Increases potential opportunities by increasing climate sensitivities and/or adaptive capacities

c) Reduces negative impacts by reducing vulnerabilities and/or exposure to hazards

d) Increases positive impacts by increasing 'vulnerabilities' and/or exposure to hazards

Resilience: "The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation."

1.2.2 Mitigation

In our mitigation analysis, we have also sought to align as closely as possible with the terminology used in the IPCC Fifth (AR5) and Sixth (AR6-SR15) Assessment Reports. However, full alignment with this terminology risked double counting some effects as both effects on GHG emissions and carbon sequestration, or as both carbon sequestration and carbon stocks.

For example, when assessing actions related to carbon capture and storage (CCS), this could be defined as either carbon sequestration or (negative) GHG emissions. AR6 defines CCS as: “A process in which a relatively pure stream of carbon dioxide (CO2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere.” This definition cross-references the definition for sequestration. However, sequestration is defined as: “The process of storing carbon in a carbon pool. See also Blue carbon, Carbon dioxide capture and storage (CCS), Uptake, and Sink.” In addition, a definition is provided for negative emissions: “Removal of greenhouse gases (GHGs) from the atmosphere by deliberate human activities, i.e., in addition to the removal that would occur via natural carbon cycle processes. For CO2, negative emissions can be achieved with direct capture of CO2 from ambient air, bioenergy with carbon capture and sequestration (BECCS), afforestation, reforestation, biochar, ocean alkalinization, among others.”

To avoid this risk of double counting effects on mitigation outcomes, we have taken the following approach to assessing UK climate actions against the three mitigation outcomes.

For **GHG emissions**, we consider whether the impact of a given action is to reduce emissions directly or indirectly e.g., by preventing the release of nitrous oxide (a potent greenhouse gas) through inhibitors (a direct impact) or the use of natural fertilisers such as legumes rather than manufactured fertilisers that are associated with high emissions (an indirect impact).

We do not consider the removal of CO_2 emissions (in absolute or equivalent terms) by sequestration as an emissions reduction (even though papers may refer to negative emissions). We only consider it to be **carbon sequestration**.

However, if a given action reduces GHG emissions “on-site” this could be considered an emissions reduction/saving for mitigation purposes. Whether it is a net emissions reduction depends on what gases are being reduced, and if there are any other impacts e.g., rewetting peatland reduces CO_2 emissions from drained land, but increases CH4 emissions over time.

The line between **carbon sequestration** and **carbon stocks** can be blurred. In some instances, papers referred to carbon sequestration not in terms of the rate of carbon accrual, but rather considering stocks (an amount of carbon). Given available resources, it was not possible to consider whether terminology used in the papers was consistent with how we were considering the definition of these processes, and thus some evidence ratings may mention sequestration in the carbon stocks column. This is particularly in relation to actions that increase soil carbon.

It may also be the case that the early effect of an action is to increase carbon sequestration rate, with limited initial impact on stocks. However, an impact on stocks is observed in the long term as transfer of carbon may occur, while sequestration rate actually declines as a given action approaches a new dynamic equilibrium, e.g., as trees reach maturity.

Given the potential for blurred lines, we emphasise that assessing whether there is an effect on each of GHG emissions, carbon sequestration and carbon stocks is not double (or triple) counting, providing users do not try to calculate an overall effect across these three components of mitigation by simply ‘adding’ them, particularly without considering the different timescales. As noted in further research needs, to calculate an effect across these three components, a common measurement currency would need to be developed, that also accounts for time delays and thus avoids double counting.

In relation to the effect on CCRA3 risk 3 (Risks to natural carbon stores and sequestration from multiple hazards leading to increased emissions) and potential for overlap with analysis of the effect on carbon stocks, we emphasise that our rating considered whether a given action would change the sensitivity, adaptive capacity, and/or exposure of carbon stores to climate hazards. In contrast, in relation to the effect on carbon stocks (mitigation), our scoring considered whether a given action would increase or decrease carbon stocks.

2. Identification of UK climate actions

Initial discussions with the Project Steering Group led to the identification of 39 potential climate actions for assessment. These comprised:

1. Actions primarily focused on mitigation drawn from the targets and ambitions of the UK's Net Zero Strategy and
2. Actions primarily focused on adaptation identified in the Independent Assessment of UK Climate Risk: Advice to Government for the UK's Third Climate Change Risk Assessment (CCRA3). as key actions to address the priority risks listed.

By agreeing to focus on these sources of UK climate actions, we aimed to include a mix of actions targeted at adaptation and mitigation. However, it became clear that there was already some overlap between adaptation and mitigation actions. Indeed, some actions appeared in both the Net Zero Strategy and CCRA3. Actions that may appear to be targeted at mitigation on their face at times were drawn from the CCRA3, and actions that appeared to be targeted at adaptation appeared in the Net Zero Strategy. Thus, already at this stage we see challenges in attempts to classify UK climate actions as adaptation or mitigation actions. We emphasise that the aim of this work package is to assess actions against both adaptation and mitigation outcomes, making an a priori categorisation superfluous and potentially biasing evidence assessment.

Actions that were effective duplicates were combined.[3] Two actions focused on monitoring[4] were removed, as such actions (while important) are not designed to have direct effects on adaptation and mitigation outcomes. To further narrow the list of actions for assessment to fit within the timeframes of this study, the Project Steering Group requested that the list of climate actions for assessment focus on those that are relevant to land use, the power sector, buildings, and other mitigation actions with the potential to deliver substantial adaptation benefits.

[3] For example, "Restoration of degraded peatlands" was included as an action in the CCRA3, and "Restore at least 35,000 ha of peatlands in England by 2025 and approximately 280,000 hectares of peat in England by 2050" was included as an action in the Net Zero Strategy. While the Northern Ireland Net Zero Strategy did not include a peatland-related action, those for Scotland and Wales did: "Support the restoration of 250,000 ha of degraded peatland in Scotland by 2030" and "Over 3,000 ha of peatland in Wales will be on a recovery pathway by 2025." Due to this overlap, and to ensure that the action on peatland that is assessed by this work package is UK-wide like the other actions assessed, the project team developed the following composite action, approved by the Project Steering Group: "Support the restoration of at least 533,000 ha of peatland in the UK by 2050."

[4] "Enhanced monitoring and surveillance of terrestrial and freshwater habitats" and "Monitoring of indoor temperatures".

As agreed with the Project Steering Group, the resultant shortlist of 17 climate actions for assessment was:

1. Active habitat management to increase resilience
2. Improved water and nutrient management on agricultural and forested land
3. Support the restoration of at least 533,000 ha of peatland in the UK by 2050
4. Suitable trees, crops, and livestock for future climate in appropriate locations
5. Soil conservation
6. Increase tree planting rates from 13,660 hectares across the UK in 2020 to 30,000 hectares each year by the end of this Parliament
7. Achieve a minimum market capacity of 600,000 heat pumps per year by 2028
8. As many fuel poor homes as reasonably practicable to Band C by 2030, and as many homes to reach EPC Band C as possible by 2035, where practical, cost effective, and affordable
9. Passive cooling measures
10. Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017
11. By 2035 all our electricity will come from low carbon sources subject to security of supply
12. 40GW of offshore wind by 2030, including 1GW floating wind
13. 5GW of low carbon hydrogen production capacity by 2030
14. Achieve a final decision on whether to enable blending up to 20% hydrogen by volume into the Great Britain gas network by 2023, subject to successful completion of safety trials
15. The offshore oil and gas sector to have an absolute reduction in production emissions of 10% by 2025, 25% by 2027, and 50% by 2030 on the pathway to net zero by 2050

16. 100% of new cars and vans sold are zero emission by 2035, 100% of new HGV sold are zero emission, and 100% of new buses/coaches sold are zero emission
17. At least 5 $MtCO_2$/yr of engineered removals by 2030

Descriptions of these actions contained in the policy documents from which they are drawn are set out in Appendix B.

During the various rounds of QA for this work package, some reviewers suggested the inclusion of additional actions for assessment. It was not possible to add further actions due to the timeframe and resourcing available. However, the method we have employed to assess these 17 actions could also be used to assess further actions if this is desired in the future.

3. Systematic Rapid Evidence Assessment

For each climate action assessed, we have:

1. Identified relevant search terms, and used them to scour the Web of Science and an agreed list of the UK Government's repositories.
2. Screened the results of these searches for relevant papers and reports.

3.1 Searching for evidence

For the Web of Science searches, the development of search terms involved the elaboration of primary 'action-related' keywords, and different sets of secondary keywords linked to climate adaptation or mitigation. Two separate searches for each action were conducted, with respect to the action's effects on climate adaptation and on climate mitigation. Conducting these searches separately, rather than conducting a combined search with both adaptation and mitigation search terms has sought to ensure that both the adaptation and mitigation effects of each climate action are considered equally. For example, conducting separate searches for each action regarding adaptation and mitigation has ensured that, for an action typically considered to be a "mitigation" action, evidence regarding adaptation has not been "crowded out" by search results related to mitigation, and vice versa.

Search strings were developed based on Web of Science search operators (see Appendix F). These search strings were refined based on the descriptions of each of the climate actions that are the focus of this assessment (see Appendix B). An iterative process of search test runs and initial screening identified actions with limited or irrelevant results, making it possible to further refine terms to improve the relevance of the search results.

