Climate Change Committee (CCC)

Modelling heat-related climate risks and nature-focussed adaptation measures for selected farm outputs

Final Report

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Summary

Key messages

This study assessed specific heat-related risks and an adaptation package for six agricultural products in the UK: wheat, barley, oats, lambs, milk and eggs.

The assessment found that heat-related climate risks are projected to impose increasing pressures on UK agriculture through the 2030s and 2050s, with cereals such as wheat, barley and oats facing yield losses when high temperature periods coincide with flowering. Sheep and lambs are subject to rising parasite risks, and outdoor milk and egg production may reduce slightly due to direct heat-related pressures. Under high warming scenarios, modelled annual economic losses for these products could exceed £0.5 billion, rising from £594 million in the 2030s to £647 million in the 2050s, with impacts greatest in England.

While a wide range of adaptation measures were evaluated to mitigate the modelled risks from heat, only a subset were considered likely to directly address the risks and result in benefits to both nature and productivity. A small number of measures were found to be cost effective, but only when carbon and ecosystem co-benefits were modelled – particularly those measures which prioritised trees and soil health. Such nature-based approaches need to be implemented early, to account for the time required to ensure that they mature and deliver their optimum benefits. Despite the significant co-benefits associated with these nature-based approaches, their ability to directly address the modelled heat-related risks was found to be modest, and insufficient to fully mitigate the losses.

Overall, the study highlights both the scale of future heat-related challenges and the importance of early, sustained investment in targeted, field-scale adaptation measures to support nature, agricultural productivity and resilience across the UK.

Introduction

Climate change is already driving significant impacts across the UK. Understanding the nature and scale of these climate-related risks is critical to inform effective adaptation strategies. Immediate and continuous action is essential to strengthen resilience within our environment, economies, infrastructure and society against today’s extreme weather and the escalating risks of tomorrow.

Farmland makes up more than 70% of the UK’s land area and produces around half of the nation’s food, forming a cornerstone of both national food security and natural capital.[1] These farmed landscapes face growing climate risks that threaten long-term productivity, environmental quality and progress toward

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[1] Defra. 2023. Agricultural Land Use in United Kingdom at 1 June 2023. Department for Environment, Food and Rural Affairs, Department of Agriculture, Environment and Rural Affairs (Northern Ireland), Welsh Government Knowledge and Analytical Services, and Scottish Government Rural and Environmental Science and Analytical Services.

net-zero targets. Rising temperatures, more frequent heatwaves and droughts, and acute events such as storms can directly reduce yields, increase livestock stress, and degrade soils through erosion and nutrient loss. At the same time, there are significant opportunities to strengthen resilience through targeted adaptation measures that enhance both productivity and nature outcomes. Approaches such as expanding hedgerows, integrating trees within arable and pastoral systems, and adopting climate-resilient crops can help reduce climate-related losses while improving soil health, biodiversity and wider ecosystem services.

This report presents the results of a targeted spatial assessment of quantifiable heat-related climate risks and adaptation across UK farmed landscapes, commissioned by the Climate Change Committee (CCC). This analysis is part of a wide evidence base supporting the Fourth Climate Change Risk Assessment's Independent Assessment (CCRA4-IA), which includes the Well-Adapted UK Report (WAUK). The WAUK aims to highlight the actions required to adapt to climate change risks across the UK and includes in-depth exploration of cost-effective adaptation pathways to a range of specific risks for sectors critical to the UK economy.

Methodology

This study followed a specified CCC methodology for estimating risk, identifying and appraising adaptation actions, and building and testing a cost-optimal adaptation package. The first phase of the project comprised a review of existing work and analysis in this space, including existing models, data and information which set out the costs of climate impacts to farmed landscapes and possible adaptation actions. This highlighted a lack of quantitative data to support suitable risk analysis at the landscape scale, and a component-focussed approach was subsequently developed with the CCC to allow the preferred model logic to be followed: identification of thresholds beyond which climate-related impacts might be expected, assessing the resulting risks in terms of financial loss from reduced productivity – and then modelling adaptation options that might reduce those risks whilst delivering a range of nature co-benefits.

Risk Analysis

The analysis investigated the impacts of different heat-related hazards on cereal crop yields, milk yields, egg weights, and parasite infections in lambs under central and high impact scenarios, linked to different Global Warming Levels (GWLs):

- **Central scenario -** 2030s: GWL 1.5; 2050s: GWL 2.0
- **High scenario -** 2030s: GWL 2.0; 2050s: GWL 2.5

Different land use scenarios were also explored to account for potential changes in adaptive capacity and productivity over time. A Business-As-Usual (BAU) scenario, which considered present day yields and land use for the six agricultural sub-components, was used for the main analysis. Two additional scenarios were developed from the CCC's Seventh Carbon Budget (CB7) Balanced Pathway approach, which assumes significant shifts such as increased agricultural productivity and land released for carbon sequestration and bioenergy by 2050. These two scenarios were used to explore vulnerability through a sensitivity analysis. The three land use scenarios[2] are summarised as:

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[2] Note that this analysis does not account for potential future cereal yield gains due to warmer temperatures or CO_2 enrichment.

- **BAU,** in which no changes in agricultural land area or productivity are considered between present day and the 2050s.
- **CB7a**, in which no changes to productivity are considered, but the area of agricultural land (hectares of cropland and numbers of livestock) reduces from present day through 2050. This is a variation of the scenario used to inform the CCC's CB7 Balanced Pathway.
- **CB7b**, in which increases to productivity (crop and milk yields) are considered along with the area of agricultural land and livestock numbers, which reduce from present day through 2050. This is the scenario used to inform the CCC's CB7 Balanced Pathway.

This analysis focussed on six key agricultural components (wheat, barley, oats[3], dairy cattle, free range hens, and lambs) for which measurable impacts caused by defined climatic thresholds were identified in the literature. Together, these components account for approximately 50% of income from UK farming. The lack of suitable climate risk thresholds meant that other important sub-sectors such field horticulture (covering vegetables as well as soft and orchard fruits) were only considered qualitatively. Nature within farmed landscapes, including biodiversity and habitats, were (likewise) omitted from the risk analysis, but the benefits delivered by and to nature through ecosystem services were quantified during the analysis of adaptation interventions.

Quantitative climate risk modelling, derived from UKCP18 local projections, was constrained to impacts from heat-related hazards. Daily maximum, minimum, and mean temperatures, as well as mean daily relative humidity were generated for each of the 16 climate model members at a 5km^2 resolution. Threshold analysis of the projection data was then used to calculate impact metrics for the six agricultural sub-components (Table 1). The spatial distributions of impacts were then cross analysed with the spatial distributions of the agricultural sub-components to determine the spatial distribution and magnitude of risk.

Table 1. Selected sub-components of the farmed landscape, with associated hazards, impact thresholds and impact metrics modelled

Sub-component	Hazard Description	Impact Threshold	Impact Metric Modelled
Oats	High temperatures from April-June	Days where $T_{max} \geq 28°C$ from April-June (days/year)	10% yield reduction/day
Wheat	High temperatures from May-June	Days where $T_{max} \geq 32\ °C$ from May-June (days/year)	10% yield reduction/day
Barley	High temperatures from April-June	Days where $T_{max} \geq 28°C$ from April-June (days/year)	10% yield reduction/day
Dairy cattle	High temperatures and humidity (heat stress)	Days where Thermal Heat Index (THI) > 74 (days/year)	Milk yield reduction of 0.55 litres/cow/day
Lambs	Temperatures conducive to parasite outbreaks (*Haemonchus contortus*)	Days where $T_{mean} \geq 9°C$ (days/year)	Potential number infected (population * (0.5 + change {%})
Laying hens (outdoor)	High temperatures	Days where T_{mean} 28-33°C (days/year)	28-33°C = 10% egg weight reduction/day

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[3] Analysis of oats was only conducted for England, Northern Ireland and Scotland. Similar data were unavailable for oats in Wales.

Sub-component	Hazard Description	Impact Threshold	Impact Metric Modelled
		Days where T_{mean} 34-38°C (days/year)[#] Days where $T_{mean} \geq$ 39°C (days/year)[#]	34-38°C = 15% egg weight reduction/day[#] ≥39°C = 20% egg weight reduction/day[#]
[#]Modelled, but no impact projected to occur between present day and the 2050s under any climate scenario			

Economic Losses

The economic analysis investigated the direct financial costs associated with the risks for each agricultural sub-component under four specific climate scenarios, derived using different Global Warming Levels (GWLs) and timeframes, as presented in Table 2 below. Broadly, the methodology can be conceptualised as total losses in revenue in a given year due to reductions in product yield.[4] Central and High climate scenarios were developed by selecting specific UKCP18 model members. Economic losses related to a GWL of 1.1°C were used to represent a present-day baseline, determined by averaging the total loss returned by each of the 16 UKCP18 model members under a GWL of 1.1°C.

Table 2. Global Warming Levels, timeframes and climate scenario naming conventions, alongside selected climate model members and rationale

Global Warming Level (GWL)	Timeframe	Climate scenario	Selected model members	Selection rationale
1.1°C	Present day	-	Average of all members	-
1.5°C	2030s	Central	Member 9	Models with median modelled economic losses
2.0°C	2050s		Member 12	
2.0°C	2030s	High	Member 13	Models with maximum modelled economic losses
2.5°C	2050s		Member 13	

Adaptation

A long list of adaptation measures was identified for each modelled risk through extensive literature reviews and insights from subject matter experts. Options were then short-listed through a qualitative multi-criteria analysis, considering their costs, co-benefits, and effectiveness at mitigating heat-related impacts, in addition to availability of relevant quantitative data. This resulted in a shortlist of 15 adaptation options that were subjected to a full, quantitative cost-benefit analysis. The shortlisted adaptation measures are shown in Table 5.

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[4] Due to a lack of robust data for estimating impacts, it is assumed that all losses occur through yield reductions, rather than a combination of yield and quality loss.

The cost-benefit analysis was developed on the assumption that adaptation could be required for each hectare of cereal crops and each animal projected to experience economic loss due to the modelled heat-related risks. We consider this reasonable for measures like lamb vaccination, soil quality enhancement and tree planting which can be widely applied to existing land management practices. This approach would not be applicable to adaptation options which require insights into site, soil and farm-business specific circumstances, such as substitution of arable crops with viticulture or cultivation of novel crops such as soybeans. The substitution of current cereal cultivars with those adapted to peaks of heat during the flowering period was also omitted from modelling, due to the absence of quantitative data on suitable varieties or evidence of breeding programmes selecting for this specific trait that are applicable to the UK context. In principle, crop varieties with appropriate resilience traits could be substituted directly for current varieties on farm.

In addition to costs and benefits, the analysis considered adaptation baselines (where measures are known to pre-exist in landscapes, such as trees and hedgerows), potential future uptake rates for measures (over and above baseline provision), the efficacy of each measure at reducing the predicted heat-related losses, and the time that measures might take to reach maturity and become effective. A subset of the measures were taken forward as a package to inform detailed modelling on costs and effectiveness out to the 2050s.

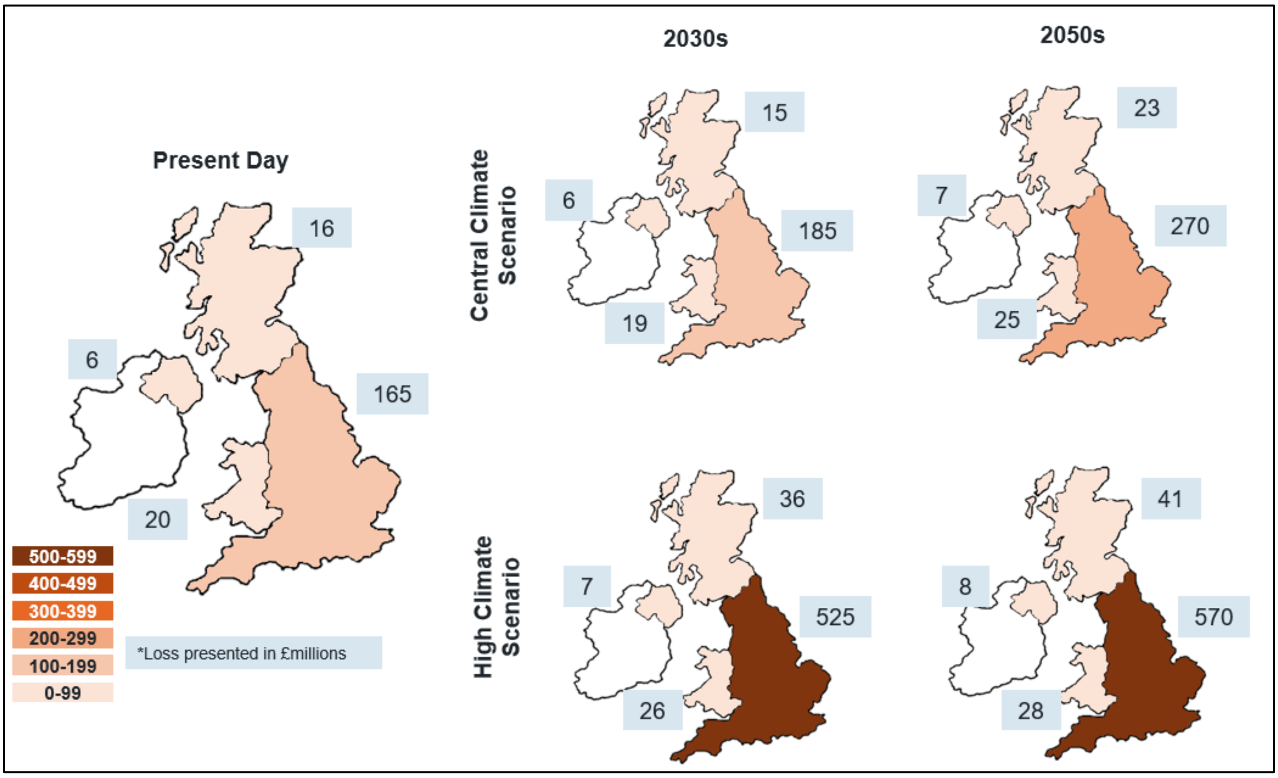
This adaptation assessment is not intended to provide farm-level insights or guidance, although the structure of the cost-benefit analysis could readily be adapted for application at this scale.

Understanding the risk

The analysis indicates that high temperatures during anthesis are likely to reduce cereal yields increasingly over time, particularly in regions such as the East of England, the Midlands and the South East of England. In England, barley and oats face annual yield losses of up to 29.9% and 36.2% of their current yields, respectively, by the 2050s due to high temperatures alone. Livestock systems also face heightened pressures: lamb farming losses are projected to increase due to additional parasite infections from *Haemonchus contortus*, particularly in Scotland and Wales, while milk and egg production show relatively minor direct losses from the modelled heat-related thresholds.

In economic terms, the results of the analysis show that under a business-as-usual, high climate scenario (GWL of 2.5°C by the 2050s), projected annual economic losses associated with the assessed heat-related risks for the six combined agricultural sub-components double when compared to a central scenario, across both the 2030s and 2050s (Figure 1). Under both the CB7a and CB7b scenarios, annual economic losses are less than the BAU scenario, primarily driven by reductions in livestock numbers and agricultural land area under these two scenarios.

Figure 1. Average annual economic losses from heat-related risks to wheat, barley, oats, milk, eggs, and lambs under Present Day, BAU 'Central' and 'High' Climate scenarios (£millions) in England, Scotland, Wales and Northern Ireland



Although projected economic losses exceed £0.5 billion per year (on average) in both the 2030s and 2050s under the High climate scenario, such losses are well within historic year-on-year variations in UK agricultural productivity.[5] However, the climate modelling indicates that these risks are much more significant (in terms of percentage of lost income) in England than in the Devolved Administrations (DAs): around 7%, compared with less than 1% in Northern Ireland (Table 3).

However, it must be recognised that the headline annual economic losses presented in Figure 1 are for averages, which obscure considerable underlying interannual variability in the climate projection data. For example, for England in the 2030s, the maximum economic loss for each agricultural sub-component in any modelled year is £1.16 billion for wheat, which is equivalent to 59% of England's 2024 income from wheat. In contrast, the minimum economic loss for wheat in England in any modelled year is £0 (no losses modelled to occur). The maximum barley losses in England and Scotland in the 2030s are also substantial, although losses from eggs and milk range from nil to negligible across all four home nations (Table 4).

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[5] Productivity fluctuations have a wide range of causes and are not all related to weather or climate stresses.

Table 3. Modelled average annual economic losses versus observed annual income from farming for the six agricultural sub-components

	England	Scotland	Wales	Northern Ireland
Observed Annual Income				
Average annual income from cereals, milk, eggs and lambs*	£8,035 million	£1,402 million	£1,120 million	£1,234 million
Standard deviation*	£1,424 million	£266 million	£128 million	£216 million
Modelled Losses				
Modelled average annual economic losses from cereals, milk, eggs and lambs (2050s, high climate scenario)	*£570 million*	*£41 million*	*£28 million*	*£8 million*
Modelled losses as a percentage of regional output (income)	*7.1%*	*2.9%*	*2.5%*	*0.6%*
*Category classifications differ slightly across the Devolved Administrations. Expressed in 2024 prices. Time periods for average figures include 2005-2024 (England and Scotland), 2015-2024 (Wales), 2018-2023 (NI). Sourced from official statistics from Defra, Scottish Government, Welsh Government, and Daera.				

Table 4. Maximum economic losses modelled for a single year (all from the 2030s, except where indicated)[6]

	England	Scotland	Wales	Northern Ireland
Barley	£795 million	£144 million	£19.4 million	£9.3 million
Wheat	£1.16 billion	£21.4 million	£8.2 million	£0.5 million
Oats	£154 million	£16.5 million	*Not modelled**	£0.7 million
Lamb	£41.6 million#	£21.1 million	£26.1 million	£8.1 million
Milk	£1.1 million	£0.1 million	£0.4 million#	£0.1 million
Egg	£0.7 million#	£0.0 million	£0.1 million#	£0.0 million
#Modelled maximum losses occur in the 2050s *Due to lack of spatial distribution data for this crop				

Sensitivity analyses using alternative (CB7-aligned) land use scenarios suggest that reducing agricultural land and livestock numbers could mitigate damages through reduced exposures, while productivity improvements may slightly offset modelled losses but still leave substantial risk. Overall, the study concludes that heat-related risks to UK agriculture will increase through the 2050s due to climate change. The findings underscore the need for robust and wide-ranging adaptation strategies and risk

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[6] NB. Columns not totalled to give aggregate losses per nation because these maximum losses by component occur in different years.

management to safeguard agricultural productivity and rural livelihoods in the face of uncertain future climate trajectories.

An effective adaptation response

The shortlisted adaptation measures and their benefit-cost ratios (BCRs) are shown in Table 5 below. A subset of the measures return a BCR >1 (alley cropping for cereals, planting trees for hens and soil water holding measures for cereals). This combination of three measures would (strictly) comprise a 'cost-optimal' package of measures. However, this would omit any measures for risk reduction in dairy cattle and lambs. In discussion with the CCC team, nature-focussed options were prioritised, while the particularly poorly performing rotational grazing approach to *Haemonchus* control was deprioritised. The low BCR of hedgerow measures (particularly when compared with those relying on trees) meant that they were also deprioritised. However, in reality, a farmed landscape will include hedgerows with trees. This produced a final compromise package of eight measures which explore the use of trees (to shade crops, dairy cattle and free range hens), the use of large ponds to provide cooling for cereals and dairy cattle, biosecurity and vaccination for lambs – and a combination of measures to improve soil water holding capacity (to deliver a cooling effect in the crop canopy).

Where more than one measure in the final package addresses the same agricultural sub-component (such as silvo-arable and soil-focussed measures), they were considered 'stackable' for both costs and benefits, with the combinations modelled accordingly. In most cases it was assumed that the implementation of the measure would not reduce the area of land available for cropping or grazing sufficiently for this to be reflected in the cost-benefit analysis. The exception was for measures requiring installation of ponds of sufficient dimensions to deliver a cooling effect, which were assumed to incur consequential losses of 12.5% of productive land.

Table 5. Shortlisted adaptation measures including benefit-cost ratios (BCRs). Derived from a UK-level analysis under the BAU: High climate scenario out to the 2050s, using discounted economic data.