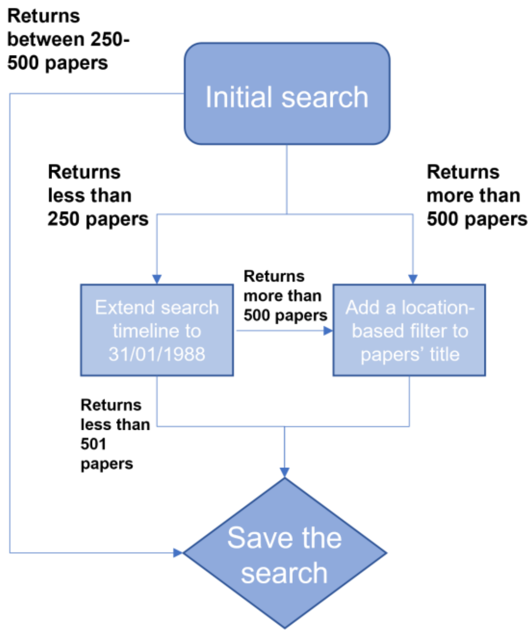
After application of the final search strings, the following criteria were applied to each of the two searches (i.e., regarding climate mitigation and climate adaptation) for each action to focus search results for screening on a manageable number of papers as follows (also presented visually in Figure 3, below):[5]

1. The publication date range was initially set at 1st January 2015 to 31st January 2022
2. If the search obtained less than 250 manuscripts, the publication date range was extended up to 31st January 1988 (the founding date of the IPCC). If the search subsequently returned:
    a. Less than 501 manuscripts, all were retained and the first 250 were screened (as discussed further below)
    b. More than 500 manuscripts, an additional location search string[6] applied to the manuscripts' titles narrowed results to areas with comparable geographical and climatic conditions to the UK. If more than 500 manuscripts were still retrieved after this filter was applied, only the first 500 manuscripts were retained.
3. If the search returned 250-500 manuscripts, all were retained and the first 250 were screened (as discussed further below).
4. If the search returned more than 500 manuscripts, an additional location search string was applied (as in Point 2b above).

[5] A language filter was not applied to the searches. However, likely due to the use of English language search terms, only English language results were retrieved. Given the geographic focus of this work package on UK climate actions and outcomes, this was considered appropriate.

[6] (global OR Eur* OR temperate OR Great Britain OR Brit* OR United Kingdom OR UK OR Eng* OR Wales OR Wel* OR Scot* OR Northern Ireland OR Northern Irish)

Figure 3: Flow chart of the search process



The grey literature searches were focused on the online publication repositories of the Department for Business, Energy & Industrial Strategy (BEIS) (as it was then called, now DESNZ), Defra, CCC, the Scottish Government, the Northern Ireland Assembly Department of Agriculture, Environment and Rural Affairs (DAERA) and the Welsh Government. Search strings developed for the Web of Science searches could not be used to filter results in these repositories due to different search engine rules.[7] Instead, the repositories were filtered using various methods, as outlined below, accounting for the characteristics of the search engines and the availability of results. In addition, only evidence from 1st January 2015 was included in the searches:

1. For the BEIS and Defra publication repositories, results were filtered by topic ("environment") and sub-topic ("climate change and energy"), and by content type ("research and statistics"). After applying the topic, sub-topic, and content type filters, all results were screened.
2. The CCC publication repository only allowed for filtering by content type ("report") and not by topic. However, given the focus of the CCC on climate change, it was

[7] For example, some of these search engines did not allow for terms and connectors or wildcards. All of these search engines also applied character limits to search strings, and the majority of our search strings were too long for these search engines.

considered likely that most results would relate to this topic. Thus, after applying the content type filter, all results were screened.

3. For the Northern Ireland DAERA publication repository, there was no single relevant topic filter available. However, a filter by content type (“research and analysis”) narrowed the results to 176 papers. All these results were screened.
4. The results from the Scottish Government publication repository were filtered by topic (“environment and climate change”) and publication type (“research and analysis”). After applying the topic and content type filters, all results were screened.
5. For the Welsh Government publication repository, filtering was only possible by topic (“environment and climate change”). All results were screened after applying the topic filter.

3.2 Screening the evidence

Results for each Web of Science searches were transferred to an Excel-based literature review table template and ordered by date. Starting with the most recently published results, up to 250 papers per search (i.e., two per action – one for mitigation and one per adaptation) per source were screened by title and, if successful, by abstract. This further restriction to 250 papers per action ensured a manageable volume of results, which could be screened within the time available for this task.

As the grey literature publication repositories did not produce results in spreadsheet format that could readily be transferred to the literature review table, only those results that passed an initial title screening were transferred to the literature review table. These results were then subject to a further abstract/executive summary/contents page review, as was done for the academic literature. As it was not possible to apply search terms related to specific actions for the grey literature searches, all results were screened for potential relevance to all actions.

When screening the actions, the project team focused on:

1. The definition of each action, drawn from the Net Zero Strategy and CCRA3, supplemented by the equivalent documents for devolved administrations, where required (as outlined in Appendix B).

2. The extent to which the evidence on the action would be relevant to the assessment of the action's effect on adaptation and mitigation outcomes, as discussed in section 1.2.

3.3 Quality assurance

After screening, a systematic and blind quality assurance (QA) process was implemented, ensuring that different experts from those who screened each action analysed up to 25 papers (i.e., at least 10% of the results) per Web of Science search, as follows:

1. For those actions having gathered more than 250 returns, manuscripts 1-5, 51-55, 101-105, 151-155, 201-205 were selected for QA.
2. For actions with fewer than 25 returns, all manuscripts have undergone QA.
3. For all other actions, 25 manuscripts have been chosen throughout the Spreadsheet to include a mix of recent and older papers.

For the grey literature, QA involved a different expert screening the retained titles and abstract/executive summary/contents page description, and assessing whether to include or exclude the document, considering all climate actions. Consideration was also given to whether the initial screener and the expert providing QA agreed on which climate actions any given report was relevant to.

If the QA process resulted in any differences between the list of documents recommended to be retained in the original screening and those recommended to be retained during QA, the individual responsible for QA discussed differences with the person originally responsible for screening for that action, and amendments were made accordingly.

3.4 Review by Project Steering Group and Expert Advisors

The Project Steering Group and Expert Advisors were then invited to review the list of documents retained for further assessment. This resulted in the inclusion of a small number of additional papers (primarily grey literature) for assessment.

4. Rating of climate actions

To understand the implications of the insights gained from the literature review for the co-benefits and tradeoffs of climate actions on UK mitigation and adaptation outcomes, we have followed a series of steps to rate each climate action:

1. Use the literature review (and in a separate analysis, using expert judgment where no literature was found on an aspect) to inform assessment of each action regarding:
    a. Its adaptation outcomes by describing and rating its effect on climate sensitivities and adaptive capacities (and, therefore, vulnerabilities), and on exposure to climate-related hazards (and, therefore, impact) for each of the seven relevant CCRA3 risks.
    b. For mitigation outcomes by describing and rating the action's effect on GHG emissions, carbon sequestration, and carbon stocks.
2. Rating the strength of the evidence supporting the ratings of the effects outlined in Step 1.
3. Rating the agreement between different sources of evidence supporting the ratings of the effects outlined in Step 1.
4. Based on the ratings of strength and agreement, rating the confidence in the ratings of the effects outlined in Step 1.
5. Based on the ratings of each actions' effect on mitigation and adaptation outcomes, and the ratings of confidence in the ratings of effect, develop overall effect and confidence ratings for mitigation and for adaptation for each action.
6. These ratings across all CCRA3 risks and all dimensions of mitigation were then analysed in the whole to identify no/low regret actions (i.e., actions with high mitigation and adaptation co-benefits and low/no trade-offs) for further assessment via case studies.

Each of these steps is outlined in further detail below.

4.1 Rating each climate action

The evidence gathered via the literature review was used to rate the effect of each climate action on:

1. Adaptation outcomes, by rating the following in relation to each of the seven climate risks identified in CCRA3 that are within the scope of this assessment:
    a) The effect on sensitivity to climate-related hazards ("sensitivity") and adaptive capacity (and thereby climate vulnerability, which will be auto-calculated by averaging the ratings for the effects on sensitivity and adaptive capacity), and
    b) The effect on the exposure of the climate vulnerability to climate-related hazards (and thereby climate impact, which will be auto-calculated by averaging the ratings for vulnerability and exposure).
2. Mitigation outcomes, by rating the effects on GHG emissions, carbon sequestration, and carbon stocks.

The assessment was recorded in an Excel workbook (see Appendix D). Separate sheets within the workbook were completed in relation to climate adaptation for each of the seven climate risks and regarding climate mitigation. Each sheet lists all climate actions, and a series of columns was completed in their regard, including:

1. Description of action – as provided in the CCRA3 or the UK Net Zero Strategy.
2. Timeframe to implement – as identified in CCRA3 or the UK Net Zero Strategy.
3. Description of effect – regarding each of the elements of climate adaptation and climate mitigation with cross-references to the literature describing the effect.
4. Rating of effect – regarding each of the elements of climate adaptation and climate mitigation. Ratings will be on a scale from +3 to -3:
    a) +3 indicates a substantial positive effect
    b) +2 indicates a moderate positive effect
    c) +1 indicates a limited positive effect

   d) 0 indicates no effect or a neutral effect
   e) -1 indicates a limited negative effect
   f) -2 indicates a moderate negative effect
   g) -3 indicates a substantial negative effect
   h) N/A indicates that there was no evidence regarding an effect
5. Confidence in each rating – based on strength of evidence and level of agreement, as outlined below. All information was recorded in the Excel workbook (Appendix D) developed in the preceding steps, with headings for each of the aspects mentioned above.
6. Timeframe for effect on climate impact (i.e., on climate adaptation) or on climate mitigation.
7. Further research needs.

Rating were undertaken by one person per climate action to ensure that the criteria were applied consistently. A second person from the study team independently screened a 10% sample of ratings per individual via blind repeat of the rating process to check that there was no bias.

It is important to note that the evidence base for these ratings was largely qualitative. It has therefore not been possible to assign specific numerical values to the ratings listed above. In addition, the definitions of some actions were not sufficiently clear to allow for such analysis – for example, lacking specific targets or measurable results, or encompassing a range of different ways in which the action could be implemented, which would hinder precise quantitative evaluation of the action's likely effect.

Given the focus of this study, it was not essential to quantify precisely the magnitude of the impact. Given the focus on identifying co-benefits and trade-offs, the most important aspect was understanding the direction of the effect, rather than quantifying its magnitude.

4.1.1 Amendments following the QA process

In addition, the expert advisers and project steering group conducted a QA of the ratings. They identified a small number of additional papers that could help fill some of the gaps in the literature, and made various suggestions which improved the presentation of the results.

For example, overall ratings for adaptation and mitigation were provided in previous versions of the rating spreadsheet shared with the project steering group and expert advisors. These were based on averages of the ratings for each of the seven climate risks, and for each of the three mitigation outcomes. However, it became apparent that, rather than helping users understand the analysis, these overall ratings led to greater confusion – particularly where evidence was unavailable regarding one or more of the components of these overall ratings, leading to challenges comparing against actions with evidence for a greater number of adaptation and mitigation outcomes.