Sub-component	Adaptation measure	BCR	Included in final package?
Cereals	Alley cropping to provide cooling via shade (silvo-arable)	1.07	Y
Cereals	This measure improves soil water holding capacity to provide a cooling effect and combines: Cover cropping; Min-till; Crop rotation; Controlled Traffic Farming; Organic matter additions	11.2	Y
Cereals	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits	0.40	Y
Lambs	Increase biosecurity measures on farms to guard against the import and/or spread of *Haemonchus contortus*	0.29	Y
Lambs	Vaccinate lambs against *Haemonchus contortus*	0.33	Y
Lambs	Deploy rotational grazing with appropriate layoff intervals to ensure demise of *Haemonchus contortus*	0.01	N
Dairy cattle	Silvo-pasture to provide shade for cattle – planting trees	0.80	Y
Dairy cattle	Silvo-pasture to provide shade for cattle – planting hedgerows	0.08	N

Sub-component	Adaptation measure	BCR	Included in final package?
Dairy cattle	House cows inside during hot periods, using winter housing facilities which have been suitably upgraded to deliver required shade and cooling	-1.47	N
Dairy cattle	Install in-field shelters/tents (semi-permanent) to provide shade	-0.03	N
Dairy cattle	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits	0.32	Y
Laying hens	Silvo-pasture to provide shade for hens – planting trees	1.10	Y
Laying hens	Silvo-pasture to provide shade for hens – planting hedgerows	0.08	N
Laying hens	House hens inside during hot weather. Upgrade nighttime housing to include fans + high-pressure fogging, and paint roof with reflective paint	0.00	N
Laying hens	Install in-field shelters/tents (semi-permanent) for free range hens to provide shade	0.00	N

Figure 2 demonstrates that without adaptation, economic losses from heat-related risks will rise over time (annual average losses increase from £168m in the baseline year, to £189m by the 2030s and £275m by the 2050s). Adaptation measures such as silvo-pastoral interventions (trees providing shade in pasture), silvo-arable interventions (alley trees in arable fields), large ponds and improved soil water holding capacity all provide cooling effects via shading and/or evaporative processes, whilst lamb vaccination and enhanced biosecurity measures help to address parasite risks. In combination, these measures reduce economic losses from heat-related risks – especially when implemented early and maintained over time – increasing from £17m in the 2030s to £52m in the 2050s. However, residual risks will remain within adapted landscapes, indicating that on-farm interventions alone cannot fully eliminate or address predicted economic losses. The effectiveness of nature-focussed adaptation measures increases over time – particularly as trees grow and mature, and soil conditions improve – and the net benefits of the package of measures grow from approximately £230 million per year in the 2030s to £1.1 billion annually by the 2050s in the central climate scenario, reflecting co-benefits of £716m and £1.6bn over the same time periods. The same pattern is evident under the BAU: High scenario, but in this case the increased economic losses (due to higher climate risk) are not fully compensated for by the co-benefits in the 2030s – and not compensated for to such a degree by the 2050s (Figure 3).

Average annual costs for implementation of the adaptation package for all modelled scenarios out to the 2030s and 2050s in the UK are £314 million and £262 million, respectively. For context, the expenditure on agri-environment schemes in England during 2023 was £553 million, and total agri-environment spend across the UK during that year was ~£670 million. The data show that adaptation measures implemented in the Present Day or early 2030s result in significantly higher net benefits by the 2050s. This finding underscores the value of early and proactive investment in climate resilience. Delaying adaptation not only increases exposure to risk but also reduces the financial efficiency of the measures. Early action allows time for interventions to mature and deliver their full benefits, particularly for measures with long lead times such as tree planting. Therefore, early implementation of adaptation should be prioritised to maximise returns and minimise future losses.

Figure 2. Annual average totals for Present Day, 2030s and 2050s under the BAU: Central scenario, combining modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦

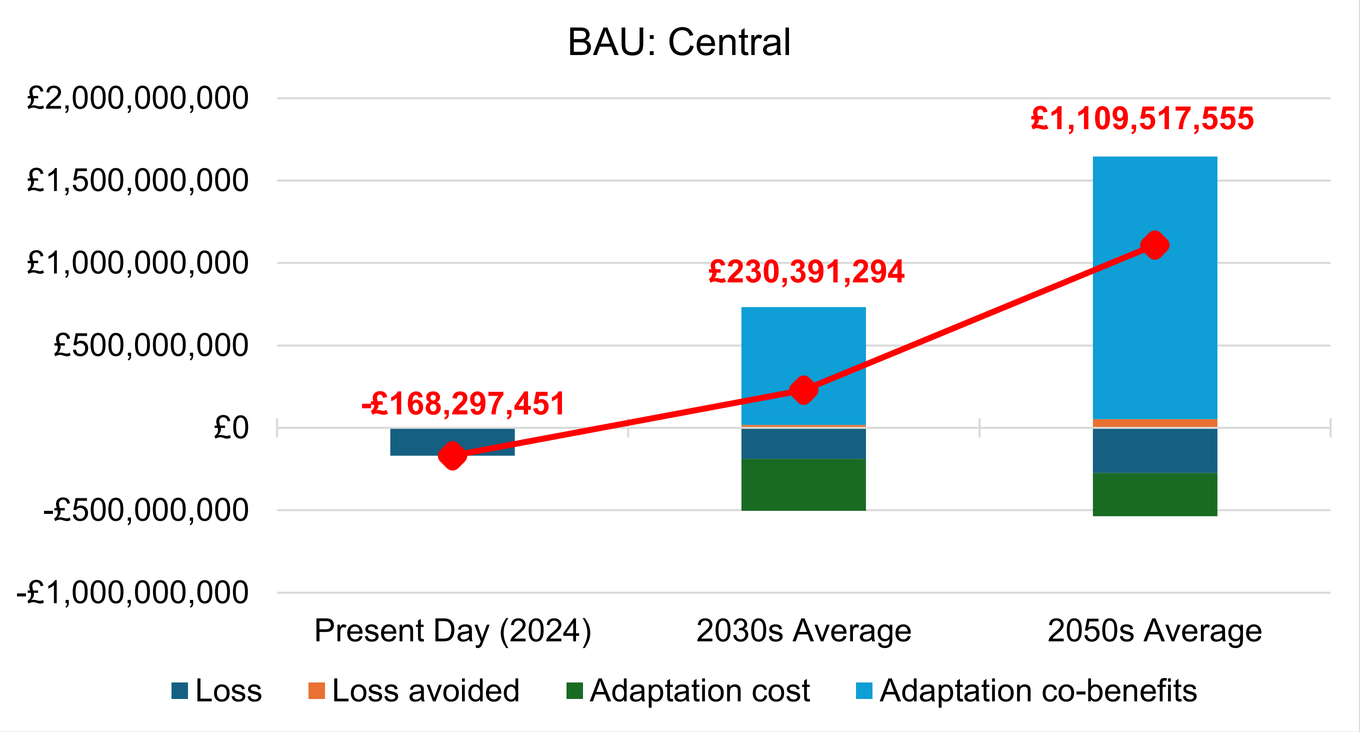
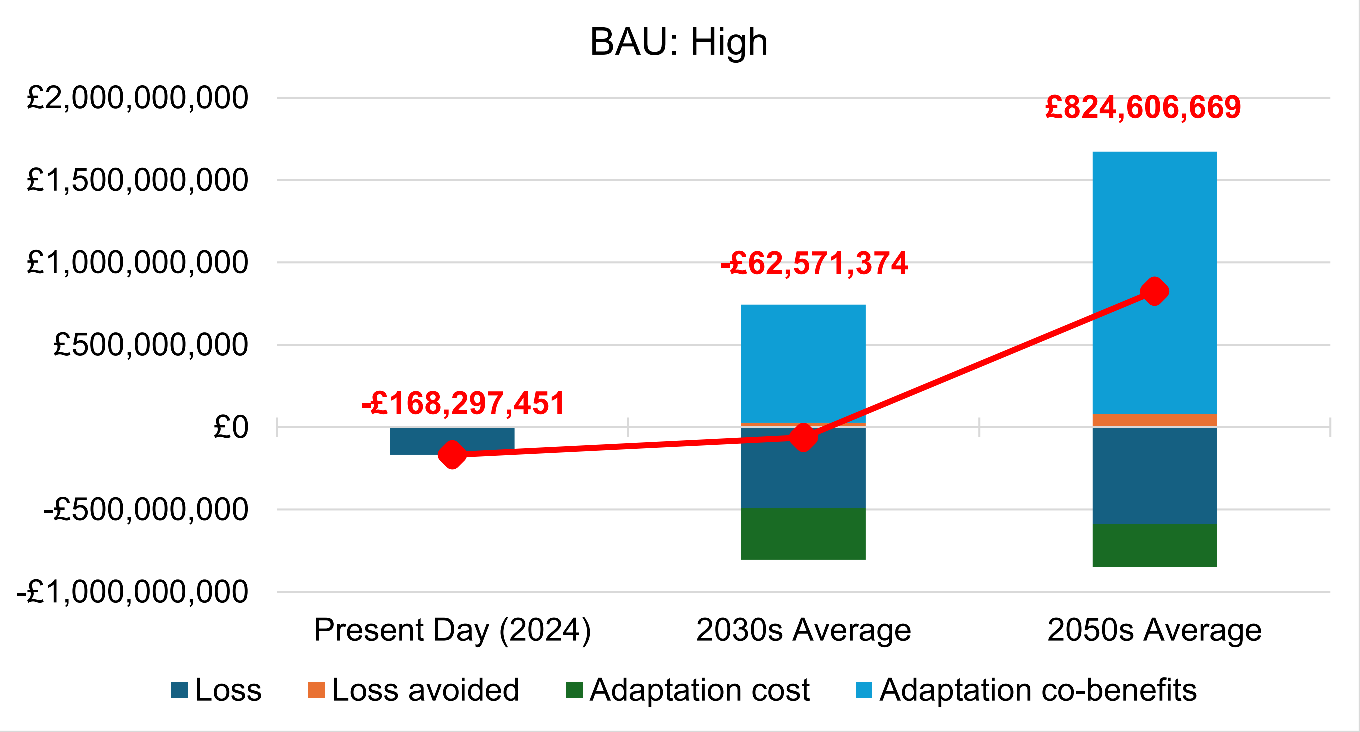


Figure 3. Annual average totals for Present Day, 2030s and 2050s under the BAU: High scenario, combining modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦



The analysis also highlights the importance of co-benefits, such as carbon sequestration and ecosystem services, which substantially increase the total value of adaptation beyond direct heat risk reduction. Sensitivity analyses reveal that adaptation remains cost-beneficial even under extreme ('peak heat') scenarios and varying cost assumptions due to these co-benefits, though the degree of benefit varies by region and scenario.

Transformative adaptation options, such as converting arable land to woodland, wetland, or wildflower meadow, show that only wetland conversion yields a benefit-cost ratio above one, illustrating that the ecosystem service benefits outweigh the costs of conversion (notwithstanding that this simple analysis excludes system impacts such as the need to replace lost grain production from elsewhere).

'Unconstrained' (100%) uptake of the adaptation package was also modelled, showing the substantial increases in annual average costs that such an approach would incur in the 2030s and 2050s (Table 6), outweighed enormously by the 2050s once planted trees have matured (Table 7).

Table 6. Annual average costs of implementing the adaptation package at 'realistic' and 100% uptake rates at a UK level. Undiscounted values expressed in 2024 prices

Adaptation costs	Present Day (2024)	2030s Average	2050s Average
BAU: Central and High (realistic uptake)	£0	£314,162,619	£261,510,434
BAU: Central and High (100% uptake)	£0	£2,145,079,234	£873,380,219

Table 7. Net annual benefits under BAU: Central and BAU: High scenarios when the adaptation package is implemented at 'realistic' and 100% uptake rates at a UK level. Undiscounted values expressed in 2024 prices

Net benefits	Present Day (2024)	2030s Average	2050s Average
BAU: Central (realistic uptake)	-£168,297,451	£230,391,294	£1,109,517,555
BAU: High (realistic uptake)	-£168,297,451	-£62,571,374	£824,606,669
BAU: Central (100% uptake)	-£168,297,451	-£813,348,037	£2,909,878,154
BAU: High (100% uptake)	-£168,297,451	-£1,086,945,383	£2,693,273,320

Overall, the findings underscore that while field-scale adaptation is essential for climate resilience against heat-related hazards, it must be complemented by broader risk management strategies, and early, sustained investment is crucial for maximising long-term benefits and minimising future losses.

Scope and limitations

This study was initially conceived as a quantitative analysis of future acute and chronic temperature and precipitation events as applied to both agricultural productivity and nature within the UK's farmed landscapes. Working within a defined quantitative methodology established by the CCC, the assessment sought to develop and model the relationships between specific climate hazards, risk metrics and adaptation solutions. However, evidence from both literature and expert stakeholders indicated that our ability to attribute quantified climatic events to causational impacts would be limited, meaning that a holistic analysis across all aspects of the UK farmed landscape was not feasible with available data. In consequence, the study has been restricted to a quantitative assessment of heat-related impacts for a small range of crops and livestock. This represents a fraction of the climate risks facing UK farmed landscapes and the adaptations needed to address them. In developing a quantitative model for risk and adaptation several assumptions have been required, and the results should be used with caution.

A more holistic future quantitative analysis would require data for a wider range of components under a wider range of climate conditions, underscoring the need for better evidence across scales – from laboratory to landscape. This should not require major upfront investment if existing activities can be appropriately leveraged – for example through the capture of metadata that allows the results of crop trials to be analysed within the context of their prevailing climatic conditions, irrespective of whether those trials were conceived to inform studies of future climate impacts. Evidence from observed events could be invaluable, yet reports of past episodes lack the detail which could have identified which aspects of those episodes resulted in losses (or gains). In terms of suggestions for future research, several key data gaps were identified throughout this study, including:

- Climate risk thresholds relevant to UK farming
- Climate risk thresholds relevant to nature within the UK's farmed landscapes
- Ability to value nature benefits beyond ecosystem services
- Quantitative effectiveness of adaptation measures in addressing specific climate risks
- Costs of adaptation measures
- Approaches to integration of impacts and adaptation measures at a system level

Lack of quantified data on the effectiveness of adaptation measures is particularly notable and represents an urgent research priority. Although beyond the scope of this project, adaptation measures focussed on soil quality (specifically those seeking to increase soil organic matter) are also climate mitigation measures, and such synergies between adaptation and mitigation (together with any antagonisms) should be integrated in any future follow-up study. Likewise, measures explored in this analysis for their reduction of heat impacts will likely confer benefit under other conditions, such as waterlogging and drought, which should be considered in future benefit-cost analyses.

Finally, this study acknowledges that farmed landscapes face multiple external pressures – some of which may be more immediately impactful than climate change. The findings underscore the importance of integrating climate resilience into broader agricultural and environmental frameworks, ensuring that adaptation strategies are economically viable, ecologically sound, and socially equitable.

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Abbreviations and Glossary

Abbreviations

Abbreviation	Description
£AAD	Annual Average Damages
£NPV	Net Present Value
BAU	Business-as-usual
CAPEX	Capital Investment Costs
CB7a	Land use scenario partially aligned to the Seventh Carbon Budget
CB7b	Land use scenario aligned to the Seventh Carbon Budget
CB7	Seventh Carbon Budget
CCC	Climate Change Committee
CCRA4	Fourth UK Climate Change Risk Assessment
CEDA	Comprehensive Environmental Data Archive
CO2e	Carbon Dioxide Equivalent
CPM	Convection-Permitting Model
DA	Devolved Administration
DEFRA	Department for Environmental, Food and Rural Affairs
ED	Environmental Destination
ELMS	Environmental Land Management Scheme
GVA	Gross Value Added
GWL	Global Warming Levels
IPCC	Intergovernmental Panel on Climate Change
MCA	Multi-Criteria Analysis
NI	Northern Ireland
NGO	Non-Government Organisation
OPEX	Annual Operating and Maintenance Costs
RCM	Regional Climate Model
REA	Rapid Evidence Assessment
SFI	Sustainable Farming Incentive
SPEI	Standardised Precipitation Evaporation Index
SPI	Standardised Precipitation Index
SSG	Stakeholder Steering Group

Abbreviation	Description
THI	Thermal Heat Index
ToR	Terms of Reference
UKCEH	UK Centre for Ecology and Hydrology
UKCP18	UK Climate Projections
WA report	Well-adapted UK report

Glossary of Terms

Term	Explanation
Adaptation	The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects. Source: IPCC AR5[7]
Adaptation Pathway	A generic term that involves the analysis of adaptation options over time to changing risk levels.
Agroforestry	Agroforestry describes the practice of growing crops along with trees and shrubs, as an integrated approach.
Agricultural Productivity	Agricultural productivity describes how efficient the output which is the yield in relation to the inputs and resources at national and UK levels.
Arable System	Arable system refers to the farming system for crop cultivation.
Blue-Green Infrastructure	Blue-green infrastructure describes the blue infrastructure as natural and semi-natural areas involving water and green infrastructure relates to any area which is land based.
Biodiversity	Biodiversity or biological diversity means the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems. Source: IPCC AR6[8]
Capital Expenditure	Funds used by an organisation to acquire, upgrade, or maintain physical assets such as property, industrial buildings, or equipment.
Chronic Water Stress	Chronic water stress refers to long-term shifts in patterns indicative of wetter or drier periods within the simulated time series.
Chronic and Acute Thresholds	Chronic thresholds refer to long term climate thresholds opposed acute thresholds which are immediate and can be reached in a shorter time period or due to certain events.
Climate	Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as

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[7] https://www.ipcc.ch/assessment-report/ar5/

[8] https://www.ipcc.ch/assessment-report/ar6/

	defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system. Source: IPCC AR5[1]
Climate Change	A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external processes such as modulations of the solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use. Source: IPCC AR5[1]
Co-Impacts/Co-Benefits	The positive effects that a policy or measure aimed at one objective might have on other objectives, thereby increasing the total benefits for society. Co-benefits are often subject to uncertainty and depend on local circumstances and implementation practices, among other factors. Source: IPCC AR5[1]
Consumer	Consumer refers to a person or a group which buys or uses a product or service such as wheat for nutrition.
Cost Effective	Cost effective describes how effective something is in relation to its cost or input required.
Cost-Optimised Adaptation Package	A package of adaption measures which seeks to balance objectives related to total cost of adaptation, risk reduction and realised co-benefits.
Crop Yield	Crop yield refers to the volume of output from a particular crop.
Deep Dive	This term used to describe the CCC commissioned projects, focused specifically on assessing climate risks and risk mitigation (through adaptation) for UK
Devolved Administration Also “Nations”	Scotland, Wales and Northern Ireland
Drought	The meaning of drought has different means in different contexts as follows: • Agricultural: insufficient rainfall or dry soil adversely affects farming and crop growth. • Meteorological: rainfall in a region falls below average levels, • Ecological: limited water availability impacts the local environment, • Hydrological: reductions in water bodies such as streams and reservoirs, which may result from low precipitation, inadequate snowmelt, or other factors.
Ecosystem	An ecosystem is a functional unit consisting of living organisms, their non-living environment and the interactions within and between them. The components included in a given ecosystem and its spatial boundaries depend on the purpose for which the ecosystem is defined: in some cases, they are relatively sharp, while in others they are diffuse. Ecosystem boundaries can change over time. Ecosystems are nested within other ecosystems, and their scale can range from very small to the entire biosphere. In the current era, most ecosystems either contain people as key

	organisms, or are influenced by the effects of human activities in their environment. Source IPCC AR6[2]
Ecosystem Services	Ecosystem Services refer to direct and indirect contributions an ecosystem make such as water management, carbon sequestration and biodiversity support
Farmed Landscapes	Refers to landscapes used primarily for agriculture and where agricultural has formed and shaped the landscape through its activities. This includes the boundaries between farming activities and the natural environment.
Genetically Engineered	Genetically engineered refers to the physical manipulation of genes of a species in a laboratory environment
Genetically Modified	Genetically modified refers to gradual modification of genes through selective breeding
Global warming levels (GWL)	Global warming refers to the increase in global surface temperature relative to a baseline reference period, averaging over a period sufficient to remove interannual variations (e.g., 20 or 30 years). A common choice for the baseline is 1850-1900 (the earliest period of reliable observations with sufficient geographic coverage), with more modern baselines used depending upon the application. Global warning Levels refer to 1.5ºC, 2.0ºC and 2.5ºC of warming above pre-industrial levels. Source IPCC AR6[2]
Gross Value Added (GVA)	The difference between the value of the final output and the input costs, including taxes, profits and wage costs
Haemonchus contortus Also, barber's pole worm	This is a blood sucking roundworm parasite that can cause a condition in animals leading to weight loss, anaemia and death.
Hazard	The potential occurrence of a natural or human-induced physical event or trend 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. In the IPCC, hazard refers to climate-related physical events or trends. Source: IPCC AR5[1].
Measure Also, Option	A single adaptation intervention assessed on its own for climate risk augmentation potential, costs, feasibility, and wider benefits, before combining into packages (i.e. Installing roof rainwater collectors on farms).
Land use	Land use refers to the total of arrangements, activities and inputs undertaken across certain land cover types (a set of human actions). The term land use is also used in the sense of the social and economic purposes for which land is managed (e.g., grazing, timber extraction, conservation and city dwelling). Source: IPCC SR1.5[9]
Land Use Archetypes	Land Use Archetypes refers to recurring patterns of land use and management which emerge from the combination of natural, social, economic, and political factors
Mitigation	A human intervention to reduce emissions or enhance the sinks of greenhouse gases. Source IPCC AR6[2]

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[9] IPCC (2020). Global Warming of 1.5 oC. [online] IPCC. Available at: https://www.ipcc.ch/sr15/.