To ensure transparency regarding the basis of the analysis, we have therefore removed the overall ratings. The summary page of the Excel workbook now displays all ratings for each adaptation and mitigation outcome for each action alongside each other. To facilitate comparison in the absence of overall ratings, the ratings have now been colour-coded along a continuous colour gradient, with green representing the most positive ratings (i.e., the highest co-benefits) and red representing the most negative ratings (i.e., the highest trade-offs).

In addition, to ensure clarity regarding the basis for the ratings when a user is viewing the summary sheet only, we have used a key to indicate where an adaptation rating is based on a rating of all three adaptation components (sensitivity, adaptive capacity, and exposure), only two of those components, or only one of those components. This does not apply to mitigation, as all three mitigation outcomes are displayed on the summary sheet.

4.1.2 Assessment based on expert judgment

Reviewers also indicated that it would be helpful, where evidence is lacking regarding the effect of an action on an adaptation or mitigation outcome, to provide a rating based on expert judgment. This would help avoid the risk that users of the spreadsheet would assume that no evidence regarding a particular adaptation or mitigation outcome meant no effect, when expert judgment might indicate otherwise. This could be particularly problematic where an action otherwise appears to have positive effects on various adaptation and mitigation outcomes, and where there is no evidence regarding other adaptation or mitigation outcome(s), but expert judgment indicates a likely negative effect.

To address this, the project team (informed by comments from the expert advisors and project steering group) collectively considered each evidence gap to determine whether a rating was possible based on expert judgment, and to reach agreement on what that rating should be. This allowed us to draw on the project team's collective expert judgment and reduce the risk of bias. We have provided a separate spreadsheet (Appendix E) in which these gaps in the evidence were filled based on expert judgment, to allow for comparison with the ratings reached solely based on extracted evidence.

4.2 Evaluating confidence

We evaluated confidence in each of the ratings of effects based on the evidence to better inform decision-making. Confidence was rated according to the methodology used in IPCC AR5[8] and AR6[9] regarding:

1. The number of studies and the strength of their evidence:
    a) 3 indicates robust evidence: relevant[10] evidence from multiple peer-reviewed sources
    b) 2 indicates medium evidence: relevant evidence from one peer-reviewed source, supported by independent grey literature and our expert judgment

[8] Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe, and F.W. Zwiers, 2010. Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on consistent treatment of uncertainties. Intergovernmental Panel on Climate Change (IPCC).
[9] IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.), at page SPM-4.
[10] The relevance of the evidence was determined based on expert judgment: for example, where no UK evidence is available, the extent to which evidence from elsewhere is likely to be applicable to the UK.

   c) 1 indicates limited evidence: no relevant peer-reviewed literature, only relevant grey literature and our expert judgment

2. The degree of agreement between different sources of evidence (i.e., “low (1),” “medium (2),” or “high (3)”) based on our expert judgment.

These ratings of strength and agreement were averaged to provide an overall confidence rating for each of the ratings of effects.

When rating confidence, we avoided taking undue account of the same study being published in more than one place – such studies were only be counted once, regardless of duplicate publication. However, the common authorship of multiple papers did not, on its own, reduce the confidence rating if each document provided new and different evidence (for example, by focusing on a different effect of a climate action).

Confidence rating were be undertaken by one person per climate action to ensure that the criteria are applied consistently. These were also reviewed by a second person from the study team alongside the blind 10% sample screening of ratings outlined above.

4.2.1 Amendments following the QA process

As noted in the preceding section, following the initial assessment based on the REA only, we created a separate spreadsheet in which we applied expert judgment to fill gaps in the evidence. In addition to a rating of the strength of the effect of the action on mitigation and adaptation outcomes, we also provided a confidence rating. This confidence rating combined with the lowest rating for strength of evidence, and an assessment of level of agreement amongst ourselves in accordance with the scale provided above. We took account of comments and quality assurance from expert reviewers in finalising such judgements.

4.3 Combining ratings of effect and confidence in ratings

To obtain an overall rating for the effect of each action on each adaptation and mitigation outcome, the rating for the magnitude of the action’s effect was multiplied[11] by the

[11] Multiplying ensured negative effects remained with a negative rating, positive effects with a positive rating. For example, if an effect rating of -1 was added to a confidence rating of +3, the

confidence rating for that effect. This ensures that the differing amount of evidence available to support ratings is taken into account when comparing actions.

Under this approach, an action with a relatively small, but relatively certain, effect on an adaptation or mitigation outcome, will receive a similar overall rating as an action with a relatively large, but relatively uncertain effect. For example, an action that receives a +1 rating for the magnitude of its effect and receives a confidence rating of 3 will receive the same overall rating as an action that receives a +3 rating for the magnitude of its effect and a confidence rating of 1.

Ultimately, policymakers will need to decide whether they want to prioritise actions that are likely to have a small but certain effect or actions that may have a large effect but are less certain to achieve the desired outcomes. For transparency, the Excel workbook provides a record of all information underpinning the ratings, including the components via which the ratings were calculated.

4.4 Identifying knowledge gaps and research needs

By evaluating the available evidence and confidence in that evidence for each adaptation-related and mitigation-related element of the assessment and recording this information in the Excel workbook, we have been able to identify areas where evidence is not readily available, or where confidence in that evidence is low due to the limited amount available and/or its limited agreement.

The areas where there are knowledge gaps or further research needs has been noted in the Excel workbook.

4.5 Identifying caveats

Specific caveats that should be attached to the ratings of individual climate actions in relation to their effect on climate impact (i.e., on adaptation) across the seven risks identified in CCRA3 that are within the scope of this assessment and on climate mitigation,

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overall score would be +2, potentially leading to confusion as to whether the overall effect was positive or negative.

have been noted in the Excel workbook. Broader caveats regarding the interpretation of the results are addressed below.

Importantly, the caveats section of the spreadsheet notes where, depending on the way the action is implemented, the rating could be different in magnitude or direction. Some of the actions identified involve several different measures or sub-actions, or are broad enough that they could be implemented in a number of different ways. Where we have identified evidence that the manner of implementation would affect the magnitude or direction of the effect, this has been noted in the caveats. In these cases, the rating provided is based on the weight of the evidence and the most likely manner in which the action will be implemented based on its description in policy documents.

5. Case study selection

Of the 17 UK climate actions analysed by this work package, two actions were selected by the Project Steering Group for further investigation as case studies:

- CA5: Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017
- CA16: Soil conservation

These actions were selected due to their high co-benefits and lack of trade-offs.

Appendix B: Final list of climate actions for assessment and descriptions

Action	Description
CA1: Achieve a minimum market capacity of 600,000 heat pumps per year by 2028	"Heat pumps will be the best low carbon heating option for some types of buildings, for example, if they are new buildings or off the gas grid. A third of the targeted heat pumps will be installed in new dwellings."
CA2: As many fuel poor homes as reasonably practicable to Band C by 2030, and as many homes to reach EPC Band C as possible by 2035, where practical, cost effective, and affordable	"60% of UK homes have an Energy Performance (EPC) Band D and below. Following the recent trend in energy performance improvements in the housing sector, the UK will adopt measures to enhance energy efficiency and reduce emissions from energy use."
CA3: Passive cooling measures	"The UK will address overheating in new and refurbished homes with passive cooling measures such as better shading, reflective surfaces and green cover. Parallelly to providing adaptation to climate variability, passive cooling reduces energy demand, especially during summer."
CA5: Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017	"Direct emissions from public sector buildings account for around 2% of total UK emissions. The UK aims to further abate emissions investing in measures to reduce fossil fuel use, such as low carbon heating, energy efficiency improvements, and the integration of low carbon electricity systems such as rooftop solar PV."

CA6: 5GW of low carbon hydrogen production capacity by 2030	“The UK will harness its skills and capabilities to produce CCUS-enabled and electrolytic low carbon hydrogen. Fuel switching to low carbon hydrogen will decarbonise sectors and processes harder to electrify.”
CA7: Achieve a final decision on whether to enable blending up to 20% hydrogen by volume into the Great Britain gas network by 2023, subject to successful completion of safety trials	“Blending hydrogen into the gas grid will be used as an initial strategy to decarbonise heating. This shift must be done ensuring safety, operability, security of supply and affordability, and with the recognition that it cannot be a long-term solution.”
CA8: The offshore oil and gas sector to have an absolute reduction in production emissions of 10% by 2025, 25% by 2027, and 50% by 2030 on the pathway to net zero by 2050	“The reduction in production emissions from the offshore oil and gas sector will result from abatement from electrification and flaring. Zero routine flaring practices are essential in order to meet the targets.”
CA9: 100% of new cars and vans sold are zero emission by 2035, 100% of new HGV sold are zero emission, and 100% of new buses/coaches sold are zero emission	“The decarbonisation of the UK transport sector is driven by the transition to zero emission cars and vans. These have significant advantages over the existing carbon intensive technology, and register reducing costs and growing consumer demand. Large investments are also being made in zero emission HGVs and buses.”
CA10: At least 5 MtCO2/yr of engineered removals by 2030	“The UK will deploy mature BECCS technologies and commercial scale DACCS systems to deliver net-negative emissions. This infrastructure will be likely located within or near industrial processes.”