Natural Capital Accounting	Natural Capital Accounting is a tool to measure the total economic value of natural assets.
Net Present Value	Net Present Value is a generic term for the sum of a stream of any future values that have been discounted to bring them to a present value.
Net Zero	Condition in which metric-weighted anthropogenic greenhouse gas (GHG) emissions are balanced by metric-weighted anthropogenic GHG removals over a specified period. The quantification of net zero GHG emissions depends on the GHG emission metric chosen to compare emissions and removals of different gases, as well as the time horizon chosen for that metric. See also: Greenhouse gas neutrality, Land use, land-use change and forestry (LULUCF), Net zero CO2e emissions. Source IPCC AR6[2]
Operational Expenditure	The ongoing costs for running a business, asset, or system, including maintenance and utilities.
Optimisation	Optimisation is the process of identifying the most effective sequence and combination of decisions over a planning period, while satisfying defined constraints and objectives.
Pastoral System	Pastoral system refers to the agricultural system of raising livestock.
Perturbed Physics Ensemble	Perturbed Physics Ensemble refers to a set of climate model simulations with each member using a slightly different settings for the model's physical parameters, based on the uncertainty of those parameters and helping provide new estimates on climate sensitivity.
Resilience	IPCC AR5[1] defines as: the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation.
Risk	The potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain. In the context of the assessment of climate impacts, the term 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. Source: IPCC SR1.5.[3] Note that in CCRA3, the term risk is used for negative consequences (i.e. threats).
Sequestration	The net uptake of carbon from the atmosphere and long-term storage as non-volatile carbon. This can be in the wood of living trees, in soil, or in long lived wood products. Source Forest Research(Carbon Glossary - Forest Research)[10]
Seventh Carbon Budget (CB7)	The Climate Change Committee's 2025 advice to Government on the setting of the cap of the UK's greenhouse gas emissions over the five-year period 2038 to 2042 (CB7).

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[10] Forest Research. (2025). Carbon Glossary - Forest Research. [online] Available at: https://www.forestresearch.gov.uk/climate-change/carbon/carbon-glossary/ [Accessed 13 Feb. 2026].

Silvo-arable and Silvo-pastoral	Silvo-arable describes the agricultural practice of growing crop or rearing livestock simultaneously to longer term tree crop, for a more immediate income.
Thresholds	These represent levels above which there is step-change in risks, and which may necessitate much greater levels of adaptation. These include biophysical thresholds, engineering thresholds, performance thresholds and policy thresholds.
Total Expenditure (TOTEX)	This refers to the combined value of capital expenditure (CAPEX) and operational expenditure (OPEX).
Uncertainty	A state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of Sources, from imprecision in the data to ambiguously defined concepts or terminology, incomplete understanding of critical processes, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g., a probability density function) or by qualitative statements (e.g., reflecting the judgment of a team of experts). Source: IPCC AR5[1].
Uptake rate	The proportion actually achieved of a notionally achievable level, such as a maximum technically or socio-economic feasible level or a target level set by policymakers.
Vulnerability	The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt. Source: IPCC AR5[1].
Water scarcity	Water scarcity refers to a condition where water demand exceeds available supply in a given region, either permanently or seasonally. It is driven by a combination of climatic factors, population growth, land use changes, and water management practices. Scientifically, it is often quantified using metrics such as the Water Scarcity Index (WSI),the ratio of water demand to water supply; or the Falkenmark Indicator, which defines scarcity as less than 1,000 m³ of renewable freshwater per person per year. Source: Global assessment of water challenges under uncertainty in water scarcity projections | Nature Sustainability[11]

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[11] Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., Fischer, G., Tramberend, S., Burtscher, R., Langan, S. and Wada, Y. (2018). Global assessment of water challenges under uncertainty in water scarcity projections. Nature Sustainability, [online] 1(9), pp.486–494. doi:https://doi.org/10.1038/s41893-018-0134-9.

Introduction

Context

The Climate Change Committee (CCC), an independent statutory body established under the 2008 Climate Change Act, is tasked with advising the UK Government on climate risks and carbon budgets. The CCC was commissioned by DEFRA to lead the Independent Assessment for the Fourth UK Climate Change Risk Assessment (CCRA4-IA), due in mid-2026, which would inform HM Government's Fourth UK Climate Change Risk Assessment, expected to be submitted to Parliament in January 2027.

To complement the CCRA4 Technical Report, the CCC introduced a new output – the Well-adapted UK Report (WAUK). This aims to highlight the actions required to adapt to climate change risks across the UK and includes in-depth exploration of cost-effective adaptation pathways for a range of specific risks in sectors critical to the UK economy.

In developing the WAUK report, the CCC has commissioned a series of 'deep dive' assessments that explore how it might be possible to measure risk, quantify adaptation and unlock investment in key economic sectors. These 'deep dives' focus on current ability to quantify climate risk and adaptations by projecting climate-related hazards, risks and costs out to the 2030s and 2050s, evaluating the cost-effectiveness and co-benefits of adaptation interventions to build a national-scale scenario of cost-optimised adaptation packages across this period. Together, these deep dives aim to build a strong evidence base to feed into CCRA4, ensuring that adaptation measures are both effective and grounded in the realities faced by core sectors across the UK.

WSP UK Ltd. was commissioned to lead a consortium to deliver one of the bespoke 'deep dive' projects, focused specifically on assessing climate risks and adaptation for UK farmed landscapes. The analysis aimed to quantify the cost and effectiveness of adaptation interventions that could mitigate climate risks to agriculture and nature within farmed landscapes, while also delivering broader ecosystem and societal benefits. The intention of this 'deep dive' was to provide a strong evidence base to support CCRA4, by exploring and quantifying actions required to address climate change risks to agricultural production and natural capital.

This study was initially conceived as a quantitative analysis of future acute and chronic temperature and precipitation events as applied to both agricultural productivity and nature within the UK's farmed landscapes. Working within the constraints of a quantitative methodology established by the CCC, the assessment sought to develop and model the relationships between specific climate hazards, risk metrics and adaptation solutions. However, evidence from both literature and expert stakeholders indicated that our ability to attribute quantified climatic events to causational impacts would be limited, meaning that a holistic analysis across all aspects of the UK farmed landscape was not feasible with available data. In consequence, the study has been restricted to a quantitative assessment of heat-related impacts for a small range of crops and livestock. This represents a fraction of the climate risks facing UK farmed landscapes and the adaptations needed to address them.

Background

Farmland covers more than 70% of the UK and produces about half of the nation's food.[12] Farmland also represents a significant part of the UK's natural capital, estimated at £1.5 trillion.[13] Climate change presents a wide range of risks to the UK's farmed landscapes that could affect future sustainability, productivity, and the achievement of Net Zero targets. Extreme weather events like heatwaves and droughts can directly reduce crop yields and harm livestock health, leading to reduced agricultural productivity. Additionally, acute hazards such as storm events can degrade soil health through erosion and nutrient loss, which negatively impact soil structure, soil fertility and water quality.[14] Despite these challenges, there are various opportunities for adaptation targeted at maintaining or improving both productivity and nature outcomes within farmed landscapes. These range from using more resilient crop varieties to planting more hedgerows and integrating trees within arable and pastoral systems. Not only do such adaptations offer the potential to reduce risks to core agricultural productivity, but also to increase the provision of ecosystem services across farmed landscapes.

Recent years have provided stark illustrations of these vulnerabilities. For example, the hot, dry summer of 2018 led to significant reductions in crop yields, with carrots and onions particularly affected, and highlighted the sector's exposure to acute climate shocks. Increasingly frequent and severe hazards, such as flooding, further undermine soil health and fertility, compounding risks to both food security and the wider environment. Opportunities for adaptation are available, such as the introduction of new crop varieties and new planting cycles to capitalise on longer growing seasons. However, robust evidence is required before these can attract investment or be reflected in strategic plans that support implementation.

The CCC's Farmed Landscapes 'deep dive' project was commissioned to explore critical gaps in the evidence base regarding the systemic and spatial climate risks facing UK farmed landscapes. Previous assessments have often relied on qualitative analysis, lacking the spatial and quantitative rigour needed to inform policy and investment decisions at both national and local levels. This project sought to overcome these limitations by integrating quantitative data on climate impacts with qualitative insights from stakeholders, thereby supporting the development of cost-optimal adaptation strategies that deliver benefits for agriculture, nature, and society. Following detailed literature review and stakeholder engagement, data were found that allowed prior limitations to be overcome in part – informing a quantitative analysis of heat-related impacts on a representative range of crops and livestock.

A key driver for this deep dive was the recognition that farmed landscapes are not only vital for food production but also for the delivery of wider ecosystem services, such as water management, carbon sequestration and biodiversity support. The project's approach was grounded in a hazard-exposure-vulnerability framework, enabling a nuanced assessment of risks across different landscape archetypes and regions. By modelling present-day and future risks under various climate and land use scenarios, the project provided a targeted spatial risk assessment, quantifying direct costs of explicit heat-related climate hazards to the identified agricultural sub-components. While informative for broad consideration of the challenges and opportunities in managing climate risk, the lack of sector-depth and breadth within

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[12] Defra. 2023. Agricultural Land Use in United Kingdom at 1 June 2023. Department for Environment, Food and Rural Affairs, Department of Agriculture, Environment and Rural Affairs (Northern Ireland), Welsh Government Knowledge and Analytical Services, and Scottish Government Rural and Environmental Science and Analytical Services.

[13] Office for National Statistics (ONS), released 27 November 2023, ONS website, bulletin, UK natural capital accounts: 2023

[14] Arnell, N.W. and Freeman, A., 2021. The effect of climate change on agro-climatic indicators in the UK. Climatic Change, 165(1), p.40.

the study's results highlight significant evidence gaps and underscore the need for improved monitoring and development of robust climate risk thresholds to inform future adaptation strategies.

Furthermore, the project placed strong emphasis on stakeholder engagement, recognising the importance of integrating practical knowledge from farmers, land managers and policymakers throughout the analysis. This collaborative approach ensured that the recommended adaptation actions were grounded in the realities of land management across the UK. It also ensured that the project could reflect, rather than duplicate, the many current initiatives in this domain that are seeking to ensure resilience across farming and the natural environment. The project also sought to address the distributional impacts of climate risks and adaptation measures, highlighting the need for equitable and effective interventions.

This deep dive aims to provide the CCC and government decision-makers with a targeted quantitative assessment and evidence base to inform the Fourth UK Climate Change Risk Assessment and the Well-adapted UK report. The findings reveal critical gaps in available evidence, emphasising the necessity for enhanced data capture and the establishment of clear, scientifically robust climate risk thresholds, impact metrics and tested adaptation solutions. Filling these evidence gaps is essential to support informed decision-making and the development of effective adaptation strategies across UK.

Research Design

The analysis followed the CCC's 'deep dive' methodology across three sequential stages, to first define the problem (hazard-impact); second, estimate the baseline current and future risk (and vulnerability), and finally, to develop and test a package of cost-optimised adaptation interventions. A mixed methods research design was adopted, facilitating integration of both quantitative and qualitative data where available. This approach enabled the development of contextual and explanatory narratives alongside quantitative model outputs when attributable and causational evidence was missing from the literature. A balance between computational efficiency with methodological rigour was required, emphasising transparent communication of uncertainties, systematic scenario design and the incorporation of stakeholder expertise to ensure the validity of findings.

Given the breadth and complexity of the project, the team promoted a collaborative approach that drew on interdisciplinary expertise across farming, nature and economics. The analysis was designed to be spatially explicit, economically grounded and socially informed ensuring that the adaptation scenarios developed were technically sound and actionable. The aim was to deliver insights that could help shape resilient agricultural landscapes capable of sustaining productivity, enhancing biodiversity and delivering long-term socio-economic value in the face of climate change-exacerbated heat hazards.

It should be noted that – by its nature – this analysis represents only a limited quantitative view of the climate risks affecting UK farmed landscapes and the adaptations required to address them. Its scope was confined to heat-related thresholds for a subset of crops and livestock. Benefits to nature were considered through carbon and ecosystem services delivered by specific adaptation options, rather than through population growth or diversity. Consequently, the findings should be interpreted with caution, as they are constrained by data availability and shaped by significant uncertainties and assumptions.

Guiding principles

The following principles guided the research design for this project:

- The risk assessment centred on, where possible, quantifying and qualifying direct economic losses resulting from climate change at both national and UK levels. This administrative scale ensures that the analysis captures the scale of impacts and provides insights that are relevant to strategic decision-making across all home nations.
- Whilst quantification is a key part of this assessment, many assumptions and simplifications are necessary due to data constraints.
- Hazards and impacts should only be quantified where they are grounded upon a solid evidence base.
- The research should advance the adaptation agenda through the provision of an evidence-based, cost-effective range of adaptation measures, emphasising the importance of nature-based and landscape-scale interventions.
- The assessment method should be designed to maintain and enhance consistency with other previous or concurrent CCC deep dive studies. By aligning methods and analytical frameworks where possible, the research contributes to a coherent evidence base across key sectors of the UK economy that can be readily integrated with existing national and regional initiatives.
- The assessment must align with the CCC's established approaches for climate framing, risk assessment, and economic analysis. This ensures that the study's methodology is consistent with other research supporting CCRA4 and the Well-adapted UK Report.
- There should be proactive engagement of stakeholders, including policymakers, regulators, sector representatives and other experts, throughout the research process. This approach not only assures the validity and credibility of findings but also helps secure stakeholder buy-in, fostering confidence in the outcomes and supporting effective implementation of CCC's ultimate recommendations to Government.

Project summary

The project was delivered in accordance with the scope, tasks and methodology set out by the CCC and amended where necessary due to data constraints. The work was structured across three phases, each comprising distinct but interrelated tasks.

Phase 1: Project Inception

The project team convened a multidisciplinary stakeholder steering group, focused on balanced representation and meaningful participation from across the UK, including Scotland, Wales, and Northern Ireland. This group provided critical input throughout the project lifecycle. Engaging stakeholders effectively and proportionately was critical to the success of the project. The team designed engagement processes that were efficient and respectful of stakeholders' time, while still gathering the necessary input to inform key decisions.

A rapid evidence review was conducted, synthesising academic and grey literature on climate impacts, adaptation actions and investment requirements. This review informed refinements to the modelling approach and ensured alignment with existing CCC workstreams. The context across the UK's nations was documented, and recommendations for scope adjustments were agreed with the CCC within the original project envelope.

Phase 2: Modelling and Analysis

This phase was delivered in line with the CCC's established 'deep dive' methodology. The team estimated present-day and future risks (Task 2.1), identified and appraised adaptation options (Task 2.2), constructed cost-optimised adaptation scenarios (Task 2.3), and conducted sensitivity analyses (Task 2.4).

Initial aspirations to model the impacts on farmed landscapes as an interconnected system were constrained by available data, leading to the adoption of a focussed approach that considered only defined and evidence-based heat-related hazard-impact relationships within the specified six agricultural sub-components (i.e., wheat, barley, oats, lambs, laying hens and dairy cattle). These constraints meant that certain key sub-sectors – such as field horticulture (encompassing vegetables, soft fruits, and orchard crops) – could only be assessed qualitatively. Similarly, risks to nature within farmed landscapes, including biodiversity and habitat impacts from projected heat stress, were excluded from the modelling. However, the analysis did quantify the ecosystem service benefits delivered by nature-focussed adaptation measures.

Heat-related climate hazards were modelled using UKCP18 local ensemble members and assessed to determine the frequency with which identified impact thresholds could be exceeded. Using specific data on the geographic distribution and yields/numbers of the six agricultural sub-components, climate risk from exposure to identified heat hazards was assessed spatially across the UK as lost productivity. The economic losses associated with the climate risks were monetised using financial cost metrics related to this lost agricultural productivity.

Spatial analysis was conducted across the four nations and aligned to land-use archetypes where possible.

Adaptation options were collated from a combination of published evidence and stakeholder expertise, covering operational, infrastructure and nature-based measures. A longlist of measures was screened through a qualitative multi-criteria assessment to deliver a priority shortlist. Co-benefits and trade-offs were assessed quantitatively, for each measure on this shortlist, using Natural Capital Accounting methods to reflect their total economic value, which informed the selection for an 'optimum' package of measures.

Different climate and land use scenarios were explored to test high vulnerability and exposure conditions, relative to a Business-As-Usual (BAU) position. In addition, further analysis was conducted to explore extreme event peaks, increased adaptation uptake and cost fluctuations in the cost-benefit modelling.

Phase 3: Reporting

All modelled datasets developed during the project were documented and forwarded to the CCC. Where proprietary models were used, limitations were clearly stated. Evidence gaps and suggestions for future work were documented. The team presented key results to the CCC and the steering group, ensuring validation, clarity and relevance of the findings without making policy recommendations.

Challenges, Assumptions and Limitations

During the delivery of the project, the team encountered and addressed a range of challenges, summarised here.

Lack of Data Availability

The project relied on the best available datasets rather than undertaking new primary data collection. While this approach ensured efficiency and leveraged established models and databases, it also presented the challenge of working within the constraints of data with gaps and varying levels of detail across four nations. Access to required datasets proved to be a significant challenge, particularly relating to the spatial distribution of crops and livestock across the UK's farmed landscapes. Some data was not publicly available and delays in obtaining permissions and access impacted early-stage timelines. These issues were particularly pronounced in the DAs, where data governance and availability varied. To mitigate this, the team proactively identified data availability risks during project planning and purchased proprietary data with the required spatial granularity.

Data for distribution of crops and livestock across Northern Ireland were particularly challenging to obtain, so the team accounted for these differences by applying region-specific adjustments and documenting the limitations and assumptions used in the process. Comparable data for oats were also unavailable for Wales.

Attributable and causational data to support the development of impact thresholds and metrics were limited and contributed to the focus on a small subset of agriculture production (i.e., cereals, dairy cattle, laying hens and lambs). Nonetheless, these six agricultural sub-components account for ~50% of total income from farming. Stakeholders highlighted the need to quantify risks to the UK horticulture sector, which contributes disproportionately to farm income with respect to the area of land it occupies, and is uniquely exposed to climate change in key locations such as the Fens of eastern England. Since quantification was not possible, horticulture has been explored qualitatively in Appendix H - UK horticulture. The parallel Water Scarcity 'deep dive' project[15] also covers risks to horticulture specifically from unmet irrigation demand.

Data availability was also a challenge in developing the final adaptation package. The greatest data gap was quantifying the efficacy of adaptations and establishing mechanisms of effect (i.e., in mitigating the hazard itself or the impact). Much of the literature on adaptation does not specify these considerations, which are a vital component of cost-benefit analysis. Additionally, baseline rates of uptake (i.e., the quantum of an adaptation measure already present in the landscape or farming system) and potential future uptake of adaptation measures had to be estimated.

Scope

The breadth and complexity of the project required careful scoping. Applying the CCC's 'deep dive' methodology through an analytical approach that accurately reflects the natural variability of climate parameters as well as the complex interactions arising from the natural environment and agricultural activities was a substantial challenge. Capturing these dynamics is critical for realistic risk assessment, yet modelling such processes involves intricate climatic and operational considerations, that are only represented at a high level in national-scale datasets. Working within the project's methodological

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[15] "UK projections of climate risks and effectiveness of adaptation measures for water scarcity"

constraints and in collaboration with the CCC, a realistic and achievable plan for quantification was developed.

As such, the risk assessment addresses and seeks to model only a specific set of heat-related changes and their associated impact thresholds to six agricultural sub-components. This study did not model the growing season or whole growth cycle of the crops and livestock. It only modelled defined climate parameters and impacts. As such, climate changes that might be beneficial to the agriculture sector, such as longer growing seasons, increased insolation or CO_2 enrichment, were excluded. Chronic changes refer to long-term shifts in patterns indicative of a warming trend within simulated time series, whereas acute heat stress events pertain to variations of high-temperature events. The farmed landscape will be impacted by both the steady increases in temperature (chronic) and periodic extreme (acute) temperature events. Quantifying the compound interactions of impact from both types of changes remains challenging.

Precipitation-related risks were also initially considered but could not be directly linked to field-level impact thresholds such as consecutive days of waterlogging leading to crop losses. As such, the costs of heavy rainfall and waterlogging were considered qualitatively through review of historic extreme precipitation events (Appendix I - Waterlogging).

In addition to this study, water scarcity risks to agriculture and related adaptations were considered in another of the CCC ‘deep dive’ projects. This examined risks to irrigated crops from scarcity in water supply through the lens of unmet water demand.