CA11: Active Habitat Management to increase resilience	"Through the Environment Bill we will legislate for Local Nature Recovery Strategies – a new system of spatial strategies that will map proposals for improving or creating habitat for nature and wider environmental benefits, helping to deliver net zero objectives."
CA13: Improved water and nutrient management on agricultural and forested land	"Agriculture emissions are largely from livestock and nutrient management. The pathway assumes emissions will be reduced through improved and innovative farming practices." Agriculture, forestry, and other land use (AFOLU): "We will introduce three environmental land management schemes: the Sustainable Farming Incentive (SFI), Local Nature Recovery (LNR) and Landscape Recovery (LR). The SFI will be open to all farmers and will incentivise low carbon practices, for example, soil and nutrient management."
CA14: Support the restoration of at least 533,000 ha of peatland in the UK by 2050	"Tackling the drivers of peatland degradation is essential. The EPAP commits to ending the horticultural use of peat in the amateur sector...... Legislation to end managed burning on protected blanket bog that is 40 cm deep or more...... From 2024, public funding for peatland restoration will be available in England through the new environmental land management schemes..... Where it is not possible to restore peatlands, we will support new responsible management measures for lowland peatlands......"
CA15: Suitable trees, crops and livestock for future climate in appropriate locations	"While reducing emissions, we must also adapt to the inevitable changes in our climate, ensuring that policies supporting net zero are resilient to current and future

	climate risks, and preventing locking in future vulnerabilities or maladaptation”
CA16: Soil conservation	“Beneficial adaptation actions involve soil-friendly farming practices, including no-till and precision farming, to minimise erosion and pollution, and good water management on agricultural and forested land to keep soil moisture in balance.”
CA17: Increase tree planting rates from 13,660 ha across the UK in 2020 to 30,000 ha each year by the end of this Parliament	“Forestry and woodlands currently act as carbon sinks and, in 2019, captured about 4% of our emissions. Since 2010, 123,000 hectares of new woodland has been planted across the UK, an area equivalent to Bedfordshire. The England Tree Action Plan (2021) committed to increasing tree planting rates from 13,410 hectares across the UK in 2020/21, to 30,000 hectares each year by the end of this Parliament.”
CA18: By 2035 all our electricity will come from low carbon sources subject to security of supply	“This means increased investment in the grid network, electricity storage solutions and flexible grid management, to ensure decarbonisation without risking security of supply”...... “whilst meeting a 40-60% increase in demand.”
CA19: 40 GW of offshore wind by 2030 including 1GW floating wind	“We need to continue to drive rapid deployment of renewables, for example offshore wind, so we can reach substantially greater capacity beyond 2030, and accelerate the cost reduction and commercialisation of floating offshore wind. As we decarbonise our electricity system our wholesale prices will become less exposed to fluctuations in global fossil fuel prices, and we would expect wholesale prices to be lower.”

Appendix C: Evidence extraction to support rating of climate actions

Please see the attached Excel file.

Appendix D: Rating of climate actions based on evidence extraction only

Please see the attached Excel file.

Appendix E: Rating of climate actions based on evidence extraction and expert judgment to fill gaps

Please see the attached Excel file.

Appendix F: Literature search approach and search strings per action

As noted in the methodology, Web of Science was searched systematically up to the end of January 2022. We conducted all searches with “Topic = ”, and sorted by date order, newest first.

Action specific search terms were as follows:

Table 5: Action specific search terms for systematic literature review

Action	Search terms
1: Achieve a minimum market capacity of 600,000 heat pumps per year by 2028	(((heat pump*) AND (building* OR dwelling*)) NOT (solar heat* OR geotherm* heat*))
2: As many fuel poor homes as reasonably practicable to Band C by 2030, and as many homes to reach EPC Band C as possible by 2035, where practical, cost effective, and affordable	((energ* efficien* OR electric* efficien* OR energ* perform* OR electric* perform* OR energ* use*) AND (home* OR hous* OR residen* OR dwelling*) AND (insulat* OR draught proof* OR double glaz* OR condensing boiler* OR low* energy* light* OR solar water heat*))
3: Passive cooling measures	((passive cool* OR passive therm* manag*) AND (solar shad* OR double glaz* OR triple glaz* OR green roof* OR green wall* OR green cover* OR tree* OR radiant cool* OR insulat* OR heat spread* OR heat sink* OR heat pip* OR therm* material* OR reflectiv* surface*) AND (building* OR hous* OR hom* OR infrastructur* OR propert*))

5: Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017	((public sector* OR public building* OR municipal* building* OR government* building* OR hospital* OR school* OR universit* OR college* OR librar* OR courthous*) AND (fossil fuel* OR GHG* OR greenhouse gas* OR emission* OR energy* efficien* OR electric* efficien* OR decarb* OR low* carb* heat* OR low* carb* electric* OR rooftop* solar))
6: 5GW of low carbon hydrogen production capacity by 2030	((carb* capt* OR CCUS OR electrolytic OR green OR low* carb* OR low* CO2 OR sust*) AND hydrogen)
7: Achieve a final decision on whether to enable blending up to 20% hydrogen by volume into the Great Britain gas network by 2023, subject to successful completion of safety trials	(Hydrogen blend* OR hydrogen integrat* OR hydrogen incorporat* OR hydrogen addit*) AND (gas* grid* OR gas* pipeline* OR gas* network*)
8: The offshore oil and gas sector to have an absolute reduction in production emissions of 10% by 2025, 25% by 2027, and 50% by 2030 on the pathway to net zero by 2050	(offshore oil* OR offshore gas* OR offshore petrol*) AND (electrifi* OR flaring* OR zero flaring* OR zero routine flaring*)
9: 100% of new cars and vans sold are zero emission by 2035, 100% of new HGV sold are zero emission, and 100% of new buses/coaches sold are zero emission	((zero emission* vehicle* OR electric* vehicle* OR hydrogen vehicle* OR zero emission* van* OR electric* van* OR hydrogen van* OR zero emission* bus* OR electric* bus* OR hydrogen bus* OR zero emission* HGV* OR electric* HGV*

	OR hydrogen HGV*) AND (decarb * OR net zero OR transport sector OR transition* OR integrat*))
10: At least 5 MtCO2/yr of engineered removals by 2030	((Direct air capt* OR carb* capt* OR carb* remov* OR CO2 capt* OR CO2 remov* OR ccs OR ccus OR GHG remov* OR greenhouse gas* remov*) AND (beccs OR daccs))
11: Active Habitat Management to increase resilience	((Restor* OR Active hab* manag* OR interven* OR rehab* OR reclam* OR reintrod*) AND (Biodiv* OR Resil* OR resist*))
13: Improved water and nutrient management on agricultural and forested land	((Water OR drain* OR irrig* OR eros* OR nut* OR nitr* OR phos* OR pot* OR sul* OR micronut* OR fert*) AND (Manag*) AND (Agric* OR field* OR pastur* OR forest* OR wood* OR decid* OR conif* OR plantat*))
14: Support the restoration of at least 533,000 ha of peatland in the UK by 2050	((Restor* OR rehab* OR manag* OR reclam* OR reintrod* OR rewet* OR biodiv*) AND (fen OR Peat* OR moor* OR bog*))
15: Suitable trees, crops and livestock for future climate in appropriate locations	((Adapt* manag* OR assist* migr* OR breed* OR reintrod* OR heirloom OR rare breed* OR mobil* OR future) AND (Tree* OR veget* OR crop* OR cereal* OR root veg* OR anim* OR livestock))

16: Soil conservation	(Soil conservation OR soil monit* OR soil health OR soil-friendly farm* OR soil biodiv*)
17: Increase tree planting rates from 13,660 ha across the UK in 2020 to 30,000 ha each year by the end of this Parliament	(Afforest* OR Reforest* OR Tree plant* OR wood* creat* OR for* creat*)
18: By 2035 all our electricity will come from low carbon sources subject to security of supply	((Low carb* OR Low C OR nuclear OR wind OR wave OR tid* OR sol* OR renewable* energ* OR sust* energy* OR hydro* OR H2) AND (electric*))
19: 40 GW of offshore wind by 2030 including 1GW floating wind	(Offshor* wind OR float* wind)

General terms applied to each adaptation search and mitigation search were as follows:

Adaptation

((Clim* vulnerab* OR clim* risk* OR clim* adapt* OR sensitiv* OR adapt* capacit* OR clim* resilien*) AND (Mean air temperature* OR extreme heat* OR Cold spell* OR Frost* OR Mean precipitation* OR River* flood* OR fluvial* flood* OR heavy precipitation* OR pluvial flood* OR landslid* OR arid* OR dry* temperature* OR dry clim* OR hydrolog* drought* OR water scarc* OR agricultur* drought* OR ecologic* drought* OR fire weather* OR wildfire* OR wind* OR Mean wind* speed* OR Severe windstorm* OR Lake* ice* OR River* ice* OR heav* snow* OR ice storm* OR Hail* OR Snow* avalanch* OR Sea* level* ris* OR Coast* flood* OR Coast* ero* OR Mean ocean* temperature* OR Marine* heatwave* OR Ocean* acid* OR Ocean* salinit* OR sal* intrusi* OR Dissol* oxygen OR overheat* OR new pest* OR novel pest* OR novel disease* OR new disease* OR invasi* specie*))

Mitigation

(Climat* mitigat* OR carb emission* OR CO2 emission* OR C emission* OR GHG* emission* OR Greenhouse gas* emission* OR C sequest* OR CO2 sequest* OR carb sequest* OR C stock* OR CO2 stock* OR carb stock* OR C stor* OR CO2 stor* OR carb stor*)

Where we needed to apply a location filter, based on the number of returned results from the general search, we used the following string:

Location filter

(global OR Eur* OR temperate OR Great Britain OR Brit* OR United Kingdom OR UK OR Eng* OR Wales OR Wel* OR Scot* OR Northern Ireland OR Northern Irish)

Appendix G: Case study – soil conservation

1. Key messages

Soil conservation encompasses a wide range of management practices, including: intercropping, leys, buffers and cover crops; tillage (minimum and no-till); soil inputs; and appropriate grazing. The effects of the climate action on climate adaptation and mitigation outcomes varies depending on which practice is employed and how it is implemented.

Overall, these practices represent a **no-regret option** since they have clear benefits for climate adaptation and mitigation outcomes without any obvious trade-offs among CCRA3 risks and/or between climate adaptation and mitigation outcomes.

Multiple lines of peer-reviewed evidence agree that soil conservation practices can reduce the climate risks (in decreasing order of the magnitude of effect) to:

1) Soil health from increased flooding and drought (CCRA3 Risk 2)
2) Crops and, possibly to a lesser extent, livestock and commercial trees from multiple climate-related hazards (CCRA3 Risk 4)
3) The viability and diversity of terrestrial and freshwater habitats from multiple climate-related hazards (CCRA3 Risk 1)

The reduction in climate risks for crops will also reduce climate risks to food supply chains (CCRA3 Risk 5). Soil conservation practices may also reduce climate risks to natural carbon stores and sequestration (CCRA3 Risk 3). These two risk area outcomes rely on expert inference.

Peer-reviewed evidence on climate mitigation agrees, albeit with nuance, that adopting soil conservation practices will increase soil carbon sequestration rates and soil carbon stocks, especially in the topsoil. Evidence suggests soil conservation practices tend to reduce greenhouse-gas (GHG) emissions but we assess this to be of lower impact than sequestration and stocks. This is because emission reduction depends on multiple factors, including the counterbalance between reductions in some GHGs and increases in others.

There was no evidence of soil conservation practices reducing risks to people and the economy from climate-related failure of the power system (CCRA Risk 6) and risks to human health, well-being and productivity from increased heat exposure in homes and/or buildings (CCRA Risk 7), and they would not be expected to do so.

Policymakers need to be aware that for almost all the CCRA3 risks, there was no direct evidence of how soil conservation practices might affect the components of risks (i.e., the adverse or beneficial *sensitivity* to climate-related hazards of systems or species, their associated *adaptive capacity* regarding the ability to adjust to potential damage or to take advantage of opportunities, and their *exposure* to climate-related hazards). Some practices have only been implemented for a short time so their effect on CCRA3 risks is unknown where climate-related hazards have not yet occurred. Suitable comparisons were also lacking (e.g., with and without the adoption of a soil conservation practice and with the occurrence of one or more climate-related hazards). Thus, our scoring of the effect of soil conservation practices on adaptation outcomes typically relies on inference, emphasising that targeted research is urgently required. Some papers presented evidence and inferred outcomes, others presented evidence from which we inferred outcomes. Our rating took this into account, especially where multiple sources were involved. We assigned lower ratings where it was our expert judgement alone, without direct underpinning evidence. Further, across all CCRA3 risks, we were unable to infer scores for the effect of soil conservation practices on at least one of adaptive capacity and/or exposure.

There was limited evidence on the timelines for accrual of benefits from soil conservation practices for climate adaptation and/or mitigation. The timeline to benefits being realised likely varies with the type of soil conservation practice. Climate mitigation benefits will be realised during the time it takes the system to reach a new (dynamic) equilibrium. At that stage, benefits will need to be maintained by avoiding future soil degradation. If degradation occurs, climate adaptation and mitigation benefits will be lost.

2. Description of the action

Soil conservations practices are referred to, indirectly, in both the CCRA3 and the Net Zero Strategy. These reports use terms such as improving soil health, helping farmers adopt low-carbon farming practices and increasing the carbon stored on their farm, including through schemes such as the Sustainable Farming Incentive (Net Zero Strategy).

Based on the description of soil conservation practices in the CCRA3 and Net Zero Strategy, our study categorised them as:

1) Intercropping, leys, crop rotation, buffers (of perennial vegetation), and cover crops. These practices involve increasing the diversity of vegetation in a field, such as planting two types of crops in alternate rows, setting aside field margins, including hedgerows within the landscape, or strategic planting of perennial vegetation (e.g., alongside a river). This category also includes practices that reduce the time that the field spends as 'bare' soil
2) Tillage and terracing, which prepares the soil for planting, the latter on sloping land
3) Soil inputs, such as fertilisers and other organic matter, as well as how they are applied
4) Improved crop varieties (cultivars) specifically selected for ecological impact and benefits for yields
5) Grazing by livestock (e.g., rotational grazing and/or a lower stocking rate).

Soil monitoring, which is included in the focal climate action, does not directly affect climate adaptation and/or mitigation outcomes, so was not assessed, although it is important for assessing progress towards associated goals.

The systematic REA for this case study found evidence that was mainly concerned with mineral and organo-mineral soils. It is important to note that conservation and restoration of organic soils, involving protection of peatlands, water table management and rewetting (e.g., ditch blocking), are widely recognised as effective tools for conserving carbon stocks in natural peatland systems. Actions that raise the water table can also reduce GHG emissions from drained organic soils under intensive agriculture and may, therefore, be considered soil-friendly farming practices. However, the impact of such practices on organic soils is not considered here and was reviewed in relation to another climate action: the restoration of peatlands across the UK (see Climate Action 14 and accompanying Microsoft Excel workbooks).

3. Results of the adaptation assessment

It can be inferred from the evidence found that soil conservation practices can be expected to reduce the CCRA3 risks with the exceptions of “risks to people and economy from climate-related failure of the power system” (CCRA3 Risk 6) and “risks to human health, wellbeing and productivity from increased heat exposure in homes and/or buildings” (CCRA3 Risk 7), where no evidence was found.

Below, we present the evidence of how soil conservation practices affect the components of each relevant CCRA3 risk, together with implications for policymakers. Each CCRA3 risk is addressed in a separate subsection, and they are presented in decreasing order of the extent to which the risks are reduced by soil conservation practices. We have high confidence in the scores for reduced sensitivity to climate-related hazards associated with risks to soil health (CCRA3 Risk 2), and to the viability and diversity of terrestrial and freshwater habitats (CCRA3 Risk 1). Soil conservation practices are also likely to increase adaptive capacity regarding CCRA3 Risk 2. Contrarily, and somewhat surprisingly, we failed to uncover evidence of the effect of soil conservation practices on the sensitivity and adaptive capacity of *existing* natural carbon stores to multiple climate-related hazards (i.e., regarding CCRA3 Risk 3). However, as soil conservation practices can reduce the erosion of natural carbon stores, we inferred that their exposure to climate-related hazards is thereby also reduced.

For the climate risks to crops, trees and livestock (CCRA3 Risk 4) and due to collapse of food-supply chains (CCRA3 Risk 5), we inferred that soil conservation practices moderately increase adaptive capacity, providing measures are implemented effectively. We do not expect soil conservation practices will affect the exposure of these elements to climate-related hazards.

3.1 CCRA3 Risk 2 Assessment: Risks to soil health from increased flooding and drought

3.1.1 The effect of the climate action

Soil conservation practices can help reduce the risks to soil health (i.e., stability and functioning) from increased flooding and drought. Soil conservation practices do so by directly or indirectly reducing the sensitivity and increasing the adaptive capacity of soils to these climate-related hazards.

No-tillage or reduced-tillage moderately reduces the sensitivity of soil health to floods by increasing infiltration and reducing erosion. For instance, SMI 2001 cited in ref 79 notes that reduced tillage increased infiltration by 41% and reduced soil erosion by 68%. Such responses prevent associated reductions in soil quality, nutrient status, and soil water (ref 34, ref 40, ref 57, ref 61). Terracing, cover crops, windbreaks (such as tree shelterbelts) and riparian buffers can also reduce the sensitivity of soil health to flooding, including through the enhancement of soil carbon, which in turn improves water retention capacity (ref 49).

Terracing, cover crops, windbreaks and riparian buffers can reduce the sensitivity of soil health to drought by increasing water retention (e.g., Derpsch et al. 2010 cited in ref broad 29). These practices also reduce sensitivity to drought-induced wind erosion (e.g., ref 40).

Soil conservation practices create wider environmental benefits through improvements to biodiversity (see Risk Area 1). An increase in soil biodiversity is considered an improvement to soil health and will increase adaptive capacity to flooding and drought (see ref broad 34, ref 55).

3.1.2 Key caveats

The types of practices selected for implementation need to take account locally of the sensitivities and adaptive capacities of soils regarding climate-related hazards, soils' likely exposure to those hazards, and the ways in which the practices reduce the sensitivities and/or increase the adaptive capacities of soils.

3.1.3 Implications for policymakers

Soil conservation practices need to be applied to a large percentage of agricultural land (as much as 50%, according to the CCRA3) to effectively reduce sensitivity and increase adaptive capacity to flooding and drought (ref 34). Hence, soil conservation practices need to be implemented at a complementary scale if they are to substantially reduce this risk.

A one-size-fits-all approach will not maximise the potential benefits for climate adaptation outcomes of the various soil conservation practices in different contexts. Reduced sensitivity and increased adaptive capacity of soils in relation to flooding and drought, and the benefits of reduced erosion, increased water quality and reduced loss of nutrients for soil health will only be realised where the soil conservation practice selected is appropriate to the specific situation.

3.2 CCRA3 Risk 4 Assessment: Risks to crops, livestock and commercial trees from multiple hazards

3.2.1 The effect of the climate action

Soil conservation practices can help reduce climate risks to crops by reducing their sensitivity and increasing their adaptive capacity regarding multiple climate-related hazards. We did not uncover direct evidence for soil conservation practices affecting climate risks to livestock and commercial trees.

No-tillage or minimum-tillage, terracing, vegetation buffers, and cover crops that protect soils from erosion (ref broad 29, ref 40, ref 49, ref 55, ref 57, ref 61, ref 70) and/or increase organic carbon stocks (ref 2, 65, 71) potentially reduce the sensitivity of crops to climate-related hazards by enabling better growth conditions. The literature emphasizes that a combination of soil conservation practices could offer the greatest reduction in sensitivity (ref broad 29, ref broad 30, ref 60). Nevertheless, soil conservation practices are deemed only to have a marginal rather than moderate effect on sensitivity due to the nuance through which this process can work for crops and interaction with other factors (e.g. ref 23). For instance, combining no-till practices with residue retention and crop rotation can increase yield in water-limited agroecosystems but if used independently, and in other contexts, there can be decreases in yield (Pittelkow et al. 2014 cited in ref broad 30).

Adopting new soil conservation practices, such as plastic-film mulching or selecting species with specific root traits or with microbial associations to promote soil health moderately increases the adaptive capacity of crops by promoting crop yields under climate change (ref 3, ref 43, ref 54). For example, although not from the UK, ref 3 highlights a successful study that identified root phenotypes that improved phosphorus and water acquisition and thereby improved yields.

There may be an indirect reduction in the sensitivity of livestock to multiple hazards if soil conservation practices increase or improve pasture yield that leads to healthier livestock. However, this outcome was not evidenced by the literature.

3.2.2 Key caveats

The use of soil conservation practices may have negative effects on adaptation outcomes depending on how they are applied (e.g., stand-alone), and on soil type and context (ref 23, ref broad 30).

3.2.3 Implications for policymakers

Soil conservation practices should be tailored to the local context (e.g., climate, soil type, topography, climate, land use and existing practices) to maximise benefits for climate adaptation. Applying more than one practice in combination may provide greater benefits for reducing climate risks to crops from multiple hazards.