Climate data and future projections

Quantifying future risk and costs based on climate projections required complex modelling and scenario development. Careful consideration was given to both the strengths and limitations of the UKCP18 Regional and Local Climate Models and their associated products. While these models provide valuable insights into emerging trends for future climate scenarios, their resolution does not capture all the relevant factors that contribute to the natural variability seen in UK climatic conditions. In addition, when using UKCP18 data as an input to the climate risk assessment, constraints were experienced through:

- the sample size of 16 model members, which is a relatively small climate data ensemble;
- variability of intra-annual weather is not simulated or harmonised well across climate parameters;
- difficulty in bias correction across different geographies and climate parameters;
- spatial averaging to the UK scale may hide the magnitude of the changes at the regional or local scale; and
- only considering change through the 2050s (rather than to 2080s) and only looking at Global Warming Levels (GWLs) up to 2.5°C may not produce sufficient changes in the climate projections to assess cost-optimal adaptation in the longer-term or to a more pessimistic degree of warming.

Evidence for economic loss quantification

This project is limited to identification of direct financial costs only. It is acknowledged that indirect losses could be significant. For example, reductions in wheat yield are directly reflected in the modelling, whilst sunk costs associated with production of lost crops (such as labour, fertilisers and pesticides) are not. Additionally, exploration of the impact on livelihoods (such as labour availability or access to financial capital) was not possible through this study. This means that the modelled economic losses are likely to be underestimates, with consequential implications for assessing the costs and benefits of adaptation measures. Likewise, other indirect system losses such as the costs associated with securing forage in the event of local crop or pasture failures were excluded from the analysis.

It is also noted that the loss could be transmitted through the value chain, for instance from farmer to consumer. The financial costs have only been calculated on lost income relative to the direct farm losses. The loss does not represent direct losses to UK GVA through (for example) the need to import specific produce to make up for shortfalls in domestic production as a result of modelled climate risks. The geopolitical risks of such supply chain exposures are also out to scope for the analysis.

Not all climate impacts and adaptation co-benefits could be monetised using available evidence. The team prioritised costing the most significant impacts and clearly identified which costs and benefits could be valued. The team also ensured that benefits were not double-counted and that ecosystem services were appropriately valued. Where monetisation was not feasible, qualitative assessments were provided, and evidence gaps were highlighted for future research.

Approach to assumptions and considerations for future use of the results

The use of assumptions was essential throughout the project, to bridge gaps in available evidence. This was the case particularly for estimating current and future risk, and in evaluating the effectiveness and potential adoption of available adaptation strategies. Throughout the delivery, the team remained responsive to project-specific constraints, including data limitations and sectoral nuances. Where deviations from the preferred methodology or assumptions were necessary, these were clearly justified and reviewed collaboratively with the CCC to ensure alignment and accountability. Assumptions were documented and validated through literature review or with expert engagement where possible. Data gaps and modelling limitations were reduced through sensitivity testing, expert validation, and scenario analysis.

This study has been restricted to assessing specific heat-related impact thresholds for a small number of crops and livestock, representing a small fraction of the climate risks facing UK farmed landscapes and potential adaptations needed to address them. The analysis and findings are limited by their underpinning data and the resulting uncertainties mean that these results should be used cautiously.

Structure of this Report

This report is organised into five main sections:

- Phase One details the formation and remit of the stakeholder steering group, the institutions involved, and the engagement approach throughout delivery. It also summarises the approach to and outputs from the rapid evidence assessment (REA) and the influence of the REA on subsequent project tasks.
- Phase Two presents the methodology for conducting the assessment. This includes the climate risk modelling approach, scenario analysis, identification and appraisal of adaptation options, and the development of a cost-optimal adaptation package. It concludes with a sensitivity analysis exploring the implications of peak hazard events, application of the adaptation package to 100%

of impacted cereals and livestock, changes in costs of adaptation measures, and the cost impacts of taking land out of production and transforming it for nature benefit.

- The Conclusions highlight the need for more research, monitoring and evaluation that is needed across the agricultural and natural environment sectors in order to better understand, quantify and address the impacts of climate change and make evidence-based investments in short- and long-term adaptation.
- Beyond the Deep Dive explores broader themes and topics that could not be modelled through the CCC's deep dive quantification methodology due to data limitations. It draws on literature and stakeholder input to highlight critical factors that would not otherwise be captured, but which are of vital importance for understanding climate risks and adaptation needs within the context of farmed landscapes.
- The appendices include further detail and analysis on specific aspects of the project.

In addition to this report, several annexes and additional files have been provided to support the CCC's development of the WAUK report including raw data files, supporting research reports, and geodatabases.

Phase 1

Task 1.1 - Stakeholder Steering Group

Purpose and Remit

The topic of adaptation to climate change in farmed landscapes has been subject to extensive prior research, reflecting the contribution of these landscapes to UK productivity, resilience and identity. Many initiatives are ongoing at a range of scales - from growth rooms to whole farms - and it was essential that this project learned as much as possible from these initiatives, avoiding duplication. To capitalise on this wealth of experience, a Stakeholder Steering Group (SSG) was established at the outset of the project. Stakeholder engagement was seen as a key contributor to success in different areas:

1. The complexity and scale of the project required expertise from a range of domains, including academia, government, non-governmental organisations (NGOs), regulators and the farming community itself. Each group brought unique perspectives, data and practical experience, ensuring that the project's outputs were relevant and grounded in the realities of UK agriculture and environmental management;
2. The project's outcomes are intended to inform government policy and practice. As such, it was vital that government stakeholders had visibility of the project's approaches and assumptions as they were developed. This transparency allows policymakers and other stakeholders to understand the limitations and strengths of the research, facilitating the appropriate translation of findings into actionable policy considerations; and
3. Stakeholder engagement was crucial for ensuring the practical utility of the project's outputs. By involving those who would ultimately be responsible for implementing adaptation measures - whether through policy, regulation, or on-the-ground action - the project team could ensure that recommendations were feasible.

Input from the SSG was also sought on specific project tasks:

- Agreeing the Rapid Evidence Assessment (REA) search protocol to inform Task 1.2; and
- Shaping the team's approach to the risk, adaptation and sensitivity analysis (Task 2.1, Task 2.3 and 2.4 respectively).

The SSG was a task-and-finish group, created specifically for the project, and was not a decision-making body. Its primary roles were to support the project team in identifying relevant information and analysis, to review and provide feedback on key outputs and to act as champions for the project within their respective organisations. The SSG's membership was carefully curated to ensure representation from across the UK and from relevant sectors. To facilitate engagement and ensure interactivity, the SSG was divided into two sub-groups:

1. Attending members: 16 organisations, split equally between England, Scotland, Wales, and Northern Ireland, who were invited to attend virtual meetings and participate directly in discussions.

2. Corresponding members: 24 organisations, most of which operated UK-wide, who contributed feedback and insights via correspondence.

A full list of stakeholder organisations is provided in Appendix B - Stakeholders.

Working Arrangements

The SSG's meetings were chaired and facilitated by the WSP project manager, with secretariat support provided by the wider WSP project leadership team. Documents for comment and other relevant papers were distributed in advance of scheduled engagement activities and all feedback was collated and considered in project delivery.

Attending organisations were requested to provide one attendee at meetings, with substitutes allowed if necessary. Corresponding members were requested to circulate papers within their organisations and submit consolidated feedback. All meetings took place virtually, using MS Teams, and all documents were shared via a dedicated SharePoint site to which all stakeholders had access.

The SSG operated under clear protocols regarding confidentiality, conflict of interest and reporting. Members were required to declare any real or perceived conflicts of interest and discussions were not to be reported to third parties without prior consent.

To anticipate and avoid stakeholder fatigue, engagement activities were structured around key project tasks and time-bound, such that no stakeholder was expected to contribute more than 20 hours of their (voluntary) time over the duration of the project, which was approximately 12 months.

Activities

SSG activities are summarised in the appendices, with the following documents provided as separate project documentation:

1. Invitation to participate;
2. Terms of reference and project briefing;
3. Progress reports (from February and April 2025); and
4. Requests for data and other insights (from May and July 2025).

Stakeholder inputs were wide-ranging, reflecting the diversity of organisations and experiences represented in the SSG. All signposted resources and other suggestions were followed up by the WSP team, although the narrow methodological constraints imposed on the quantification aspects of the project meant that, in some cases, it was not possible to directly draw from or reflect the suggested resources.

It has not been possible to include horticulture (field vegetables and fruits) quantitatively in the analysis as a result of data gaps in published literature. Stakeholders felt that this was a particularly important aspect, and a qualitative analysis of this sector has therefore been developed as part of Appendix H - UK horticulture.

Task 1.2 - Rapid Evidence Assessment

Scope and Rationale

This section outlines the approach and results from a Rapid Evidence Assessment (REA) of academic and grey literature, intended to provide an evidence base to shape and inform subsequent project activities and methodological development - based on an initial premise that evidence would be available to allow risks to farm landscapes to be quantified at a system level and onto which adaptation measures could be applied systemically. The full REA report has been submitted as a standalone deliverable.[16] Key methodological constraints have been set out in the section "Challenges, Assumptions and Limitations" and for the REA included a focus on acute heat and rainfall events. Chronic events, drought and potential impacts on farm woodlands were out of scope.

Methodological Approach

Research questions and sub-questions were formulated together with project technical leads across the agriculture, climate risk, adaptation, economics, and natural capital disciplines, and agreed with CCC. These questions included:

- What are the reported precipitation and temperature impacts of climate change on food production in the UK's farmed landscapes and how have they been modelled?
- What are the reported precipitation and temperature impacts of climate change on nature within the UK's farmed landscapes and how have they been modelled?
- What are the reported adaptation options - to precipitation and temperature-related impacts - and costs / benefits / other modelled or measured impacts on food production and nature within farmed landscapes?
- What metrics and/or standards are used to measure the climate resilience of food production and nature in farmed landscapes?
- What is the current policy landscape within which farmed landscapes are managed for food production and/or nature?

Using a PICO approach (Population, Intervention, Comparator, Outcome)[17], a set of primary and secondary keywords were identified, informing subsequent search strings. Search strings covered the full scope of the project as initially conceptualised by the CCC, including chronic climate-related impacts on farmed landscapes, as well as on crops, livestock and/or nature specifically. Costs of relevant impacts, adaptation options and associated costs, resilience standards and information on the UK policy landscape for farmed landscapes across the four devolved administrations were also scrutinised.

Search strings were finalised in discussion with the CCC, run through Scopus (a bibliographic database of peer-reviewed academic literature), Google Scholar and Google to capture both academic and grey literature - and revised as required. Literature was filtered initially by title, then abstract / summary and

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[16] As "CCC Farmed Landscapes REA_v2 SHARED"

[17] Knox, J.W., 2024. 'Technical literature reviews, systematic reviews and rapid evidence assessments'. Cranfield University.

then by full content. Extracted content focussed on a number of themes: geography, climate hazards/metrics, reported impacts and their costs, adaptation measures and associated costs.

Reported Impacts

Climate change is already impacting farmed landscapes across the UK, with various studies highlighting specific regional effects. While the definition and interpretation of climate-related 'impact and risk' and adaptation 'efficacy' differs by study,[18] this section summarises reported impacts to both farm productivity and the natural environment.

Impacts on farm productivity

Crop yields

Most papers that assess climate risks to agricultural systems in the UK cite affected crop yields as a key issue. One paper notes that while increased temperatures and CO_2 levels might initially boost crop yields from 2020-2050, the overall impact of extreme weather events and changing precipitation patterns could lead to significant yield reductions and financial losses past the 2050s.[19] This finding is important to highlight, as the scope of this project only considers the period through the 2050s, during which (climate-related) decreases in wheat yields may not become evident. Additionally, a site-specific study in southeast England found that increased variability in rainfall and elevated temperatures in the winter can significantly affect wheat yields: warm winters may initially increase vegetative growth, but the shortening of the growing cycle by three or four weeks due to higher summer temperatures may lead to lower yields in the longer term.[20]

For UK potato production, one study reported that soil waterlogging, as well as increased heat stress, pose risks to tuber development, reducing overall potato crop quality and yields.[21] Additionally, higher temperatures and associated increased evapotranspiration rates are expected to cause significant potato crop quality and yield losses in the East and West Midlands. UK production was predicted to drop from 5,366 kt in 2020 to below 4,000 kt a year if adaptation measures and strategies were not adopted in the future (2050-2080).[21] In Scotland, it has also been estimated that increased temperatures and water stress during the spring and summer months could decrease barley yields.[22]

In terms of reported quantitative impacts, one review study reported that the hot, dry summer of 2018 resulted in a 10% reduction in spring barley yields and 6% annual reduction in wheat yields across the UK, compared to the 5-year average. This drought also resulted in losses to silage crops, with one farmer in the Peak District reporting a 25% loss of silage and 40% loss of hay. It also reported that due

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[18] For example, 'flooding' is considered an impact in some studies, while others define 'soil erosion' or 'declining crop yields' as impacts. Risks can be defined in relation to hazard like flooding or consquence like costs or damage. Adaptation effacy can relate to hazard, impact or risk reduction.

[19] Rial-Lovera, K., Davies, W.P. and Cannon, N.D., 2017. Implications of climate change predictions for UK cropping and prospects for possible mitigation: a review of challenges and potential responses. Journal of the Science of Food and Agriculture, 97(1), pp.17-32.

[20] Ferrara, R.M., Trevisiol, P., Acutis, M., Rana, G., Richter, G.M. and Baggaley, N., 2010. Topographic impacts on wheat yields under climate change: two contrasted case studies in Europe. Theoretical and Applied Climatology, 99, pp.53-65

[21] Adesina, O.S. and Thomas, B., 2020. Potential impacts of climate change on UK potato production. International Journal of Environment and Climate Change, 10(4), pp.39-52

[22] Aitkenhead, M., Pakeman, R., Gagkas, Z. and Rivington, M., 2022. D12 An overview of issues concerning Climate Change Impacts on Scottish Natural Capital. Literature review submitted to RESAS

to the wet autumn of 2019, operational delays may have contributed to a 13% reduction in winter wheat drilling.[23]

Impacts on livestock morbidity & mortality

Future increases in heat stress are also cited as a key impact on livestock across the shortlisted literature. One study estimated that the hot and dry conditions in the summer of 2018 resulted in decreased milk yields, one million fewer lambs, and the slaughter of an additional 30,000 cows (compared to the preceding year).[23]

In Wales, one study noted that extreme heat events can lead to the death of newborn lambs, and droughts can lead to a shortage of drinking water for livestock, with health and mortality implications.[24]

The natural environment

The shortlisted studies report several climate-related impacts on the natural environment, relevant for both biodiversity/nature and agricultural systems. In Scotland, it is estimated that reduced water availability and increased evapotranspiration will increase risks of soil moisture deficits, particularly in soils with a low water holding capacity. This means that there will less water available for wild plants, potentially reducing species richness across Scotland's farmed landscapes – although the study also notes that there are very large uncertainties as to how climate change will impact different species and habitats across Scotland[22].

In UK upland landscapes, increased winter rainfall intensity and flooding pose significant risks to ecosystem services. One paper noted that high flows are projected to increase in magnitude by up to 25% in upland catchments, posing significant flood risk during winter months. Additionally, repeated droughts in upland landscapes could lead to long-term carbon loss from organic-rich soils, exacerbating soil degradation, water quality issues, and contributing to a loss in biodiversity.[25,26]

While many of the shortlisted studies discuss generalised impacts to agricultural soils or biodiversity associated with increased temperatures, increased winter rainfall, or water scarcity, no quantified impact metrics relevant for biodiversity were reported. This represents a key evidence gap.

Impact costs

Globally, it is estimated that climate change impacts will affect farm productivity, reducing income levels and overall economic stability for farmers.[27] Several assessed studies report cost estimates associated with climate-related impacts on farmed landscapes, but the level of detail across papers is inconsistent. Reported cost estimates associated with specific climate impacts in the UK are elaborated below.

In England, flood events in the summer of 2007 resulted in lost production and additional costs to farmers that ranged from £400–£1400 per hectare. From the total damage costs, it was estimated that

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[23] Wheeler, R. and Lobley, M., 2021. Managing extreme weather and climate change in UK agriculture: Impacts, attitudes and action among farmers and stakeholders. Climate Risk Management, 32, p.100313

[24] Farmlytics. 2024. Extreme weather and its impact on farming viability in Wales. WWF Cymru.

[25] Orr, H.G., Wilby, R.L., Hedger, M.M. and Brown, I., 2008. Climate change in the uplands: a UK perspective on safeguarding regulatory ecosystem services. Climate Research, 37(1), pp.77-98

[26] Shackley, S., Wood, R. Hornung, M. Hulme, M., Handley, J. Darier, E. and Walsh, M. 1998. Changing by Degrees - The Impacts of Climate Change in the North West of England: Technical Overview. University of Manchester, Manchester. 63pp

[27] FAO. 2015. Climate change and food security: risks and responses. ISBN 978-92-5-108998-9

62% of these costs were associated with losses in farm output and additional production costs.[28] A different paper summarising the summer 2007 flood events reported that 42,000 hectares of agricultural land were flooded, resulting in a total agricultural economic impact of £50 billion, or £1200 in losses per flooded hectare. In the south of England and Wales, flood events during the winter of 2013/2014 are estimated to have flooded 44,405 hectares of agricultural land, resulting in a loss of £155 per hectare, and a total agricultural economic impact of £6.9 million.[29]

The paper 'Extreme weather and its impact on farming viability in Wales' presents a wide variety and detailed breakdown of financial impacts on Welsh farming associated with extreme weather events from 2018-2023, covering heatwaves, droughts, storms, and wildfires.[30] Selected costed impacts include:

- Estimates that extreme weather events in 2018 (summer drought followed by Storm Callum) cost up to £4 million due to reduced crop yields. For livestock losses, the same events are estimated to have resulted in a £206.7m loss, representing 11% of the total output that year
- Estimates that extreme weather events (Storm Dennis) are estimated to have cost Welsh arable production £19 million in 2020
- Estimates that extreme weather events in Wales (drought and wildfires) are estimated to have resulted in £3.9 million for upland sheep and cattle, and £3.1million for lowland sheep and cattle in 2022

Adaptation Options

The REA also identified and captured insights from a wide range of adaptation measures aimed at addressing temperature and precipitation-mediated impacts on farmed landscapes. An overview of these is provided in the following sections, broadly themed as either cereal, livestock or institutional measures.

Cereal crops

This category of adaptation measures includes practices related to adaptation of specific crop varieties (such as changing planting dates and breeding for heat tolerance) and improving soil health (through measures such as application of organic amendments, minimum tillage, cover cropping and crop rotation).

Adaptation options

Implementing soil management techniques

Effective soil management is crucial for maintaining soil health and mitigating climate change impacts. Practices such as reduced tillage, establishing cover crops and applying organic amendments are promising due to their benefits for soil quality and water retention, protecting against both precipitation and heat / drought-related hazards.[31] A catchment-level modelling study in Spain found that using reduced tillage and establishing cover crops (green manures) across 38% of the catchment significantly

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[28] Hess, T., Knox, J., Holman, I. and Sutcliffe, C., 2020. Resilience of primary food production to a changing climate: on-farm responses to water-related risks. Water, 12(8), p.2155

[29] Rial-Lovera, K., Davies, W.P. and Cannon, N.D., 2017. Implications of climate change predictions for UK cropping and prospects for possible mitigation: a review of challenges and potential responses. Journal of the Science of Food and Agriculture, 97(1), pp.17-32

[30] Farmlytics. 2024. Extreme weather and its impact on farming viability in Wales. WWF Cymru

[31] Eekhout, J.P.C. and de Vente, J., 2019. Assessing the effectiveness of Sustainable Land Management for large-scale climate change adaptation. Science of The Total Environment, 654, pp.85-93.

reduced the impacts of climate change on water security for cereals, orchard crops, and vineyards.31 Soil drainage, cover crops and minimum tillage also represent viable options for addressing soil compaction and improving soil health.[29] Improved soil management also supports carbon sequestration.[29]

Updating crop management practices

Under future climate scenarios, traditional crops and planting schedules may no longer be viable. Temperature-sensitive crops can potentially be replaced with more resilient varieties.[32] To address yield reductions caused by high temperatures, farmers in the UK can potentially use a combination of earlier crop establishment, use of longer duration varieties, adopt sequential planting, or switch to more heat-tolerant crops.[29] For late frosts, swapping to varieties with different flowering and maturity dates may also be beneficial. Additionally, implementing more diverse crop rotations and swards, such as including legumes or herbs in reseeded leys, can help retain soil moisture and maintain pasture quality.[29]

Enhance biodiversity on farms

Enhancing biodiversity on farms is another strategy for improving system resilience. Wildlife habitats can be established along field perimeters via hedgerow planting, which provides biodiversity-mediated benefits to crop production while reducing losses from flood and erosion events.[33] A study conducted at a commercial arable farm in central England found that by removing up to 8% of cropped land from production along field edges (setting aside that land for wildlife habitats, such as hedgerows or deciduous trees) resulted in no significant wheat or oilseed rape losses in those fields. On plots with field beans where this intervention was implemented, yields increased after four years.33 Agroforestry practices are another intervention that can enhance biodiversity and resilience to heat-related climate hazards by sequestering carbon, stabilising soils, providing shade and shelter to livestock (and crops), and creating habitats and green corridors that support a wide range of species.[22, 34] In Scotland, a study found that employing agroforestry interventions (i.e., shelterbelts and silvo-pastoral systems) on dairy farms boosted productivity and the resilience of natural capital assets on site.[22, 34]

Costs

Few studies detailed the specific costs associated with implementing the outlined crop and soil management adaptation measures. However, one review paper noted that implementing crop-level adaptation measures (including reduced tillage, use of more resilient crop varieties, amended timings for field operations, etc.) could increase overall global yields by an average of 7-15%. Additionally, the review reported one study where simulated farm profits in Europe increased modestly (1.5%) by 2040 if farm-level adaptation measures were implemented, but could decline by 2.3% in the absence of adaptation.32

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[32] Zhao, J., Bindi, M., Eitzinger, J., Ferrise, R., Gaile, Z., Gobin, A., Holzkämper, A., Kersebaum, K.C., Kozyra, J., Kriaučiūnienė, Z. and Loit, E., 2022. Priority for climate adaptation measures in European crop production systems. European Journal of Agronomy, 138, p.126516.

[33] Pywell, R.F., Heard, M.S., Woodcock, B.A., Hinsley, S., Ridding, L., Nowakowski, M. and Bullock, J.M., 2015. Wildlife-friendly farming increases crop yield: evidence for ecological intensification. Proceedings of the Royal Society B: Biological Sciences, 282(1816), p.20151740.

[34] Jenkins et al., (2023). ClimateXChange Adapting Scottish agriculture to a changing climate. Available at: https://www.climatexchange.org.uk/projects/adapting-scottish-agriculture-to-a-changing-climate/

Livestock

This category of measures covers livestock-specific adaptations (e.g., cooling systems, shade structures, grazing management) and pasture-related practices like rotational grazing, shelterbelt planting, and feed adjustments.

Adaptation options

Optimise grazing strategies

As weather patterns become more unpredictable and dry spells more frequent, traditional grazing methods may no longer be sustainable. Adjusting grazing regimes, budgeting forage/feed, and reducing stocking rates can help manage feed availability during dry periods.[23] Implementing rotational grazing can also prevents overgrazing and soil damage while supporting grass yields, reducing runoff and maintaining soil moisture.[35]

Enhance livestock facilities

Key interventions are more applicable to intensively reared rather than pasture-raised livestock, such as increased ventilation and mechanical cooling systems for broiler chickens. However, movable shelters can be useful to provide shade for dairy cattle, reducing heat stress. In Scotland, rather than changing breeds or species to those with higher levels of resilience to heat, disease, and other environmental stresses, a study found it would be more cost-effective to invest in enhanced natural (green) and grey infrastructure. This included creating shade with trees and shelterbelts and constructing well-designed buildings that offer protection from extreme weather. Overall, these measures were considered to result in improved productivity, although the study did not report how cost-effectiveness was assessed.[34]

Implement temperature-related adaptation measures

Adopting different grazing and housing patterns, such as nocturnal grazing of cattle, can reduce exposure to peak temperatures.[36] In its guide for conducting farm climate risk assessments in England, the Environment Agency also recommends installing additional cooling (such as misting systems and gable end fans) and upgrading insulation to maintain optimal temperatures in intensive systems. Reducing stocking ahead of peak temperature periods can also help manage heat stress in intensive systems. For housed poultry, adjusting the lighting schedule so that livestock are encouraged to feed during cooler parts of the day can further enhance animal comfort and productivity.[37]

Costs

Few studies detailed the specific costs associated with implementing livestock-related adaptation measures, with no UK-specific costs identified (although there was anecdotal evidence of costs increasing following hot / dry periods when farmers were required to use winter fodder supplies to supplement poor grazing). In Australia, a study exploring exactly this scenario estimated that costs could

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[35] Harrison, M.T., Cullen, B.R. and Rawnsley, R.P., 2016. Modelling the sensitivity of agricultural systems to climate change and extreme climatic events. Agricultural Systems, 148, pp.135-148.

[36] Met Office and ADAS, 2023. Research to assess resilience measures that support UK agriculture in adapting to drought, extreme heat, and wildfires - SCF0140. Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796

[37] Environment Agency, 2023. Guidance - Intensive farming: examples for your adapting to climate change risk assessment.

rise from between 29% and 100% under the RCP8.5 scenario.35 A study estimating the costs and benefits of adaptation in England estimated that over the course of a century the NPV of adaptation for some livestock heat stress scenarios could be as much as £3,279 million (although some soil management measures were estimated to deliver a negative NPV of more than £100 million over the same period).[38]

Institutional measures

This category encompasses actions at a landscape, regional, or higher level that can enhance farm resilience, including climate-resilient policies, education, farmer training, community-based strategies and insurance schemes. It should be noted that these options were not taken forward for analysis in Phase 2 as they do not directly address the modelled heat impacts. They would – nonetheless – be expected to form part of a balanced adaptation response.

Adaptation Options

Foster a collaborative environment for knowledge transfer

Promoting industry collaboration fosters knowledge-sharing and the dissemination of best practices, leading to development and adoption of innovative strategies.[23] This involves providing advice and forming knowledge-sharing spaces to help farmers access critical information. For example, a paper investigating agricultural adaptation options for Scotland identified farmer co-operatives as a key vehicle for facilitating collective action and resource sharing, enhancing the capacity of individual farmers to implement adaptation strategies.[34] This measure was also noted to be successful in Denmark. Peer learning through demonstrations and discussion groups allows farmers to learn from each other's experiences, building trust and encouraging the adoption of proven adaptation measures.[23] Additionally, education programmes can equip farmers and growers with the necessary knowledge and skills.35

Strengthen policies and institutional support for climate adaptation

Effective policies and strong institutional support are vital for collective adaptation efforts in the farming industry. These policies should focus on preventing and managing both climate and climate-modified risks and vulnerabilities, such as flooding, droughts and heat stress in livestock.[39] Policies that promote sustainable agriculture and provide financial incentives are key drivers of climate resilience across the sector.35 For example, schemes such as England's Environmental Land Management Scheme (ELM) play a critical role in supporting soil health, enhancing biodiversity, mitigating flood risks and delivering a range of appropriate infrastructure improvements on farms. [23,40]

Implement insurance and risk management schemes

These schemes provide a safety net in the absence of effective adaptation options, typically covering a range of climate-related damages such as crop losses, livestock deaths, and damage to farm

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[38] Wreford, A., Moran, D., Moxey, A., Andy Evans, K., Fox, N., Glenk, K., Hutchings, M., McCracken, D.I., McVittie, A., Mitchell, M. and Topp, C.F., 2015. Estimating the costs and benefits of adapting agriculture to climate change. EuroChoices, 14(2), pp.16-23.

[39] Gitz V, Meybeck A, Lipper L, Young CD, Braatz S. Climate change and food security: risks and responses. Food Agric Organ United Nations (FAO) Rep. 2016, 110(2).

[40] Coyne, L., Kendall, H., Hansda, R., Reed, M.S. and Williams, D.J.L., 2021. Identifying economic and societal drivers of engagement in agri-environmental schemes for English dairy producers. Land Use Policy, 101, p.105174.

infrastructure. By providing compensation for these losses, insurance helps farmers recover more quickly and maintain their livelihoods,[41] contributing to long-term sustainability and productivity. Insurance schemes can also be linked with government policies and financial incentives. Integrating insurance with risk management education can empower farmers and growers to make informed decisions about their adaptation strategies.35

Leverage community-based approaches and data for climate adaptation

Effective climate adaptation requires the integration of community-based approaches with robust data capture, management and analysis.35 An Australian study assessing adaptation measures for dairy farms noted a need for improved data collection and analysis to better monitor climate impacts and the effectiveness of adaptation measures. This data-driven approach can allow communities of practice to continuously refine and improve their strategies based on real-world outcomes, ensuring they remain effective and responsive to changing conditions.35

Costs

As noted for other adaptation measure categories, data on costs for implementing specific adaptation measures is limited across the available literature. However, several papers highlight the importance of access to finance to ensure delivery of resilience and adaptation at farm and landscape scales.[30]

Conclusions and Relevance to Subsequent Project Tasks

The findings of the REA had significant implications for the methodological development in the next phase of the project. The minimal identification of well-represented impact data for England, Wales, and Scotland provided a basis, but limited ability to complete the quantitative climate risk assessments in these regions. The REA also identified a lack of studies covering Northern Ireland.

The REA identified and reviewed a wide range of adaptation measures aimed at addressing temperature- and precipitation-mediated impacts on farmed landscapes. These measures ranged from farm-level interventions, such as the adoption of more resilient crop varieties, improved soil and water management practices, and livestock management strategies, to higher-level policy and financial instruments, including insurance schemes and community or regional capacity building. Measures relating to hedgerows and agroforestry also highlight the potential for adaptation to deliver both productivity and natural capital benefits. However, the REA found that quantified data on the costs, benefits, and effectiveness of specific adaptation measures were generally scarce, representing another key evidence gap - and meaning that these aspects may need to be addressed through more qualitative or narrative approaches.

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[41] Devot, A., Royer, L., Arvis B., Deryng, D., Caron Giauffret, E., Giraud, L., Ayral, V., and Rouillard, J. 2023, Research for AGRI Committee – The impact of extreme climate events on agriculture production in the EU, European Parliament, Policy Department for Structural and Cohesion Policies, Brussels.

Phase 2

Phase 2 - CCC’s Deep Dive Methodology

The CCC’s ‘deep dive’ methodology was designed to ensure a consistent and transparent approach to modelling and analysing climate risks and adaptation options for the Well-Adapted UK Report. The methodology, summarised in this section, provided a framework for the portfolio of deep dive projects to follow through Phase 2.

Task 2.1 - Climate Risk Analysis

The project began by estimating present-day and future baseline risks using a framework that considered hazards, exposure, and vulnerability. Following CCC guidance, UKCP18 local climate projections were used, as these provided the most appropriate spatial and temporal resolution for the study’s climate risk assessment.

To analyse exposure and vulnerability, the team modelled how selected climate parameters and distributions of crop and livestock productivity varied across the UK, over time and over different global warming levels. The individual susceptibilities of the six agricultural sub-components (i.e., oats, wheat, barley, dairy cattle, lambs, free range hens) to the projected changes through exceedance of the defined temperature-related thresholds were derived from the Rapid Evidence Assessment (REA) and subsequent stakeholder input, establishing a series of impact metrics which could be used to determine risk spatially across the UK. This ensured that the analysis was grounded in both the latest scientific understanding and the practical concerns of those affected. The economic losses resulting from the modelled climate risks were then estimated at national and UK levels. Distributional impacts were also considered, such as how risks affected different region. These were presented spatially and disaggregated by region and agricultural sub-component to support decision-making.

In assessing risks, the CCC required that the project accounted for the inherent uncertainty in UK climate projections, and this was addressed through the use of both ‘central’ and ‘high’ scenarios with each encompassing its own set of plausible extremes from intramodal variability. Results with the median and highest economic losses for specified time periods and global warming levels were selected from the outputs from the modelled 16 UKCP18 Local ensemble members, representing central and high scenarios, respectively. This aligned with requirements that each climate model be treated as an equally plausible representation of the future, and that this diversity of outcomes be reflected in the analysis.

Task 2.2 - Adaptation Options

A longlist of potential actions was developed through literature review and stakeholder engagement. This list was narrowed down using qualitative multi-criteria analysis, considering factors such as cost, risk reduction, feasibility, carbon and nature-related co-benefits. Refinements were also made to ensure that the final shortlist of possible measures included a combination of operational, infrastructure and nature-focussed solutions. Shortlisted options were quantitatively appraised for their costs and benefits, including wider ecosystem impacts, reflecting the CCC’s aspiration that adaptation should support both productivity and nature outcomes.

Task 2.3 - Adaptation Package

Benefit-cost ratios (BCRs) were developed for each shortlisted adaptation measure - including consideration of time requirements for measures to become effective (particularly relevant for nature-focussed solutions, but also for measures relying on operational changes such as using different tilling practices to improve soil quality) and their effectiveness and ability to reduce the modelled climate impacts. A final package of measures was then developed, initially based on the BCRs but then expanded to include measures that would address the full range of heat-related risks demonstrated for the agricultural sub-components.

The package of measures was also selected to ensure that benefits could be ‘stacked’, for example by simultaneously delivering multiple adaptive actions like improving soil quality while also utilising agroforestry. Based on the climate risk modelling, it was assumed that all adaptation measures could (potentially) be applied to all impacted crop and livestock sub-components within each home nation. Where risks and adaptation solutions were spatially dependent, such as in the case of temperature patterns or distribution of agricultural production, the CCC required the project consider how this spatial dependence was reflected in the analysis. This ensured that the spatial distribution of hazards, exposures, vulnerabilities and cost-optimised adaptation was incorporated, providing more nuanced and actionable insights for adaptation planning.

Task 2.4 - Sensitivity Analysis

Sensitivity analyses were conducted to test the outputs of the model under different climate and land use scenarios, such as higher warming levels, threshold peaks, differences in the costs of adaptation, and changes in the proportion of impacted sub-components that adopted each adaptation. The contribution of ecosystem services to the cost-benefit case was explored in detail, including a separate analysis of more transformative measures in which productive farming was ceased and replaced with woodlands, wetlands or wildflower meadows.

The approach described above was aligned with CCC’s technical guidance throughout, ensuring that the outputs are robust, comparable, and policy-relevant within the specific constraints of the required quantification methodology. The following sections provide details of how this methodology was applied for this ‘deep dive’ project to model climate risks to selected UK farmed landscape components, including climate hazard and impact metric identification, risk modelling, calculation of direct economic costs, identification and appraisal of adaptation options, development of the cost-optimised adaptation package, and sensitivity analysis.

Limitations of the study

This study was originally designed as a quantitative assessment of climate-related hazards – both acute and chronic temperature and precipitation events – affecting agricultural and environmental systems at the landscape scale. Operating within the CCC’s defined quantitative framework, the aim was to link specific risk metrics to climate hazards and adaptation strategies.

However, limitations in data availability and quality – both from literature and expert sources – restricted the ability to attribute climatic events to causational impacts. As a result, a fully costed, holistic analysis of climate impacts across the UK farmed landscape was not feasible. Current evidence gaps mean that this quantitative analysis only addressed specific impacts from heat, a small portion of the challenge, highlighting the need for improved data across all scales, from laboratory to landscape. Leveraging data from existing farm trials – whether or not they were set up specifically to explore climate risk or adaptations – could help bridge these gaps without major upfront investment. A major frustration when analysing evidence from prior significant weather events (such as winter flooding) is that it is impossible to determine the specific cause or causes from the published information, whether related to poor drainage, late harvest of a prior crop, fluvial flooding etc. Critical gaps include climate risk thresholds relevant to UK farming and thresholds for nature (as distinct from 'ecosystem services', as modelled in this study) within farmed landscapes.

Consequently, this study represents only a fraction of the climate risks facing UK farmed landscapes and the adaptations required to address them. The analysis is limited to specific heat-related thresholds for a small number of crops and livestock. Findings should therefore be interpreted with caution, as they are constrained by significant uncertainties and assumptions inherent in the available data.

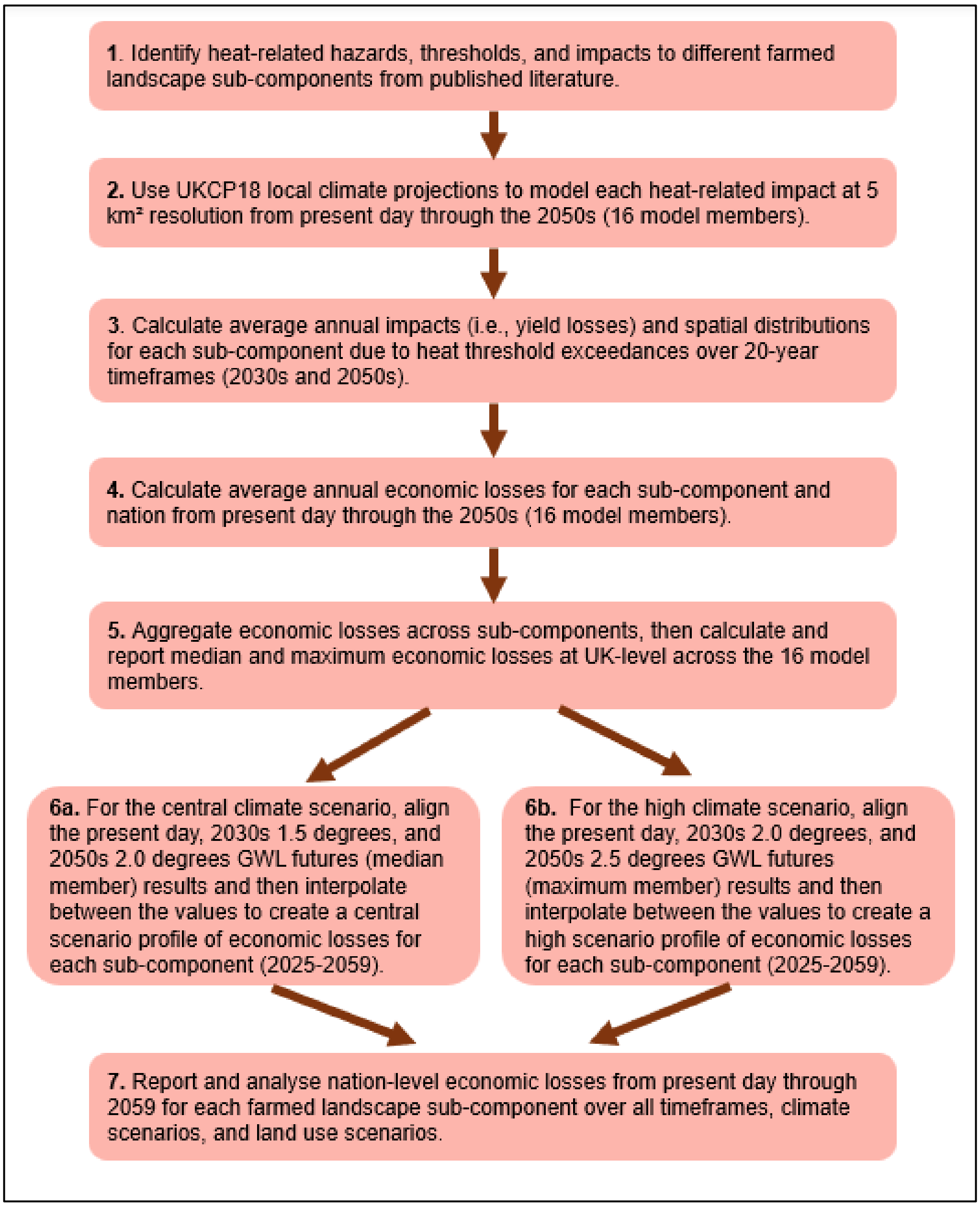
Task 2.1 - Climate Risk Analysis

Approach

Identification of climate risks and scenarios

This section describes the approach followed to identify and model selected risk metrics. An overview is provided in Figure 4.

Figure 4. Flow diagram of climate risk analysis methodology



1. Identify heat-related hazards, thresholds, and impacts to different farmed landscape sub-components from published literature.

2. Use UKCP18 local climate projections to model each heat-related impact at 5 km² resolution from present day through the 2050s (16 model members).

3. Calculate average annual impacts (i.e., yield losses) and spatial distributions for each sub-component due to heat threshold exceedances over 20-year timeframes (2030s and 2050s).

4. Calculate average annual economic losses for each sub-component and nation from present day through the 2050s (16 model members).

5. Aggregate economic losses across sub-components, then calculate and report median and maximum economic losses at UK-level across the 16 model members.

6a. For the central climate scenario, align the present day, 2030s 1.5 degrees, and 2050s 2.0 degrees GWL futures (median member) results and then interpolate between the values to create a central scenario profile of economic losses for each sub-component (2025-2059).

6b. For the high climate scenario, align the present day, 2030s 2.0 degrees, and 2050s 2.5 degrees GWL futures (maximum member) results and then interpolate between the values to create a high scenario profile of economic losses for each sub-component (2025-2059).

7. Report and analyse nation-level economic losses from present day through 2059 for each farmed landscape sub-component over all timeframes, climate scenarios, and land use scenarios.