3.3 CCRA3 Risk 1 Assessment: Risks to the viability and diversity of terrestrial / freshwater habitats from multiple hazards

3.3.1 The effect of the climate action

Soil conservation practices can reduce the impacts of climate-related hazards that affect the viability and diversity of terrestrial and freshwater habitats. They do so by improving ecological function and ecological health. Soil conservation practices indirectly reduce habitat sensitivity through increasing biodiversity. Practices can also potentially reduce habitat exposure to impacts of climate change including soil erosion, decreased water quality, and loss of soil nutrients.

Nutrient management plans, riparian buffers, hedgerow planting, cover crops, and management of soils in the vicinity of plant roots (“rhizosphere engineering”) moderately reduce the sensitivity of freshwater habitats (nearby and downstream) to climate-related hazards by reducing nitrogen and nitrate losses to freshwater systems (ref 2, ref 5, ref 40, ref 86, ref 87).

Riparian buffers and windbreaks (such as tree shelterbelts) that reduce soil loss (ref 40) can be inferred to moderately reduce the sensitivity of terrestrial habitats to climate-related hazards by increasing biodiversity. For instance, field margins that are taken out of production as part of a soil conservation strategy (e.g. riparian buffers, hedgerow planting) will have an indirect positive effect on wildlife (ref 34). It can also be inferred that such soil conservation practices potentially reduce exposure of freshwater habitats (nearby and downstream) to reduced water quality by interrupting the delivery of sediment and nutrients to watercourses (ref 40).

Where soil conservation practices enhance biodiversity, they may potentially increase the adaptive capacity of terrestrial and freshwater ecosystems to climate-related hazards. However, this benefit was not evidenced by the literature, so was not scored.

3.3.2 Key caveats

The way soil conservation practices can indirectly reduce the sensitivity and/or exposure of the viability and diversity of terrestrial and freshwater habitats to multiple climate-related hazards can be inferred with varying degrees of confidence from the available evidence. Inferences regarding improved ecological function and ecological health from increased diversity are strong. However, we did not find quantitative evidence of how soil conservation practices can directly reduce this climate risk.

3.3.3 Implications for policymakers

A one-size-fits-all approach will not maximise the ways in which soil conservation practices reduce the climate risks to the viability and diversity of terrestrial and freshwater habitats. When targeting soil conservation practices to this effect, policymakers need to consider: the soil type; location in relation to freshwater habitats nearby or downstream; the climate-related hazards; the ways in which the practice reduces the sensitivity and/or exposure of ecosystem structures, processes, or functions to the climate-related hazards; and the type of habitat, its current condition and potential for improvement.

3.4 CCRA3 Risk 5 Assessment: Risks to supply of food, goods and vital services due to climate-related collapse of supply chains

3.4.1 The effect of the climate action

There is no expectation that soil conservation practices will directly affect the sensitivity, adaptive capacity, and/or exposure of most supply chains. However, since crop production is linked to food supply, it can be reasoned that the evidence found regarding CCRA3 Risk 4 demonstrates that soil conservation practices can reduce the sensitivity and increase the adaptive capacity of food supply chains to climate-related collapse.

3.4.2 Key caveats

Further research is required into the trade-offs for food-supply chains of the potential benefits from improvements to crop yields at a site scale of using soil conservation practices versus how large-scale implementation of some such practices could substantially reduce the area of land available for food production.

3.4.3 Implications for policymakers

Reducing the sensitivity and increasing the adaptive capacity of crops to multiple climate hazards (CCRA3 Risk 4) should reduce the risk of climate-related collapse of food supply chains. However, as noted in CCRA3 Risk 4, targeting of soil conservation practices needs to be tailored to the local context to achieve such benefits and, as noted immediately above, there could be trade-offs if large-scale implementation of soil conservation practices reduces the area of land available for food production.

3.5 CCRA3 Risk 3 Assessment: Risks to natural carbon stores and sequestration from multiple hazards

3.5.1 The effect of the climate action

Soil conservation practices can have multiple climate mitigation benefits by conserving carbon stocks and increasing carbon sequestration, as presented in Section 4.2 (noting, as explained in Section 2 that effects on organic soils are not considered by this case study). However, there was no direct evidence of how soil conservation practices affect the sensitivity of existing natural carbon stores or sequestration to multiple climate hazards. In the absence of contrary evidence, our scoring assumed that their sensitivity remains unchanged.

We did not find any direct evidence of how the adaptive capacity of natural carbon stores or sequestration is affected by soil conservation practices, and made no judgment in that regard.

We anticipate that soil conservation practices may potentially reduce the exposure of natural carbon stores to multiple climate-related hazards, but again found no direct evidence. However, as soil conservation practices can reduce erosion from climate-related hazards (refs 29, 34, 40, 49, 55, 57, 61, 79), we inferred that they reduce the exposure of natural carbon stores in that regard.

3.5.2 Key caveats

Research quantifying how soil conservation practices can affect the sensitivity, adaptive capacity and/or exposure of natural carbon stores and sequestration to multiple climate-related hazards is urgently required.

3.5.3 Implications for policymakers

Although not further evidenced by our review, CCRA3 suggests that the use of soil conservation practices to reduce climate risks to natural carbon stores and sequestration should consider the local and landscape context.

4. Results of the mitigation assessment

Soil conservation practices are expected to have the greatest benefits for climate mitigation by conserving carbon stocks while also enhancing rates of carbon sequestration and (sometimes) reducing direct GHG emissions (noting that this statement does not relate to organic soils, which are not considered by this case study, see Section 2).

There is high level of agreement across the peer-reviewed literature regarding the positive effects of soil conservation practices on carbon stocks and sequestration (e.g., refs 6, 8, 17, 49, 55). However, the quantity and timescale of benefits delivered depend on the specific practice adopted, soil and landscape context, as outlined in more detail in the subsections below. These factors explain why we scored soil conservation practices as having a greater effect on carbon stocks than on sequestration.

In contrast, there is some contradiction between different sources regarding how soil conservation practices can contribute to reducing GHG emissions from natural carbon stores. For instance, soil conservation practices such as no-till management that tend to reduce CO_2 may also increase other GHGs (e.g. CH_4 or N_2O emissions) (Freibauer et al., 2004; Rochette, 2008 cited in ref 79; ref 86). Context also plays a significant role in the direction and magnitude of the effects on GHG emissions. Thus, emissions reduction has the lowest overall score across the three components of climate mitigation.

4.1 Effect on GHG emissions

Reduced tillage, integration of crop residues back into the soil, cover or catch crops, intercropping, improved/longer crop rotations and addition of manure can reduce GHG emissions by 0.5 to 1 tonnes of CO_2 equivalent per ha per year (Environment Agency 2021 cited by broad ref 32).

Adopting windbreaks (such as tree shelterbelts) and riparian buffers can save 1 to 1.4% of EU-28 emissions (ref 40).

Improved grazing practices (such as rotational grazing and/or a lower stocking rate, which can lead to soil conservation) can reduce emissions by 0.28 tonnes of CO_2 equivalent per ha per year (broad ref 32). However, implementing grazing can increase N_2O emissions depending on existing landcover (e.g., by 33% compared to hay meadows) (ref 39).

There can be both direct and indirect benefits of adopting soil conservation practices on emissions reduction. For instance, precision farming increases yield while reducing nitrogen fertiliser application. Lower nitrogen fertiliser application should reduce N_2O emissions directly at the field site. A reduced demand for fertiliser would lead to lower emissions from the initial manufacture, an indirect benefit when considered ‘in field’ (ref 71).

The extent to which GHG emissions are reduced depends on the type and amount of fertiliser applied given the range of emissions factors (e.g. urea has a lower emission factor as compared to calcium ammonium nitrate), as well as context-dependency from sites themselves (as demonstrated in Ireland (ref 52)).

Some may consider the use of microbial inhibitors as a soil conservation practice, but the application of this technology has unclear effects on GHG emissions with the potential for pollutant swapping of N_2O for NH_3 (ref 87). However, uptake of nitrification and urease inhibitors by 2050 is projected to deliver a reduction in 71 kg CO_2 equivalent per ha (ref 75). Adopting cover crops can indirectly mitigate 0.12 to 0.46 tonnes of CO_2 equivalent per ha per year due to surface albedo change (broad ref 34).

Much of the literature examined the potential for biochar to reduce GHG emissions (e.g., refs 18, 22, 28). This soil improvement practice exemplifies the dependency of emissions reductions on context. Biochar use in fine-textured soils results in significant CO_2 emissions, while coarse-textured soils significantly reduce N_2O and CH_4 emissions (although note findings in the following section (4.2) on carbon sequestration). In addition to soil texture, the effect on emissions of all these GHGs is considerably dependent on the physical and chemical properties of both the biochar and soil, through their pH and carbon to nitrogen ratio (ref 28).

4.2 Effect on carbon sequestration

Soil conservation practices generally have a positive effect on soil carbon sequestration. For instance, soil improvement practices, such as the application of exogenous organic matter, can increase the soil organic carbon (SOC) storage rate with the increase in sequestration depending on the specific improver used (ref 8). Thus, compost and sewage sludge has been found to have sequestration rates of 334.02×10^{-3} Mg C per ha per year and 101.58×10^{-3} Mg C per ha per year while manure is less effective (18.7×10^{-3} Mg C per ha per year). However, some practices that are meant to help with soil conservation may lead to a decline in sequestration, with a combination of slurry and mineral fertilisers having a negative rate of -7.02×10^{-3} Mg C per ha per year (ref 8).

The importance of the specific improver is also observed for biochar: that from plant material showed higher potential for carbon sequestration than that from faecal matter, due to a higher carbon to nitrogen ratio. In contrast to our findings regarding GHG emissions (see section 4.1 above), increases in SOC sequestration after biochar application were higher in medium-to-fine-textured soils, as compared to coarse-textured soils (ref 22).