Agricultural components, hazard thresholds, and impact metrics

Sources for quantified hazard threshold, exposure, vulnerability and impact data for different components and sub-components of the farming system were identified through a snowball method originating from the REA and using the library of resources collated during the REA (>130 grey and peer-reviewed articles) as a starting point. Given the complexity of processes that take place within farmed landscapes and the range of research into the impacts of climate change on farming (both published and ongoing), it was essential to establish inclusion criteria which focussed on the main contributors to the UK agriculture sector and which could be modelled quantitatively throughout subsequent project tasks. A wide range of agriculture sub-components (i.e., cattle, pigs, sheep, hens, cereals, grasses, fruits, vegetables, potatoes, etc.) was included in the scope of the literature review. If the answer was YES for any 2 of the criteria below AND that the identified sub-components' combined land area cover and (agricultural) economic contribution was over 50% of the total respective, the sub-components could be move forward for analysis:

- Geospatial distribution **(must be present in 2 of 4 devolved administrations)**
- Total land area cover **(must be greater than 10%)**
- Contribution to the economic output from agriculture **(must be greater than 10%)**
- Relevant to UK food security **(Yes)**

Few studies presented all required data, from component to costed climate-related impact, meaning that each hazard-impact metric combination had to be developed from multiple separate sources. To provide as much consistency and local applicability as possible to facilitate the development of the proposed hazard-impact combinations, a further set of screening criteria were applied:

- Data availability **(YES - Quantified impact and attributed climate parameter)**
- Geographic location of data **(1-UK, 2-EU, 3-NA. 4-AUS/NZ, 5-Other)**
- Data quality **(1-observed in the field, 2-researched experimentally, 3-modelled)**
- Data sources **(1-academic, 2-sector specialists, 3-sector advocates, 4-other)**

Following extensive literature review and engagement with the project Stakeholder Steering Group (SSG), cereals and livestock (dairy cattle, free range hens, and lambs) emerged as farmed landscape components with sufficient data to populate the CCC's tightly defined quantitative methodology. In most cases, the team only had one datapoint to work with, or the data was from non-UK farming systems. This limited sensitivity testing and the ability to quantify uncertainty around the data as inputs into the model. Each agricultural sub-component (i.e., wheat, barley, oats, dairy cattle, free range hens, and lambs) required its own unique analysis, as each had a specific hazard threshold and corresponding risk-induced impact. The identified sub-components, hazards, impact thresholds, and impact metrics are outlined in Table 9, with additional information provided in Appendix A - Climate Risk Analysis Method Tables.[42] Engagement with the project SSG, including experts across climate change, agriculture, and nature, provided quality assurance in the approach and metrics carried forward.

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[42] Metrics related to waterlogged soils were also identified at this stage, with specific yield impacts for wheat, peas and potatoes collated. However, since waterlogging results from a combination of soil type and land use, together with duration and intensity of rainfall, it was not

Due to data constraints, the modelled impacts focus solely on heat-related thresholds for a small subset of crops and livestock. Certain key sub-sectors, such as field horticulture (encompassing vegetables, soft fruits and orchard crops) could not be assessed quantitatively, but a qualitative overview of relevant risks and adaptation options for UK horticulture is presented in Appendix H - UK horticulture.

Table 8 presents the proportion of the six assessed agricultural sub-components (or their closest proxies within available data) in the context of overall UK agricultural productivity, measured by gross production value. Collectively, these sub-components account for approximately 50% of the UK's agricultural productivity. Raw milk from cattle comprises nearly a quarter of this value, while wheat holds the second largest share among the analysed products at about 12%, although its share is less consistent over time. Although constrained by data availability, the study's six sub-components do account for a substantial proportion of UK agricultural value.

Table 8. Relative value of the study's agricultural sub-components within total UK gross production value, 2019-2023

Year	Wheat	Barley	Oats	Eggs	Meat of sheep	Milk	Total selected
2019	13.2%	5.4%	0.6%	3.4%	4.9%	22.4%	50.0%
2020	8.4%	5.8%	0.6%	3.5%	5.0%	23.9%	47.2%
2021	11.8%	4.8%	0.7%	3.4%	4.7%	23.6%	49.0%
2022	12.9%	5.1%	0.7%	3.1%	4.8%	23.1%	49.6%
2023	12.0%	4.9%	0.5%	3.3%	4.9%	23.9%	49.5%
5-yr average (2019-23)	11.7%	5.2%	0.6%	3.3%	4.9%	23.4%	49.1%

Source: FAOSTAT, 2025[43]

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possible to convert modelled future precipitation due to a changing climate with future local weather events that might contribute to waterlogging – meaning that quantification of future risks from precipitation could not be undertaken. Data associated with historic waterlogging events was also insufficiently granular to allow the waterlogging impact metrics to be used. Given the perceived importance of waterlogging, and recent history of waterlogging impacts within farmed landscapes, a qualitative case study was completed and is available in Appendix I - Waterlogging.

[43] www.fao.org. (n.d.). FAOSTAT. [online] Available at: https://www.fao.org/faostat/en/#data/QV.

Table 9. Selected components of the farmed landscape, with associated hazards, thresholds and impact metrics

Component	Sub-component	Hazard Description	Impact Threshold	Impact Metric
Cereals	Oats	High temperatures from April-June	Days where T_{max} ≥ 28°C from April-June (days/year)[44]	10% yield reduction per day[44,45]
Cereals	Wheat	High temperatures from May-June	Days where T_{max} ≥ 32 °C from May-June (days/year)[46]	10% yield reduction per day[46]
Cereals	Barley	High temperatures from April-June	Days where T_{max} ≥ 28°C from April-June (days/year)[44]	10% yield reduction per day[44,45]
Livestock	Dairy	High temperatures and humidity (heat stress)	Days where Thermal Heat Index (THI) > 74 (days/year)[46,47]	Milk yield reduction of 0.55 litres per cow per day[47]
Livestock	Lambs	Temperatures conducive to parasite outbreaks (*Haemonchus contortus*)[48]	Daily T_{mean} ≥ 9°C (days/year)[46,47]	Potential number infected (population * (0.5 + change{%})[46,47,49]
Livestock	Laying hens (outdoor)	High temperatures	Daily T_{mean} 28-33°C (days/year) Daily T_{mean} 34-38°C (days/year)* Daily T_{mean} ≥ 39°C (days/year)* [50]	28-33°C = 10% egg weight reduction/day 34-38°C = 15% egg weight reduction/day* ≥ 39°C = 20% egg weight reduction/day*[50]
*Modelled, but no impact projected to occur between present day and the 2050s under any climate scenario.				

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[44] Hakala, K., Jauhiainen, L., Rajala, A.A., Jalli, M., Kujala, M. and Laine, A., 2020. Different responses to weather events may change the cultivation balance of spring barley and oats in the future. *Field Crops Research*, *259*, p.107956.

[45] Jacott, C.N. and Boden, S.A., 2020. Feeling the heat: developmental and molecular responses of wheat and barley to high ambient temperatures. *Journal of Experimental Botany*, *71*(19), pp.5740-5751.

[46] Arnell, N.W. and Freeman, A., 2021. The effect of climate change on agro-climatic indicators in the UK. *Climatic Change*, *165*(1), p.40.

[47] Jones, L., Gorst, A., Elliott, J., Fitch, A., Illman, H., Evans, C., Thackeray, S., Spears, B., Gunn, I., Carvalho, L. and May, L., 2020. Climate driven threshold effects in the natural environment. Report to the UK Climate Change Committee.

[48] Indicator correlated with more life cycles of the parasite *Haemonchus contortus* (a major cause of illness and malnutrition in sheep) occurring.

[49] https://www.rbst.org.uk/blog/silent-killers-barber-pole-worm-haemonchus-contortus

[50] Freitas, L.C.S.R., Tinôco, I.F.F., Baêta, F.C., Barbari, M., Conti, L., Teles Júnior, C.G.S., Cândido, M.G.L., Morais, C.V. and Sousa, F.C., 2017. Correlation between egg quality parameters, housing thermal conditions and age of laying hens. *Agronomy Research*, *15*, pp.687-693.

Spatial distribution data for each of the six assessed agricultural sub-components were then obtained and plotted across the UK. These distribution data represent a snapshot of annual crop and livestock coverage and are used as a baseline for the assessment, containing numbers of livestock or hectares of crops at a 5km^2 or 10km^2 resolution depending on data availability. The data show that the modelled sub-components are widely distributed across the four nations – contributing to a representative picture of climate risk to UK farming activities. The data was sourced as follows:

- Spatial distribution data for England, Scotland, and Wales were obtained from AgCensus, which is a spatially referenced time-series database developed by EDINA that converts agricultural census data for England, Scotland, and Wales into grid-based formats.[51] The latest available data in AgCensus that was used for this assessment ranged from 2018-2021.
- Data for Northern Ireland were derived from the local agricultural census from 2024 (Daera)[52] at district council level, then spatially distributed across a 5x5km grid, assuming uniform distribution of crops and animals across each council, to enable consistent UK analysis at the 5km^2 resolution.

To establish the baseline productivity for each sub-component, baseline yields for wheat, barley, and oats were obtained from 2024 Defra statistics on cereal production in tonnes per hectare per year, disaggregated by devolved administration (DA).[53] Baseline UK productivity figures for livestock, including the average annual milk yield per cow, number of eggs laid per hen per year, and number of lambs infected by *H. contortus* were obtained from other UK sources (see 0 for a full list of all variables and sources).

Climate scenarios

To assess the occurrence of the specified climate hazard and impact thresholds, simulation output from the UKCP18 local downscaling ensemble, generated with a convection-permitting model (CPM) at a 5km resolution, were obtained via the CEDA data portal.[54] UK data were extracted for daily maximum, minimum, and mean temperature, as well as mean daily relative humidity. The thresholds for mean temperature and maximum temperature were applied for the various agricultural sub-components. For dairy cattle, the mean temperature and relative humidity were used to calculate the Thermal Heat Index (THI), using the equation below (Tu et al., 2025)[55, 56]:

$$THI = (1.8 \times T_a + 32) - (0.55 - 0.0055 \times RH) \times (1.8 \times T_a - 26)$$

$$\text{Where } T_a = \text{temperature (°C) and } RH = \text{relative humidity (\%)}$$

The analysis investigated climate changes under four different Global Warming Levels (GWLs): 1.1°C (Present day), 1.5°C, 2.0°C, and 2.5°C.To establish the GWLs, modelled year ranges based on the specified temperature anomaly (as detailed in 0) were applied to each ensemble member of the UKCP18

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[51] The AgCensus datasets used for this assessment range from 2018-2021. No oat distribution data were available for Wales (source: National Agricultural Census Data Time Series).

[52] Department of Agriculture, Environment and Rural Affairs. (2024). Agricultural Census in Northern Ireland 2024. [online] Available at: https://www.daera-ni.gov.uk/publications/agricultural-census-northern-ireland-2024.

[53] uk-cops-webseries-241212.ods

[54] CEDA | Home. [online] Available at: https://www.ceda.ac.uk/.

[55] Tu, P.A., Yeh, Y.H., Chen, Y.H., Shiau, J.W., Lin, T.Y., Banhazi, T. and Yang, M.K. (2024). Stage-specific milk yield losses and associated sweating, respiration, and rectal temperature responses under varying temperature-humidity index thresholds in lactating and dry cows. Journal of Dairy Science, [online] 108(2), pp.2023–2035. doi:https://doi.org/10.3168/jds.2024-25392

[56] National Research Council (1971). A guide to Environmental Research on Animals. https://nap.nationalacademies.org/catalog/20608/a-guide-to-environmental-research-on-animals

local projections, allowing for the identification of a specific realisation for each GWL from each ensemble member.[57] This was then used to run a 20-year climate timeseries for each GWL.

Land use scenarios

Initially framed in the CCC's methodology as 'Socio-Economic Scenarios', different land use scenarios were also explored to account for potential changes in farmland area, agricultural productivity, and livestock numbers over time. A Business-As-Usual (BAU) scenario, which considered present day yields and land use for the six agricultural sub-components, was used for the main analysis. Two additional scenarios were developed from the CCC's Seventh Carbon Budget (CB7) Balanced Pathway approach, which assumes significant shifts in agricultural production and land use to release land for carbon sequestration and bioenergy by 2050. [58] These two scenarios were used to explore vulnerability through a sensitivity analysis. The three resulting land use scenarios are described below, while detailed assumptions applied for each scenario are provided in Table 10.

- **Business-as-usual (BAU),** in which no changes in agricultural land area or productivity are considered between present day and the 2050s.
- **CB7a**, in which no changes to productivity are considered, but the area of agricultural land (hectares of cropland and numbers of livestock) reduces over time, through the 2050s. This is a variation of the scenario used to inform the CCC's CB7 Balanced Pathway.
- **CB7b**, in which increases to productivity (crop and milk yields) are considered along with the area of agricultural land and livestock numbers, which reduce over time, through the 2050s. This is the scenario used to inform the CCC's CB7 Balanced Pathway.

Table 10. Land use scenarios and assumptions*

Scenario	Land Area	Productivity
Business-as-Usual ***(BAU)***	Baseline crop land area (hectares) and livestock numbers/distributions at baseline assumed to be constant over time.	Baseline yields (e.g., tonnes/year) assumed to be constant over time.
CB7a	Crops: Land area decreased for each crop and devolved administration using the annual change in cropland area assumptions (from CB7 Balanced Pathway, provided by CCC).	Baseline yields (e.g., tonnes/year) assumed to be constant over time.

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[57] According to the CCC, Global Warming Levels (GWLs) are defined as global mean temperature anomalies relative to pre-industrial levels, although details vary between different studies (such as the time averaging period – 20 year means are used here). WSP have used GWL time slices provided by the CCC. These are outlined in the 'Going Beyond the Deep Dive' section.

[58] Climate Change Committee (2025). The Seventh Carbon Budget - Climate Change Committee. [online] Climate Change Committee. Available at: https://www.theccc.org.uk/publication/the-seventh-carbon-budget/.

Scenario	Land Area	Productivity
CB7b	Livestock: Numbers of livestock (dairy cows, sheep, poultry) decreased using the annual change in livestock numbers (assumptions from CB7 Balanced Pathway, provided by CCC).	Crops: Yield improvement assumptions in CB7 Balanced Pathway applied for all crops (10 tonnes/ha for wheat by 2050, equivalent increase for other crops). Livestock (dairy cattle only): Milk yield improvement assumptions in CB7 Balanced Pathway applied.

* A detailed breakdown of all land use scenario assumptions and % change figures applied for each sub-component per scenario in the additional project documentation submitted to the CCC.

Risk modelling

For each sub-component, risks were then estimated over the simulated years using the impact metrics and occurrence of impact thresholds modelled (see Table 9) for all climate model members at each GWL. These annual reductions (e.g., yield, population, or size) were mapped onto a 5x5km grid. The results were then aggregated to national level and reported as 20-year average, minimum, and maximum annual values for each model member, GWL and timeframe (e.g., GWL 2.0 - 2030s), climate scenario, and land use scenario to inform the estimation of financial costs associated with the modelled risks in each of the four nations.

Assumptions and limitations

The climate risk analysis is associated with several methodological limitations and assumptions:

- Small regional climate model ensemble size, and single downscaling model set-up, mean that simulations cover a limited range of possible climate conditions, not fully representing all plausible future climates. However, a perturbed physics ensemble of convection permitting models is considered the most appropriate approach available for this assessment.
- The UKCP18 climate models used have limited capacity to simulate feedback mechanisms between climate impacts and the climate system itself. Thus, the projections may underestimate or misinterpret long-term or compounding effects (such as vegetation affecting local temperatures).
- The methodology does not apply bias correction to the UKCP18 local projections, relying instead on the assumption that the CPMs provide a reasonable representation of observed temperature patterns.
- The boundary conditions (i.e., values produced by the driving general circulation models) may result in a more stable climate representation than would be realistically expected. This could potentially lead to an underestimation of variability and extremes in the projections.
- The use of binary, absolute hazard thresholds and impact metrics in this analysis (as shown in Table 9) provide only a simplified indication of actual processes. As a result, events that occur near these thresholds, or those involving multiple interacting hazards may under-represented in terms of severity of impact in the results.

- This analysis does not account for potential future crop yield gains due to warmer temperatures or CO_2 concentrations.
- Modelled impacts are based on isolated, independent events, without accounting for cumulative or prolonged conditions. For example, the effects of a multi-day heatwave or combined heatwave and drought events are not represented in this analysis.
- The locations of baseline agricultural production are considered a fixed parameter throughout this analysis.
- Agricultural production is considered to be evenly distributed across grid cells, so there is no influence from local variation in the landscape or the built environment.
- Metrics related to waterlogged soils were initially identified at the literature review stage for further analysis. However, since waterlogging results from a combination of soil type and land use, together with duration and intensity of rainfall, it was not possible to convert modelled future precipitation due to a changing climate with future local weather events that might contribute to waterlogging – meaning that quantification of future risks from precipitation could not be undertaken. Data associated with historic waterlogging events was also insufficiently granular to allow the identified waterlogging impact metrics to be used. Given the perceived importance of waterlogging, and recent history of waterlogging impacts within farmed landscapes, a qualitative case study was completed instead (Appendix I - Waterlogging).
- The AgCensus datasets used to map the baseline cropland area and numbers of livestock for this assessment for England, Scotland, and Wales range from 2018-2021. No oat distribution data were available for Wales, so impacts on oats were not modelled there. The dataset for free range hens in England was only available at a 10km resolution and was spatially distributed across a 5x5km grid to match the other sub-component resolutions by assuming uniform distribution of animals.
- Few studies presented all required data, from farmed landscape component to costed climate-related impact, meaning that each hazard-impact metric combination used as inputs and framing in the model had to be developed from multiple separate sources. In most cases, the team only had one datapoint to work or the data was from non-UK farming systems. This limited sensitivity testing and the ability to quantify uncertainty around the thresholds and impact metrics.

Estimation of Economic Costs

The next step in the analysis was to monetise the quantified risks, to estimate economic losses. To achieve this, the unit of measurement adopted was gross output, measured as yield loss multiplied by producer prices (i.e. farmgate prices). The economic analysis therefore measures revenue losses to farmers. However, this can also be seen as a proxy for broader welfare losses, since the analysis holds future product prices constant (at 2024 levels). The yield losses modelled in this analysis could be expected to increase scarcity of affected products, and therefore to lead to price increases; such a mechanism would pass losses to consumers (paying, either directly or indirectly, higher prices) and away from producers. By holding these prices constant, and not seeking to elevate prices as scarcity increases, the methodology therefore captures welfare losses, regardless of whether they would ultimately be borne by the producer or the consumer.

Economic impacts were calculated for six agricultural sub-components (i.e., wheat, barley, oats, milk, egg and lamb). While the methodology for the economic analysis is set out in full detail in a technical appendix (Appendix K - The calculation of economic losses), an overview is provided below.

1. **Climate risk modelling outputs** are first fed into the economic loss calculations. The specific indicators used are the annual average yield losses per sub-component (or the number of lambs infected), representing the mean of 20 modelled years at a given Global Warming Level, split into scenarios by land use (BAU, CB7a, and CB7b) and climate scenario (central, high), by timeframe (i.e., present day, 2030s, and 2050s) for England and the three DAs and the six agricultural products. These results are determined for the 16 model members.

2. **Initial estimations of economic losses** were calculated by multiplying the total annual yield losses (from the previous step) by prices. An adjustment was made in the case of lamb: the number of lambs treated multiplied by the cost of treatment. The total loss in revenue in a given year (t) is:

$$R_t^{loss} = R_t^{cc} - R_t^{Base} = Q_t^{cc} * P_t^{cc} * Y_t^{cc} - Q_t^{Base} * P_t^{Base} * Y_t^{Base};$$

$$as\ Q_t^{cc} = Q_t^{Base} = \overline{Q_t}\ and\ P_t^{cc} = P_t^{Base} = \overline{P_t}$$

$$[production\ units\ and\ producer\ prices\ are\ fixed\ in\ given\ year]:$$

$$R_t^{loss} = \overline{Q_t} * \overline{P_t} * (Y_t^{cc} - Y_t^{Base}) = \overline{Q_t} * \overline{P_t} * (Y_t^{Base} * (1 + L^{quant}) - Y_t^{Base}) = \overline{Q_t} * \overline{P_t} * (Y_t^{Base} * L^{quant})$$

   where R is the Revenue, ‘cc’ (climate change) refers to values considering heat stress and ‘Base’ refers to baseline values. Note that the methodology applied for lamb is somewhat different, due to data limitations; instead of revenue loss, it is the cost of treating animals infected by parasites that is estimated as the economic loss; however, the underlying rationale and calculation is broadly similar.

3. **Climate model member selection** was performed to derive a single set of economic losses for the central climate scenario, and a further set for the high climate scenario. The approach to this is set out in Table 11 and Table 12, with calculations based on aggregated economic losses (for all sub-components at a UK level). In the central climate scenario, the relevant model member was selected by calculating the economic losses for all model members at a given level of global warming and then identifying the member which reported the median loss. In the high climate scenario, the model member with the highest modelled loss was selected at a given level of global warming. This approach was repeated for both the 2030s and 2050s.