Terracing has a positive effect on SOC sequestration, although whether it is a net carbon source or sink remains unclear (ref 57). Other practices aim to conserve soil through overplanting cover crops or perennial vegetation rather than by modifying topography. Adding such vegetation to the landscape has a clear positive benefit for soil carbon sequestration (ref broad 34). For instance, cover cropping has been modelled to potentially sequester 1.06 tonnes CO_2 equivalent per ha per year in the UK (ref 71). However, as with other aspects of climate mitigation, the type of cover crop is important: leguminous cover crops are typically associated with greater SOC sequestration than non-leguminous crops (ref 82). Perennial vegetation is particularly useful for improving soil carbon sequestration with evidence suggesting that hedgerows sequester soil carbon at a rate of 1.49 tonnes C per ha per year, giving a total carbon sequestration (when including plant biomass too) of 2.1 to 5.2 tonnes C per ha per year for 50 and 20 years respectively (ref 37, ref 89).

4.3 Effect on carbon stocks

Soil conservation practices generally have a positive effect on soil carbon stocks in the topsoil of agricultural soils, which in turn has benefits for soil fertility and crop production, particularly those practices that minimise soil disturbance (ref 23). However, declines in SOC stock have been observed in deeper (20 – 40 cm) soil layers following the adoption of no-till, cancelling out any increase in the topsoil (0 – 10 cm), such that total carbon stock was unchanged (ref 82). A global analysis showed cover crops led to 1.11 Mg C per ha more soil carbon compared to a no-cover crop control. The magnitude of this impact was 20-30% greater for continuous cover crops, or those with an autumn planting and then terminated, as compared to other cover-crop growing windows (ref 59). The type of cover crop can also have an impact. For instance, one study found that rye grass led to a 3-4% increase in SOC as compared to hairy vetch, which led to declining SOC levels, as it returned only 0.7 tonnes C per ha per year, compared to 3.7 tonnes C per ha per year for rye grass (Sainju et al. 2002 cited in ref 82). Other analyses have shown a linear positive relationship between the number of years a cover crop has been included in a rotation and the SOC stock change (ref 82). As with carbon sequestration, soil carbon stocks are also improved by permanent vegetation cover, such as vegetative strips, hedgerows, and trees, which may be considered a soil conservation practice. Values show an increase of around a third in comparison to arable control situations (ref broad 34, ref 37).

The effects of biochar on SOC stocks are worth highlighting. In particular, more SOC was accumulated in field experiments that had been running for six to 10 years, as opposed to those of shorter duration. Across all experiments (with between 1 and 10 years of biochar application), stocks increased by 29% (13.0 Mg per ha) on average, with organic fertiliser co-applications significantly increasing SOC further (ref 22). Other soil inputs can be beneficial, such as manure, which can lead to increases of 7.41 ± 1.14 (95% confidence interval, CI) and 8.96 ± 1.83 (95% CI) Mg C per ha, respectively, compared to mineral fertilised and unfertilised reference soils (ref 44). As with other aspects of climate mitigation, the magnitude of this effect depends on how soil properties regulate the efficiency of manure application. Even inorganic fertilisers can improve SOC stock, although the extent to which this can be considered a soil conservation practice may be contentious, and there may be offsite impacts on biodiversity. GHG emissions produced during fertiliser manufacture also need to be considered. Ammonium nitrate, ammonium sulphate and calcium nitrate can increase SOC stocks by 12.6%, 13.1% and 26.9% respectively but SOC stocks are not significantly affected by ammonium chloride, urea or potassium nitrate application (ref 82).

One technique, plastic-film mulching, is expected to increase the adaptive capacity of crops to CCRA3 Risk 4. However, this technique can decrease soil C stock even though it did not meaningfully affect N_2O or CH_4 emissions (ref 43). Although out of scope of this assessment, plastic film mulching could also adversely affect soil biota and cause pollution (Defra review comment, pers. comm.).

As noted already, appropriate grazing can be considered a soil conservation practice and may help reduce emissions. The relationship between grazing and soil carbon stock is complex (ref 89). For grasslands in Wales both overgrazing and no grazing has been observed to reduce SOC content while appropriate stocking levels [unspecified] increase

SOC content (ref 82). Identifying the appropriate grazing plan is highly context dependent, influenced by soil type, grazing animals, alternative land cover and climate (ref 82, ref 39).

4.4 Implications for policymakers

The ways in which soil conservation practices can reduce greenhouse gas emissions, increase carbon sequestration, and improve carbon stocks are well-documented in the literature. These effects depend upon the type of practice, with the following being effective for climate mitigation: reduced or no tillage, integration of crop residues back into soil, cover or catch crops, intercropping, addition of manure or other organic matter, improved crop varieties/rotations and management of grazing intensity. There is likely to be a great deal of variability in the mitigation outcomes due to differences in soil type, climate, current land uses, and implementation (e.g., duration). However, the multitude of soil conservation practices provides useful options for balancing delivery of climate mitigation with other desired benefits.

Appendix H: Case study – Aim to reduce direct emissions from public sector buildings by 75% by 2037 compared to 2017

1. Key messages

The reduction of direct emissions from public sector buildings affects climate adaptation and climate mitigation outcomes. In terms of the adaptation and mitigation outcomes considered in this study, it affects CCRA3 Risk 6 (risks to people and the economy from climate-related failure of the power system) and CCRA3 Risk 7 (risks to human health, wellbeing, and productivity from increased exposure to heat in homes and other buildings), as well as greenhouse-gas (GHG) emissions.

As different measures can be taken to reduce direct emissions from public buildings, the effect of this action on "risks to people and the economy from climate-related failure of the power system" (CCRA3 Risk 6) may be positive or negative dependent on the measure(s) taken, although is generally expected to be positive. Energy efficiency measures and low-carbon technologies are likely to reduce sensitivity to CCRA3 Risk 6, lessening energy demand and diversifying the energy mix. However, greater electrification may increase sensitivity to CCRA3 Risk 6 by further straining the power system.

The anticipated effect of this action on "risks to human health, wellbeing, and productivity from increased exposure to heat in homes and other buildings" (CCRA3 Risk 7) is positive. Some measures, such as upgrading the building envelope, can limit the usage of air conditioning while stabilising indoor temperatures and, thus, increasing the adaptive capacity to this risk. Nonetheless, the projected increase of heat exposure in UK buildings reflects some uncertainties that should be further investigated.

The implementation of low-carbon technologies and energy efficiency measures is very likely to mitigate GHG emissions in public sector buildings. The magnitude of the reduction depends on various factors, such as the technology that is selected and the conditions of the building where it is implemented. In addition, it is crucial to support implementation of this action with a wider package of interventions to decarbonise the power supply and upgrade the support infrastructure. Embodied GHG emissions from renovation and retrofitting can be mitigated with a wise selection of construction materials, ensuring that they are resilient to current and future climate impacts.

2. Key implications for policymakers

Policymakers will need to consider how to ensure that any large-scale retrofitting initiative or other funding scheme will support building owners, design teams, or other stakeholders to address overheating risks. This is particularly important when considering:

a) Changes to insulation and glazing, as these affect heat gains and losses; and

b) Upgrades to building services, as these should be designed with climate change in mind to avoid the need for premature modifications or replacement.

Some of the measures that can be used to reduce direct GHG emissions could have the unintended consequence of increasing other sources of emissions, for example:

a) If the operational GHG reductions of a mitigation measure are outweighed by the up-front, embodied carbon emission

b) If the measure results in higher demand for cooling, causing an increase in emissions from mechanised cooling systems

c) If the building operators use more energy after a measure is introduced than they did before it was introduced (known as the “take-back” or “rebound” effect).

To avoid these issues, it is necessary to ensure that:

a) Lifecycle carbon emissions are considered; and

b) The design and specification of measures aimed at reducing direct emissions (e.g., insulation, heating system replacements) accounts for the potential impacts of future climate change.

The above issues are likely to affect individual buildings or specific climate mitigation measures. However, when scaled up across the public building stock as a whole, these could result in GHG emissions reductions that are significantly lower than 75% (which is the target in the UK Net Zero Strategy). Therefore, any policies, funding incentives, etc.

introduced under this action need to address those issues when undertaking the initial impact assessment, designing proposals and monitoring subsequent outcomes.

At present these issues are not routinely considered, or assessed in detail, as part of the building control or planning process for existing buildings and new non-domestic buildings. This represents a gap in the national regulatory and policy framework that could be addressed through (for example) updates to Building Regulations or the National Planning Policy Framework.

3. Description of the action

The UK Net Zero Strategy states that the Government will "aim to reduce direct emissions from public sector buildings by 75% by 2037 [the end of the 6th carbon budget period] compared to 2017."[12] At present, according to the Strategy, public sector buildings account for roughly 2% of total UK GHG emissions, or roughly 9% of emissions from buildings.

In this context, the majority of direct emissions result from fossil fuel combustion onsite, so a key focus of this action is to reduce fossil-fuel use. This could be achieved through various means, such as:

a) Improving the efficiency of the building fabric, and upgrading building services, to reduce energy demand

b) Replacing fossil fuel heating with low-carbon alternatives, such as heat pumps

c) Installing on-site renewable energy technologies, such as roof-mounted solar photovoltaics (PV) and solar thermal panels, wind turbines, etc.; and

d) Providing building energy management systems and/or smart controls to optimise energy use.

4. Results of the adaptation assessment

This action is expected to affect CCRA3 Risk 6 ("risks to people and the economy from climate-related failure of the power system") and CCRA3 Risk 7 ("risks to human health,

[12] This target does not apply to social housing, which is instead included in the UK Net Zero Strategy actions related to domestic buildings.

wellbeing, and productivity from increased exposure to heat in homes and other buildings”). These risks are discussed below.

No direct evidence was identified from the REA regarding the effect of reducing direct public sector building emissions on the remaining risks. In our expert judgment, there is no direct connection between reducing emissions from public sector buildings and risks to:

a) The viability and diversity of terrestrial and freshwater habitats and species

b) Soil health in the face of increased flooding and drought

c) Natural carbon stores and sequestration from multiple hazards leading to increased emissions

d) Crops, livestock, and commercial trees from multiple hazards; and

e) The supply of food, goods, and vital services due to climate-related collapse of supply chains and distribution networks.

Below, we present the evidence of how reduction of direct emissions from public buildings affects the components of each relevant CCRA3 risk, together with implications for policymakers. Each CCRA3 risk is addressed in a separate subsection.

4.1 CCRA3 Risk 6 Assessment: Risks to people and the economy from climate-related failure of the power system

4.1.1 The effect of the climate action

As different measures can be taken to reduce direct emissions from public buildings, the effect of this action on CCRA3 Risk 6 may be positive or negative dependent on the measure(s) taken.