Table 11. Model member selection by period and climate scenario

Timeframe	Central Climate Scenario	High Climate Scenario
Present day	Average across all model members	Average across all model members
Near-term (2030s)	Member 9*	Member 13**
Mid-term (2050s)	Member 12*	Member 13**
Notes	**UKCP18 Local model members with the median modelled economic losses for the relevant GWL and time period*	***UKCP18 Local model members with the highest modelled economic losses for the relevant GWL and time period*

Table 12. Mapping modelled outcomes to central and high climate scenarios

Climate scenario	Timeframe	Global Warming Level	Central year that mean values were allocated to
Central / High	Present day	1.1°C	2024
Central	Near-term (2030s)	1.5°C	2035
Central	Mid-term (2050s)	2.0°C	2055
High	Near-term (2030s)	2.0°C	2035
High	Mid-term (2050s)	2.5°C	2055

4. **Annual undiscounted economic losses** were constructed using the loss figures calculated in the previous steps. Based on discussion with the CCC, the mean of results for 20 modelled years for the selected model member were allocated to a single 'central' year in each relevant time period (2030s and 2050s). Table 12 outlines how different combinations of inputs were used to construct three separate data points for the central and high climate scenarios. Annual time series for each scenario were then constructed through linear interpolation between these central years (i.e. between 2024 and 2035, and 2035 and 2055). Extrapolation was then applied up to 2059, using the same rate of change as seen between 2035 and 2055. For example, if the average annual yield loss in 2024 and 2035 are $Loss^{2024}\ and\ Loss^{2035}$, the linearly interpolated result for year y (which is between 2024 and 2035) is:

$$Loss^{y} = Loss^{2024} + \frac{y-2024}{2035-2024} * Loss^{2035}.$$

5. **Net Present Values (NPVs)** were calculated by multiplying the undiscounted economic losses by an agreed discount factor, to calculate the annual discounted economic losses, and then summed over time. Formally: the discounted annual losses can be described as

$$Discounted\ Loss\ (DL)^{year} = Loss^{year} * discount\ factor^{year}$$

The annual discounted losses are summed up across the relevant periods to calculate NPV

$NPV^{y_{t_0}, y_t} = \sum_{t_0}^{t} DL^{t}$ (the net present value between year t_0 and t)

NPVs were calculated for the whole time period (2025-2059), but also for a number of subsets of years: 2025-39 and 2025-59, for reporting in the final analysis. In all cases, the application of discount rates starts from 2025. The Green Book guidance was followed to ensure consistency in economic appraisal.[59] Year-by-year costs were reported, and all NPV calculations were performed using appropriate social discount rates. The base price year was set to 2024, and exchange rates were sourced from the Bank of England and OBR.

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[59] GOV.UK. (n.d.). The Green Book and accompanying guidance and documents. [online] Available at: https://www.gov.uk/government/collections/the-green-book-and-accompanying-guidance-and-documents.

Assumptions and Limitations

A challenge in the estimation of economic losses was linked to prices. As noted above, future prices are held constant at 2024 levels, but assumptions were required around (for example) what proportion of impacted wheat was destined for sale into milling, rather than animal feed – or what proportion of barley was destined for sale into malting, rather than feed. Where possible, regional variations in pricing were also reflected in this 'category pricing' approach. Details of this are set out in the technical method appendix (Appendix K - The calculation of economic losses), which lists the sources used, and how different series were weighted together to estimate as robust a set of prices as possible given the innate data limitations. No distinctions are made between the values of Spring and Winter cereals – blended values are used, as derived from Defra and other data.

Results

Climate risk analysis

This section presents the results of the risk modelling for each of the study's agricultural sub-components (wheat, barley, oats, eggs, dairy, and lambs) for the BAU land use scenario. Overall, the analysis reveals that in absolute terms, the modelled heat-related thresholds will have the greatest impact on agricultural production in England, particularly in the East, Midlands, and South East. This is due to a combination of the geographic distribution of climatic changes, the modelled heat thresholds, and the distribution of agricultural activity for each sub-component across the UK. While Scotland, Wales, and Northern Ireland are also affected, the absolute impacts are significantly lower, except for lambs - which are particularly abundant, and therefore more heavily impacted in Scotland and Wales.

Table 13 presents the modelled average annual losses under the high climate scenario for each agricultural sub-component for the 2050s, also expressed as a percentage of annual regional production.[60] The nation with the highest percentage loss for each component is **highlighted in red text**. England consistently shows the greatest relative losses for most of the study's sub-components, particularly for barley (29.9%) and oats (36.2%), except for lamb infections, where more than 60% of lambs are infected by parasites annually in every nation, with the greatest percentage in Scotland (66.4%).

Table 13. High climate scenario - average annual losses projected in the 2050s, also expressed as % of regional production in 2024[61]

Agricultural sub-component (units of impact)	Nation			
	England	Scotland	Wales	Northern Ireland
Wheat	791,793	5,580	5,128	116

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[60] Average annual losses modelled to occur in the 2050s (High climate, BAU land use scenario). To establish the baseline productivity for each sub-component, 2024 yield statistics were combined with sources for baseline crop areas or numbers of livestock (2018-2024 data, depending on the nation and sub-component) to calculate estimated baseline yields for the assessment. All sources are outlined in Appendix A.

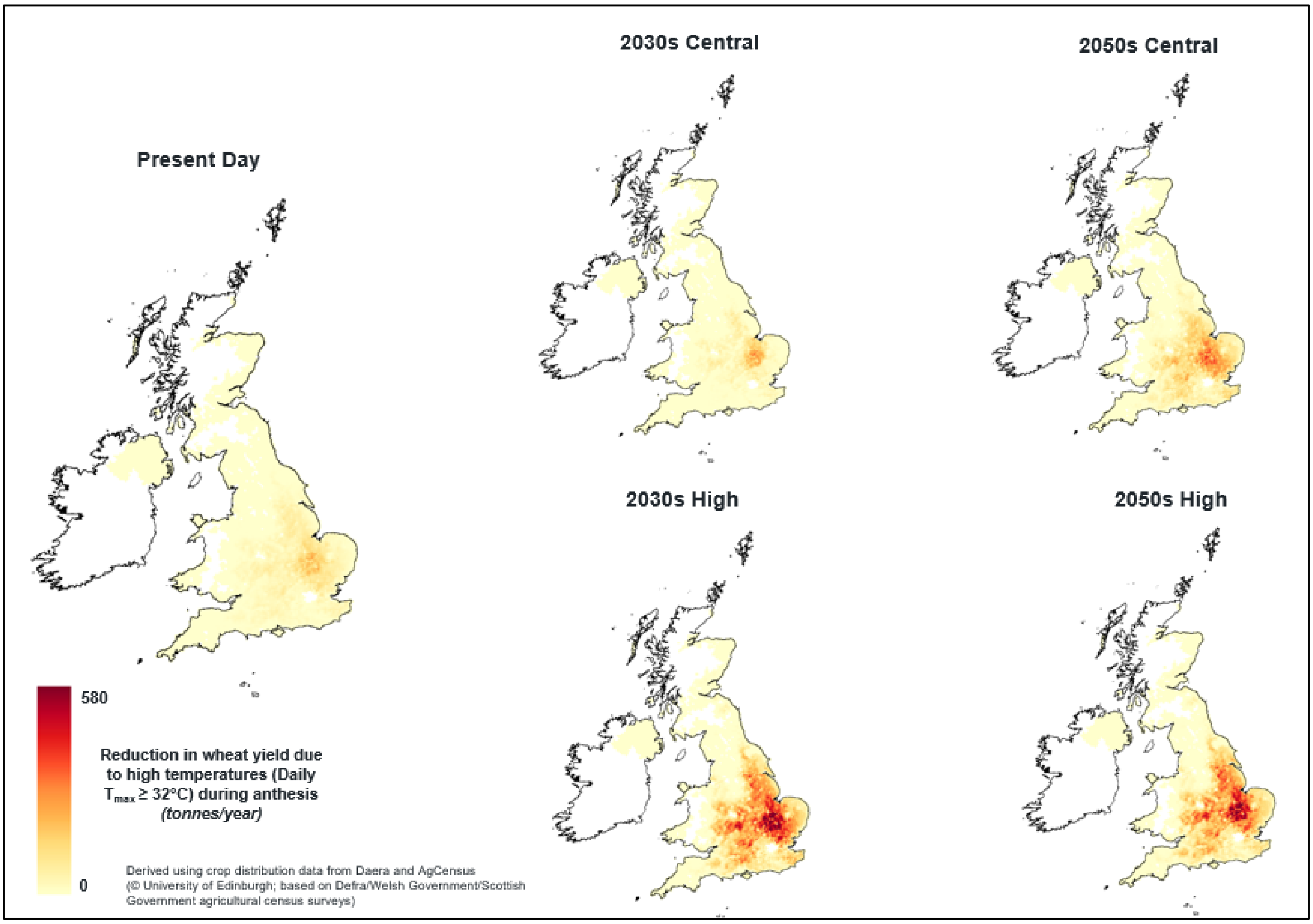
Agricultural sub-component (units of impact)	Nation			
	England	Scotland	Wales	Northern Ireland
(tonnes/year)	**(6.6%)**	(0.7%)	(3.4%)	(0.2%)
Barley (tonnes/year)	1,450,334 **(29.9%)**	94,180 (4.7%)	19,189 (15.1%)	4,903 (3.9%)
Oats (tonnes/year)	280,090 **(36.2%)**	12,409 (6.8%)	**	422 (3.9%)
Lambs (lambs infected/year)	4,527,002 (61.9%)	2,224,951 **(66.4%)**	2,833,368 (61.8%)	855,110 (61.3%)
Milk (litres/year)	658,079 (<0.1%)	17,297 (<0.1%)	119,721 (<0.1%)	21,366 (<0.1%)
Eggs (eggs laid at reduced weights/year)*	8,670,826 **(0.2%)**	45,936 (<0.1%)	756,110 (0.1%)	182,975 (<0.1%)

* Number of eggs with reduced weights, resulting in a size class downgrade from ‘large’ to ‘medium.’
** Data on the planted area of oats in Wales were not available and could therefore not be modelled in this analysis.

Cereals

The results of the risk modelling for wheat across the UK are shown in Figure 5. Overall, the modelled impacts due to days with maximum temperatures reaching or exceeding 32°C during anthesis in the spring are greatest in the East of England, expanding geographically to the Midlands and South East by the 2050s. Yield losses are projected to increase over time, rising from an average annual loss in England in the present day of 195,580 tonnes/year to 434,219 tonnes/year by the 2050s in the central climate scenario (roughly double the present-day losses). In the high climate scenario, the maximum average annual loss for wheat in England occurs in the 2030s, at 867,335 tonnes/year, which is about four times more losses than at present day.

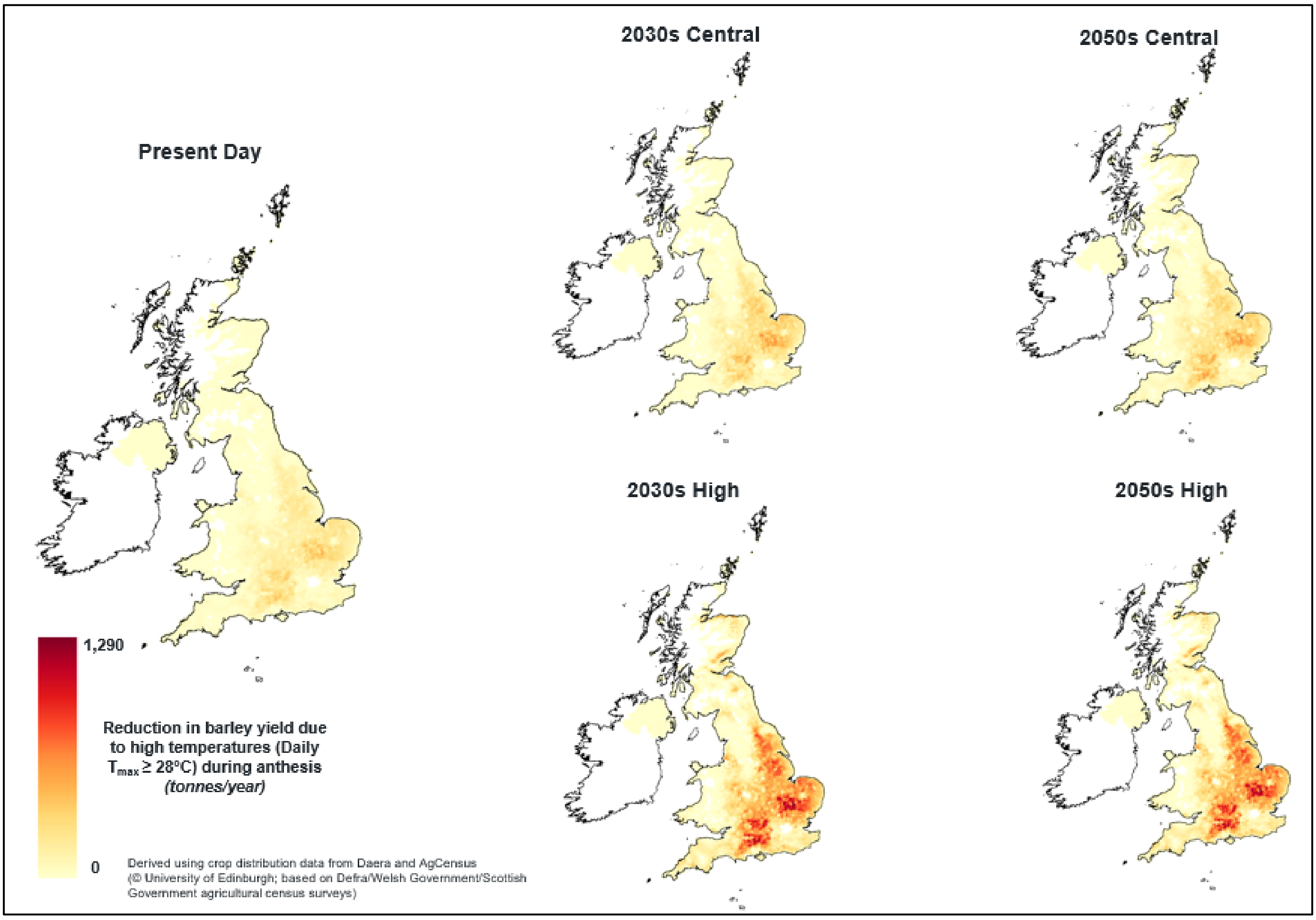
Figure 5. Average annual reduction in wheat yield due to high temperatures during anthesis (days with maximum temperatures ≥ 32°C). The key references reductions per year per 5km grid square



Derived using crop distribution data from Daera and AgCensus (© University of Edinburgh; based on Defra/Welsh Government/Scottish Government agricultural census surveys)

The spatial distributions of barley yield reductions due to high temperatures in the spring across the UK (days with maximum temperatures ≥ 28 °C) are shown in Figure 6. Impacts are greatest and concentrated in England (South East, South West, and the East Midlands). Yield losses are projected to increase over time, rising from an average annual loss in England in the present day of 375,183 tonnes/year to 551,310 tonnes/year by the 2050s (central climate scenario). In the high climate scenario, the maximum average annual yield loss for barley occurs in the 2050s in England at 1,450,334 tonnes/year, which is almost four times the present day losses. Scotland also sees high absolute losses in the high climate scenario at 94,180 tonnes/year, with the greatest impacts felt in Eastern and North East Scotland.

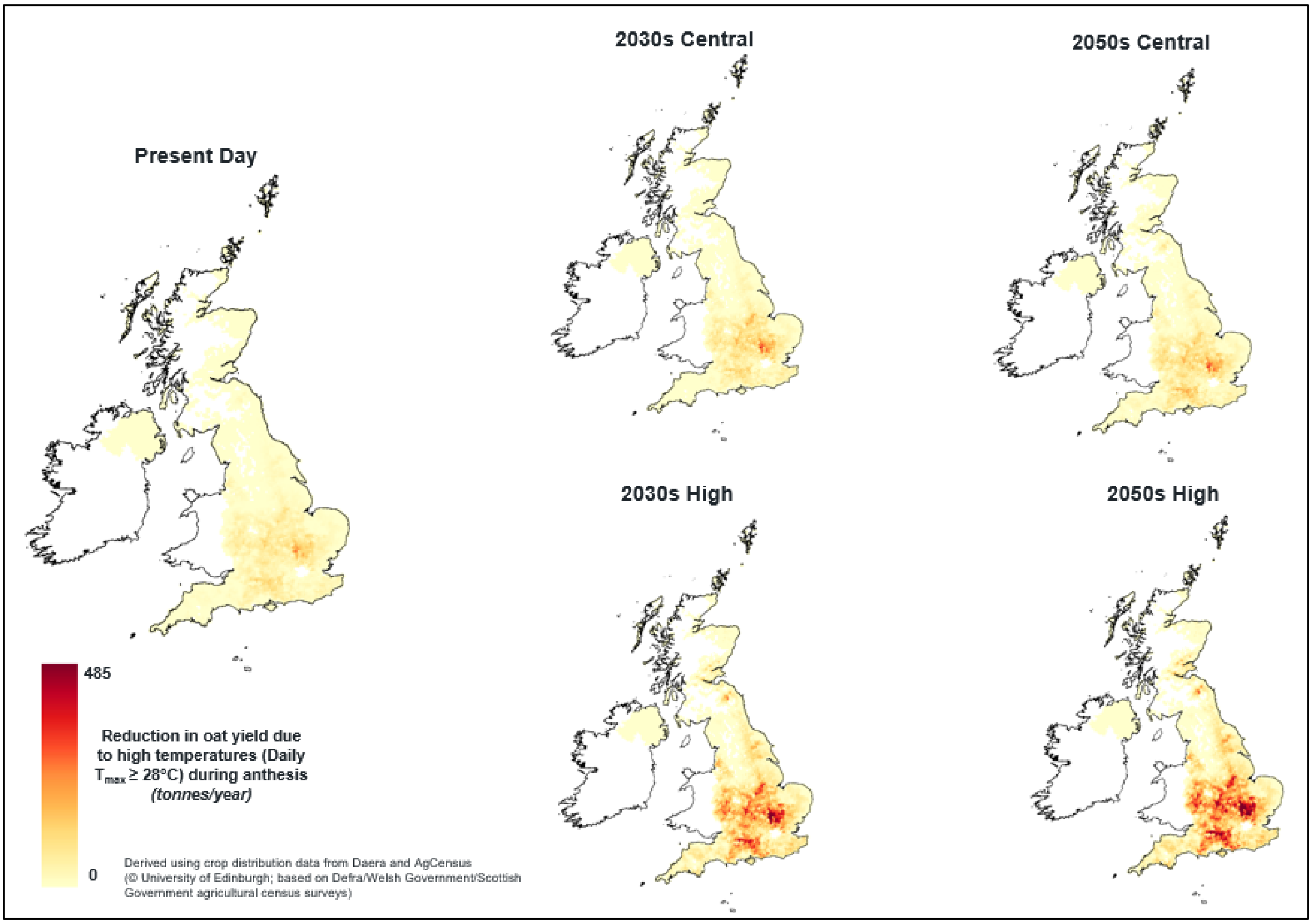
Figure 6. Average annual reduction in barley yield due to high temperatures during anthesis (days with maximum temperatures ≥ 28 °C). The key references reductions per year per 5km grid square



Derived using crop distribution data from Daera and AgCensus (© University of Edinburgh; based on Defra/Welsh Government/Scottish Government agricultural census surveys)

The spatial distribution of UK oat yield losses due to high temperatures during springtime (day with average temperatures ≥ 28°C) is shown in Figure 7. Losses are particularly severe in the East of England, Midlands, and the eastern area of South West England. Yields are projected to be impacted over time, rising from an average annual loss in England in the present day of 72,360 tonnes/year to 106,006 tonnes/year by the 2050s due to high temperatures in the spring (central climate scenario). In the high climate scenario, the maximum average annual yield loss for oats occurs in England in the 2050s, and nearly quadruples from present day losses at 280,090 tonnes/year (which is equivalent to a loss of about 36% of England's oat production in 2024). In the high climate scenario, impact also spreads geographically northward into Yorkshire and the Humber, the North East of England, and Eastern Scotland. Due to the lack of spatial distribution data from AgCensus, it was not possible to model oat yield reductions in Wales. However, oats account for approximately 11% of annual cereal production in Wales and are likely also vulnerable to future high temperature-driven yield losses.[62]

Figure 7. Average annual reduction in oat yield due to high temperatures during anthesis (day with average temperatures ≥ 28°C) (excluding Wales). The key references reductions per year per 5km grid square



Derived using crop distribution data from Daera and AgCensus (© University of Edinburgh; based on Defra/Welsh Government/Scottish Government agricultural census surveys)