Greater use of energy efficiency measures appears to reduce sensitivity to the following climate-related hazards: “flooding, water shortages, increased temperatures and wildfire, sea level rise and potential increases in storms, swells and wave heights.”[13] This action is expected to reduce sensitivity to these hazards to the extent that the action results in lower

[13] The CCRA3, in identifying “Risks to people and the economy from climate-related failure of the power system” as a key climate risk faced by the UK, has identified these as the key hazards to which the power system is sensitive.

energy demands and, thus, less reliance on the power system in the first place. Renewable and low-carbon technologies can have wider beneficial effects on reducing the sensitivity of the power system to the climate-related hazards identified above by diversifying energy sources (e.g., see ref. 40) and helping the power system to respond to peaks in demand (ref. 4). These technologies can also potentially provide backup power for connected properties, as in the case of roof-mounted PV (combined with battery storage) or cooling, heating, and power (CCHP) systems. Uptake of such technologies would reduce the risk faced by those particular buildings in the event of climate-related failure of the power system.

4.1.2 Key caveats

If this action involving greater electrification of heating is not accompanied by increased provision of (resilient, low-carbon) electricity, it could increase sensitivity to the following hazards related to climate-related failure of the power system: “flooding, water shortages, increased temperatures and wildfire, sea level rise and potential increases in storms, swells and wave heights.” Sensitivity to these hazards could be even greater when this action is combined with other actions, for example, increased use of electric vehicles and greater reliance on mechanical cooling systems due to increased temperatures (ref. 72). In other words, as more systems rely on electricity, sensitivity will increase if electricity supply is not increased in line with this higher anticipated demand.

4.1.3 Implications for policymakers

It is important to acknowledge that measures under this action will not be one-size-fits-all (ref. 4); they must be tailored to the individual buildings and local conditions.

Alongside measures aimed at phasing out fossil fuels, interventions should focus on reducing energy demands in the first place, to reduce pressure on grid infrastructure. Other key priorities should include investment in grid infrastructure and greater provision of renewables and work to ensure a diverse energy supply. This is particularly important to reduce sensitivity to the hazards listed above in a changing climate (see ref. 18).

As many of the actions set out in the UK Net Zero Strategy and other government plans involve electrification, actions, such as reducing direct emissions from public buildings through greater electrification, cannot be considered in a vacuum.

4.2 CCRA3 Risk 7 Assessment: Risks to human health, wellbeing, and productivity from increased exposure to heat in homes and other buildings

4.2.1 The effect of the climate action

Evidence suggested that improving the energy efficiency of building fabric and services can increase adaptive capacity to the risk of overheating from increased temperatures and heat waves by reducing the energy usage of air conditioning units while providing for more stable indoor temperatures. This also leads to increased productivity (see, e.g., refs. 15, 30, 40, broad 3).

Solar PV, which could be installed as part of this action, is likely to increase adaptive capacity to increased temperatures and heat waves.[14] By generating more power on hot, sunny days, the electricity can be used to power cooling systems.

4.2.2 Key caveats

Evidence gathered as part of Climate Action 2[15] indicates that, in buildings that lack air conditioning, measures such as increased use of insulation potentially have unintended negative consequences for adaptive capacity to the climate-related hazards of increased temperatures and heat waves. Non-residential buildings in the UK, including public buildings, are more likely to already have access to and use air conditioning than dwellings. One exception to this greater presence of air conditioning in public buildings is schools, where air conditioning is less likely to be present. However, as schools are generally closed during the summer months, overheating exposure is avoided to a greater extent by this seasonality of use.

Further research is needed on the extent of air conditioning in heritage buildings in the UK, and other challenges addressing overheating under the restrictions applicable in a heritage context. For instance, some evidence suggested that installing internal wall insulation *can*

[14] The Government aims to avoid widespread uptake of mechanical cooling systems, but where the use of mechanical cooling cannot be avoided, there are co-benefits of PV because it can provide renewable electricity to power cooling systems.
[15] As many fuel poor homes as reasonably practicable to Band C by 2030, and as many homes to reach EPC Band C as possible by 2035, where practical, cost effective, and affordable.

increase sensitivity to increased temperatures and heat waves unless combined with other cooling measures (ref. 47).

4.2.3 Implications for policymakers

Although the impacts will vary building-by-building, policymakers will need to consider how to ensure that any large-scale retrofitting initiative or other funding scheme will support building owners, design teams, or other stakeholders to address overheating risks. This is particularly important when considering:

a) Changes to insulation and glazing, as these affect heat gains and losses; and
b) Upgrades to building services, as these should be designed with climate change in mind to avoid the need for premature modifications or replacement.

The design of building services in new or refurbished properties needs to account for the potential increase in exposure to overheating due to climate change (see refs. 4, 7, 41). This should be reflected in energy modelling and overheating risk assessments – for example, requiring design teams to use future weather data. This might need to be supported by changes in Building Regulations and/or associated calculation methodologies.

In addition, policymakers should be aware of the importance of adopting passive cooling measures, and where relevant, include these within funding schemes, promotional materials, etc.

5. Results of the mitigation assessment

The assessment highlights a positive effect on climate mitigation, notably through the use of technologies and measures that reduce GHG emissions and increase energy efficiency. This is supported by studies from the UK and other European countries. Key implications for policymakers relate to:

a) Direct vs. indirect emissions; it is crucial that this action is accompanied by measures that support emissions reduction by electrification, such as decarbonisation of the energy supply and infrastructure upgrade

b) Choosing resilient materials to resist the impacts of climate change and reduce the embodied carbon associated with renovation and retrofitting

c) Planning for changing temperatures, especially regarding the projected increase in temperatures in the UK and the risk of overheating in buildings

5.1 Effect on GHG emissions

5.1.1 The effect of the climate action

Reducing GHG emissions is the core aim – indeed, the definition – of this action. Several measures within this action can mitigate GHG emissions in public sector buildings by improving energy efficiency or generating low-carbon electricity (where this displaces on-site fossil fuel combustion). Direct emissions from fluorinated gases (F-gases) can also be reduced through implementation of passive cooling measures and upgrades or repairs to faulty refrigeration or air conditioning systems.

Technologies such as low-carbon lighting and ICT/monitoring solutions (e.g., smart meters) can enhance energy efficiency, thus directly contributing to climate mitigation. In some UK and European schools and universities, the integration of digital technologies for the monitoring and evaluation of energy consumption successfully reduced emissions (see, e.g., refs 29 and 19). Passive cooling can also be implemented to address the projected increase in average temperature and reduce energy consumption. Interventions such as shading, window glazing, natural ventilation can be low-cost and low-carbon alternatives to mechanical ventilation or cooling during warm periods (ref. 6). In addition, combining active and passive solutions has successfully reduced emissions during a pilot project in a school in Germany (ref. 24).

Low-carbon electricity generation in public buildings can be provided by CCHP and by the integration of solar PV or other small-scale renewable energy systems. Small-scale renewable energy can substitute or reduce carbon-intensive generation (ref. 15). On another note, CCHP can generate energy for cooling, heating and electricity at the same time and provide significant benefits when coupled with user-side demand forecasting and supply-side mechanism simulation (ref. 1).

5.1.2 Key caveats

There was generally a strong agreement in the literature about this action's positive impact on reducing GHG emissions. However, the scale of emissions reduction that can be achieved varies building-to-building, depending on which measures are selected and how they are implemented.

It should be noted that some individual measures, such as certain types of high-performance glazing systems, may result in higher GHG emissions during their manufacture than will be recouped via energy savings on-site. In the case of windows, this depends on factors such as the frame material and the lifespan or replacement rate of the product (refs. 44 and 45). There is also some evidence that certain consumers may use slightly more energy post-retrofit than pre-retrofit (ref. 46). However, considering the public building stock as a whole, in our expert judgment, the net effect will be to reduce GHG emissions.

5.1.3 Implications for policymakers

Policymakers will need to consider three main issues when seeking to reduce direct emissions from public sector buildings.

First, this action focuses on *direct* emissions, which suggests that some – and potentially the majority – of the GHG reduction will be achieved via electrification. In order for this to result in a net reduction in emissions, it must be supported by a broader package of policy measures that will:

a) Decarbonise the electricity supply; and
b) Upgrade infrastructure to support higher demand (and intermittency due to renewables), while also ensuring it is resilient to the physical impacts of climate change.

Otherwise, there is a risk that reductions in direct emissions could be offset by higher indirect emissions. Similarly, if and where specific measures are being promoted (e.g., via funding schemes), this should account for the embodied carbon of the product. Those products that emit more GHGs in their manufacture than they save via reduced energy demands should generally not be supported unless they are included in a package of measures that can be shown to result in lower overall emissions.

The complete lifecycle of emissions from renovating and retrofitting buildings and how it compares to projected carbon savings should be considered. Heritage buildings face structural challenges to undergo retrofitting and energy efficiency improvements (ref. 10). Usually, significant renovation activities are expected. This may lead to higher emissions or compromise the cultural integrity of the sites.

Second, it is important that construction materials that are used to retrofit buildings are resilient to the impacts of climate change. Otherwise, there is a risk that they will need to be repaired or replaced prematurely in the event of damage (e.g., flooding, overheating, increased rainfall, soil subsidence, etc.). This would have the result of increasing the indirect emissions from embodied carbon.

Finally, policymakers need to consider the impact of changing temperatures. Although heating currently accounts for most direct GHG emissions from buildings, it is possible that heat demands will decrease in future while cooling demands increase. When upgrading building fabric or services, consideration should be given to (i) the potential increase in cooling demand due to higher temperatures, and (ii) opportunities to integrate passive cooling measures into the proposed design.

With regards to (i), it is strongly recommended that retrofitting schemes should be informed by overheating risk assessments that account for future climate conditions. Options for utilising refrigerants with low global warming potential and leak detection systems should be explored. Further research into alternative cooling systems that do not use refrigerants is also needed to build on existing research (e.g. see ref. 72).

Regarding point (ii), implementation of passive cooling measures should consider their effect on heat loss during the heating season (winter). Similarly, when insulation is implemented to reduce heat loss, its effect on cooling requirements during warm periods must be evaluated. Analyses of future temperatures and thermal modelling should address these considerations.

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