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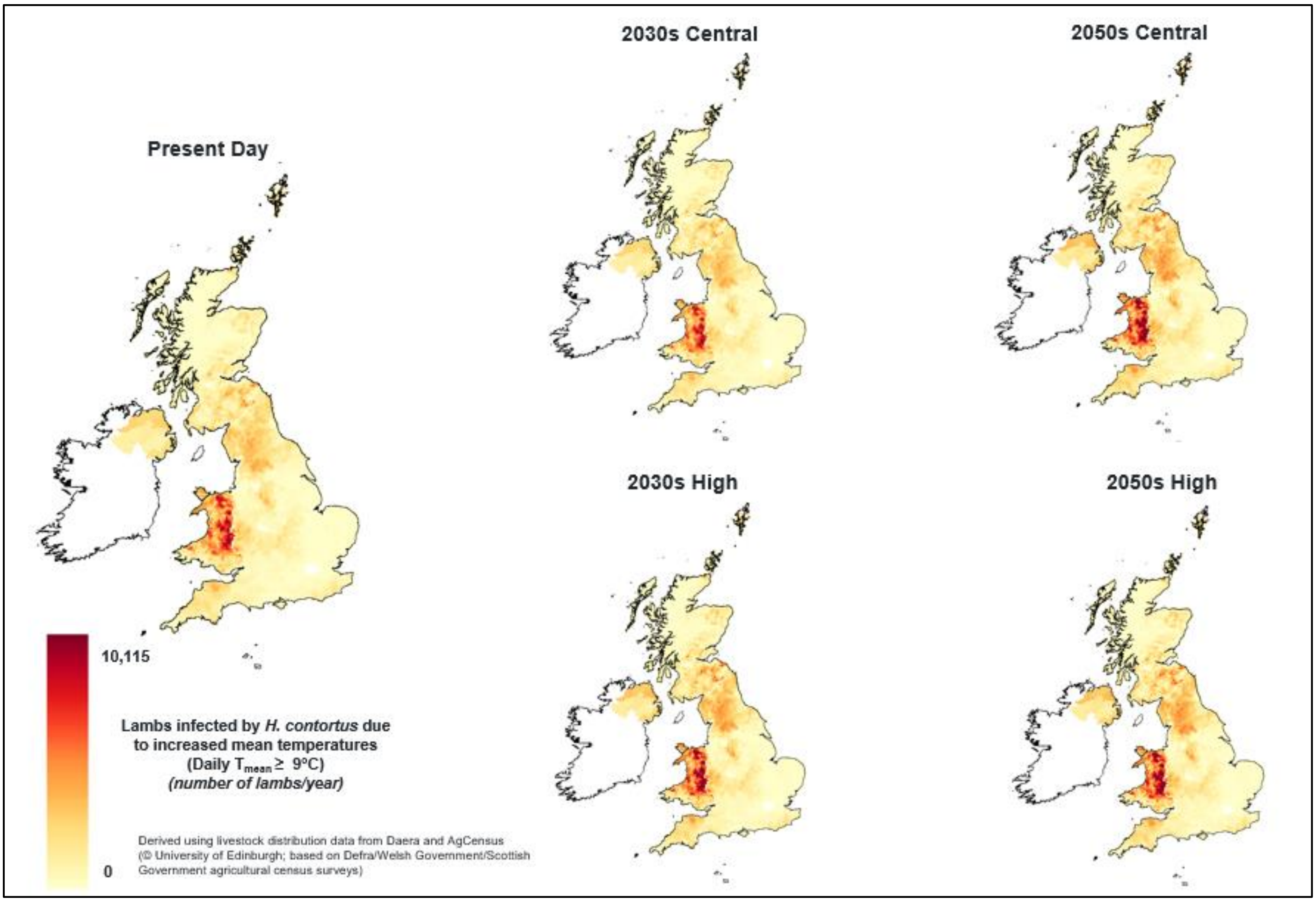
[62] Gov.wales. (2019). Crops (Hectares) by Area. [online] Available at: https://statswales.gov.wales/Catalogue/Agriculture/Agricultural-Survey/Area-Survey-Results/crops-in-hectares-by-area [Accessed 13 Feb. 2026].

Livestock

Figure 8 illustrates the projected spatial distribution of lambs infected with the parasite *H. contortus* across the UK under rising average temperatures (days with ≥9 °C daily mean temperature). The maps capture two primary drivers of the projected infection patterns: the high density of sheep farming in Wales, northern England, and southern Scotland, and the 9 °C daily mean temperature threshold for heightened infection risk, which is expected to be exceeded more often in the future across the whole UK, including Northern Ireland. Under the central climate scenario, the average annual number of infected lambs in Wales is projected to rise from 2.29 million today to 2.93 million by the 2050s (~64% of all lambs in Wales). In the high climate scenario, infections peak in the 2050s at an average of 2.83 million lambs per year, slightly fewer than projected in the central scenario. A similar trend is projected to occur in Scotland, with annual infections peaking at 2.2 million lambs/year in the 2050s (high climate scenario), equivalent to about 66% of all lambs in Scotland.

Figure 8. Average annual number of lambs infected by parasites due to increased mean temperatures (days with ≥9 °C daily mean temperature). The key references infections per year per 5km grid square



Present Day

2030s Central

2050s Central

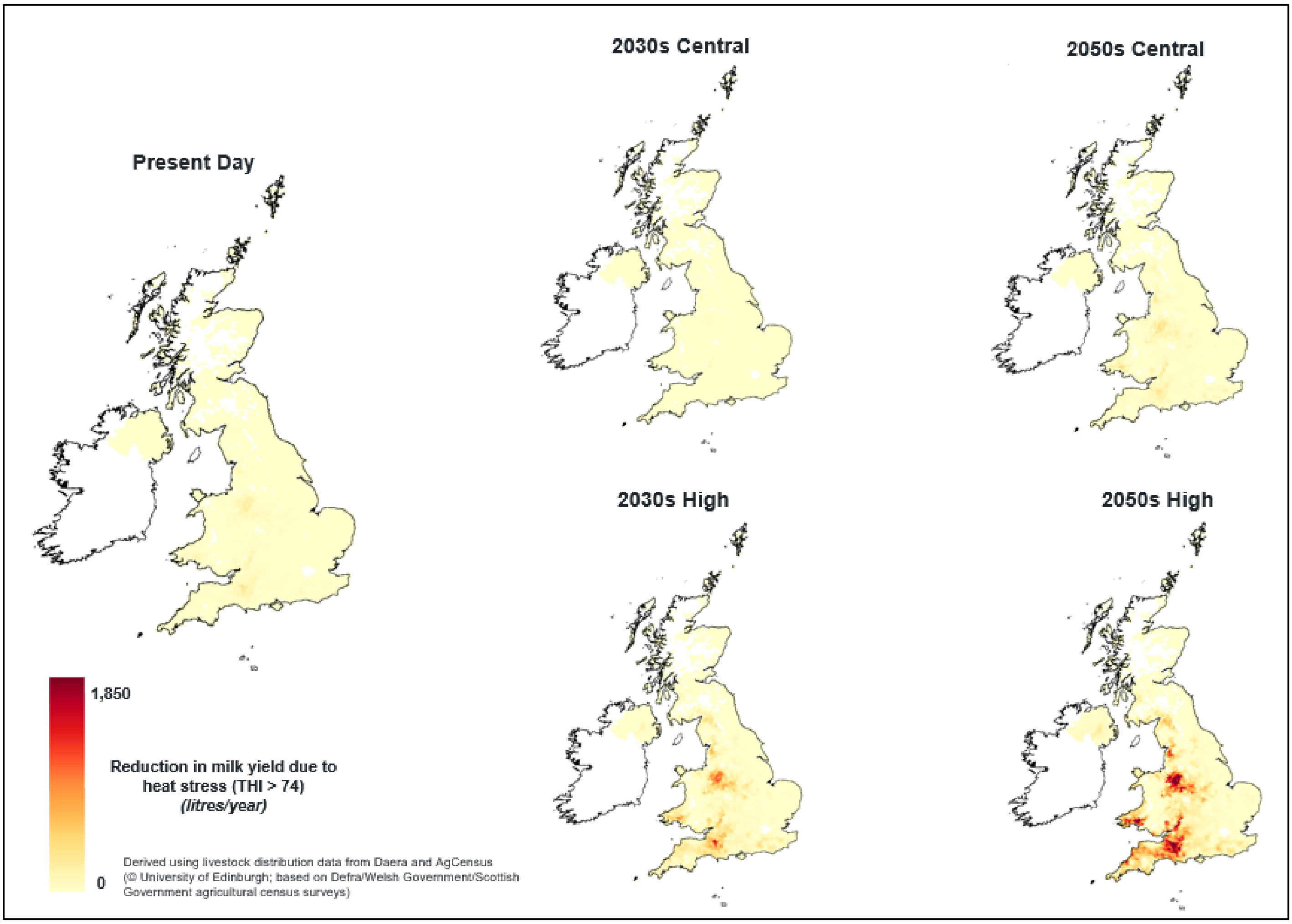
2030s High

2050s High

Derived using livestock distribution data from Daera and AgCensus (© University of Edinburgh; based on Defra/Welsh Government/Scottish Government agricultural census surveys)

Figure 9 illustrates the projected spatial distribution of milk yield reduction due to dairy cattle heat stress across the UK. In the central climate scenario, impact is relatively minimal, but concentrated in the West Midlands, South West, and North West of England. Across all of England in this scenario, the average annual milk yield losses due to thermal heat stress (THI of ≥74) are projected to rise from 69,317 litres/year today to 110,112 by the 2050s. In the high climate scenario, this figure rises to 658,079 litres/year in England, with risk becoming more concentrated in the South West of England, West Midlands, and South Wales. However, in total, the maximum average annual yield loss projected for the UK is only 816,463 litres/year, equivalent to a very small fraction of average annual milk production (~0.01%).[63]

Figure 9. Average annual reduction in milk yield due to heat stress (THI of ≥74). The key references reductions per year per 5km grid square



Derived using livestock distribution data from Daera and AgCensus (© University of Edinburgh; based on Defra/Welsh Government/Scottish Government agricultural census surveys)

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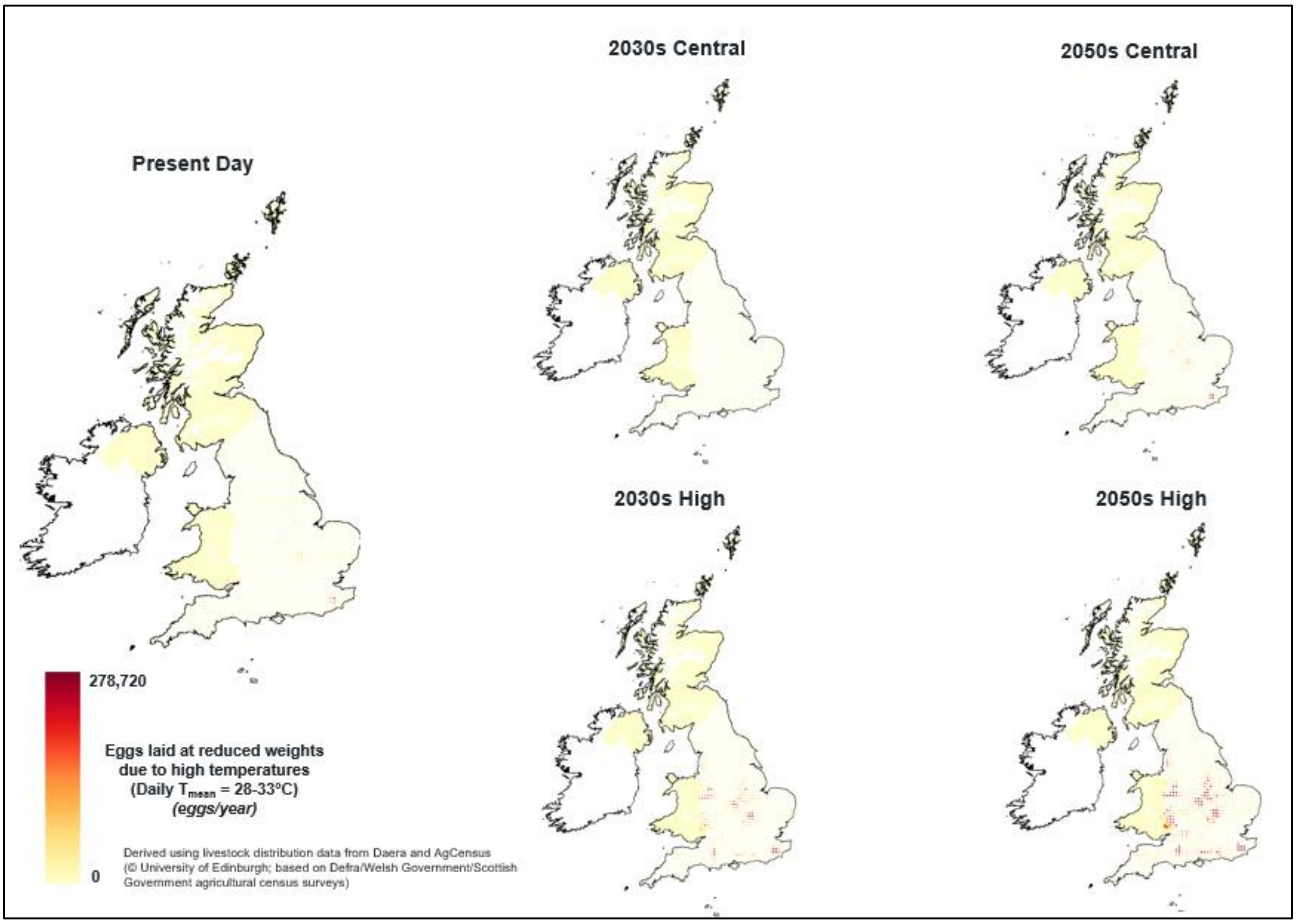
[63] Department for Environment, Food & Rural Affairs (2025). Chapter 8: Livestock. [online] GOV.UK. Available at: https://www.gov.uk/government/statistics/agriculture-in-the-united-kingdom-2024/chapter-8-livestock#milk.

Given the very high temperature thresholds to induce reductions in free-range egg weight (day with mean air temperatures of 28°C to >39°C), modelled projections of the number of free-range eggs laid at lower weights are minimal across the UK. The numbers of eggs laid at reduced weights per $5km^2$ grid square are shown in Figure 10 below. While more severe impacts associated with thresholds ranging from a daily mean temperature of 34-38°C and ≥ 39°C were modelled, no impacts were projected to occur under any selected climate scenario, timeframe, or nation. Thus, the map below portrays the average annual number of eggs laid at reduced weights associated with daily mean temperature threshold range of 28-33°C. Some impacts are felt in the central climate scenario by the 2050s in the East and South East of England, resulting in lowered weights for eggs laid during those days. However, in a high climate scenario, impacts spread across southern England and the Midlands, and along the Welsh border, associated both with higher concentrations of hens and where the high temperature thresholds are projected to be breached. In this scenario, the average annual number of eggs laid at a reduced weight across the UK, resulting in a size class difference ('medium' eggs that should have been 'large') is 9.66 million. This is equivalent to about 0.1% of free-range eggs produced in the UK.[64]

Figure 10. Average annual number of eggs laid at reduced weights due to heat stress (day with mean air temperatures of 28°C to 33°C). The key references reductions per year per 5km grid square



Derived using livestock distribution data from Daera and AgCensus (© University of Edinburgh; based on Defra/Welsh Government/Scottish Government agricultural census surveys)

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[64] UK egg industry data. https://www.egginfo.co.uk/egg-facts-and-figures/industry-information/data

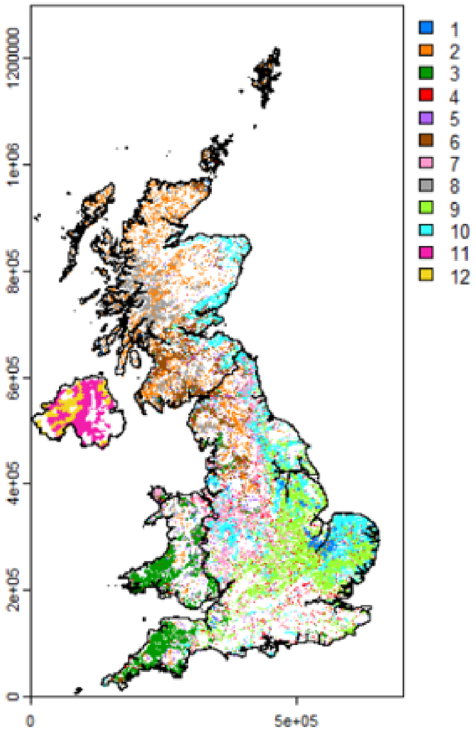
Alignment with the CCC Rural Land Use Archetypes

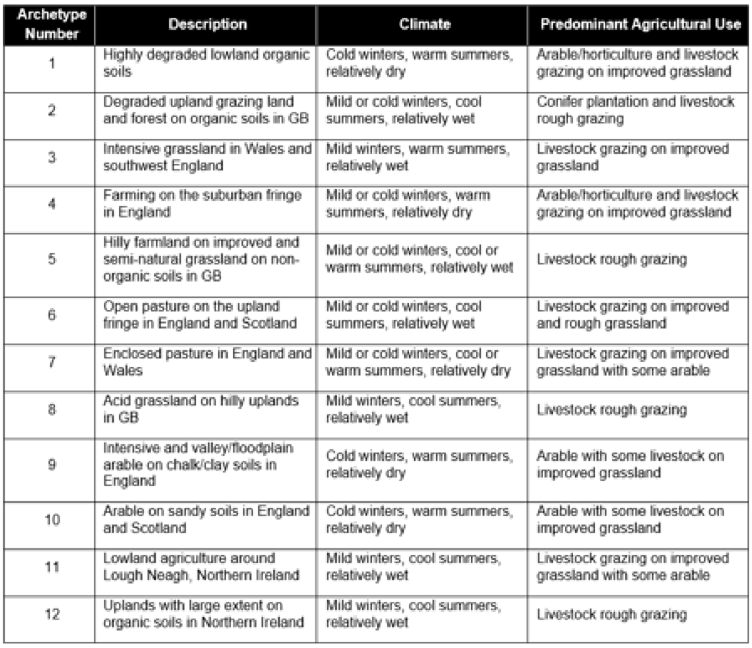
The CCC previously commissioned the development of rural land use archetypes[65] to reflect typical land use and management patterns across the UK. The twelve resulting archetypes represent distinct combinations of land cover, farming systems, and spatial characteristics, each covering substantial areas of the UK. An overview of the key characteristics of each archetype is shown in Figure 11.

When comparing the results of the climate risk analysis against the spatial distribution of the land use archetypes, several patterns emerge. For wheat, barley, and oats, the most significant impacts are concentrated in Archetypes 1, 9, and 10 (East and South East England), although other arable agriculture archetypes show some impact across the high climate scenario.

In the case of lambs infected with parasites (*H. contortus*), high risk areas are predominantly found in Archetype 3 (Wales and South West England) as well as Archetypes 2, 5, and 6 across England and Scotland. In Northern Ireland, Archetypes 11 and 12 are also impacted, consistent with their classification as livestock grazing areas. Reduced milk yields are most prevalent in Archetypes 10, 9 and 3 in England and Wales, while modelled areas of greatest egg weight losses tend to fall in Archetypes 10, 9, and 7. Overall, the highest modelled impacts for each sub-component tend to occur within the archetypes where their agricultural activities are most prevalent across the UK.

Figure 11. Summary of key characteristics of the land use archetypes[66]





Archetype Number	Description	Climate	Predominant Agricultural Use
1	Highly degraded lowland organic soils	Cold winters, warm summers, relatively dry	Arable/horticulture and livestock grazing on improved grassland
2	Degraded upland grazing land and forest on organic soils in GB	Mild or cold winters, cool summers, relatively wet	Conifer plantation and livestock rough grazing
3	Intensive grassland in Wales and southwest England	Mild winters, warm summers, relatively wet	Livestock grazing on improved grassland
4	Farming on the suburban fringe in England	Mild or cold winters, warm summers, relatively dry	Arable/horticulture and livestock grazing on improved grassland
5	Hilly farmland on improved and semi-natural grassland on non-organic soils in GB	Mild or cold winters, cool or warm summers, relatively wet	Livestock rough grazing
6	Open pasture on the upland fringe in England and Scotland	Mild or cold winters, cool summers, relatively wet	Livestock grazing on improved and rough grassland
7	Enclosed pasture in England and Wales	Mild or cold winters, cool or warm summers, relatively dry	Livestock grazing on improved grassland with some arable
8	Acid grassland on hilly uplands in GB	Mild winters, cool summers, relatively wet	Livestock rough grazing
9	Intensive and valley/floodplain arable on chalk/clay soils in England	Cold winters, warm summers, relatively dry	Arable with some livestock on improved grassland
10	Arable on sandy soils in England and Scotland	Cold winters, warm summers, relatively dry	Arable with some livestock on improved grassland
11	Lowland agriculture around Lough Neagh, Northern Ireland	Mild winters, cool summers, relatively wet	Livestock grazing on improved grassland with some arable
12	Uplands with large extent on organic soils in Northern Ireland	Mild winters, cool summers, relatively wet	Livestock rough grazing

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[65] Young, H. and Thomson, A. (2023). UK Rural Land Use Archetypes | UK Rural Land Use Archetypes. [online] Available at: https://www.theccc.org.uk/wp-content/uploads/2023/08/Archetypes-representative-of-current-UK-rural-land-use-and-land-management-UKCEH.pdf.

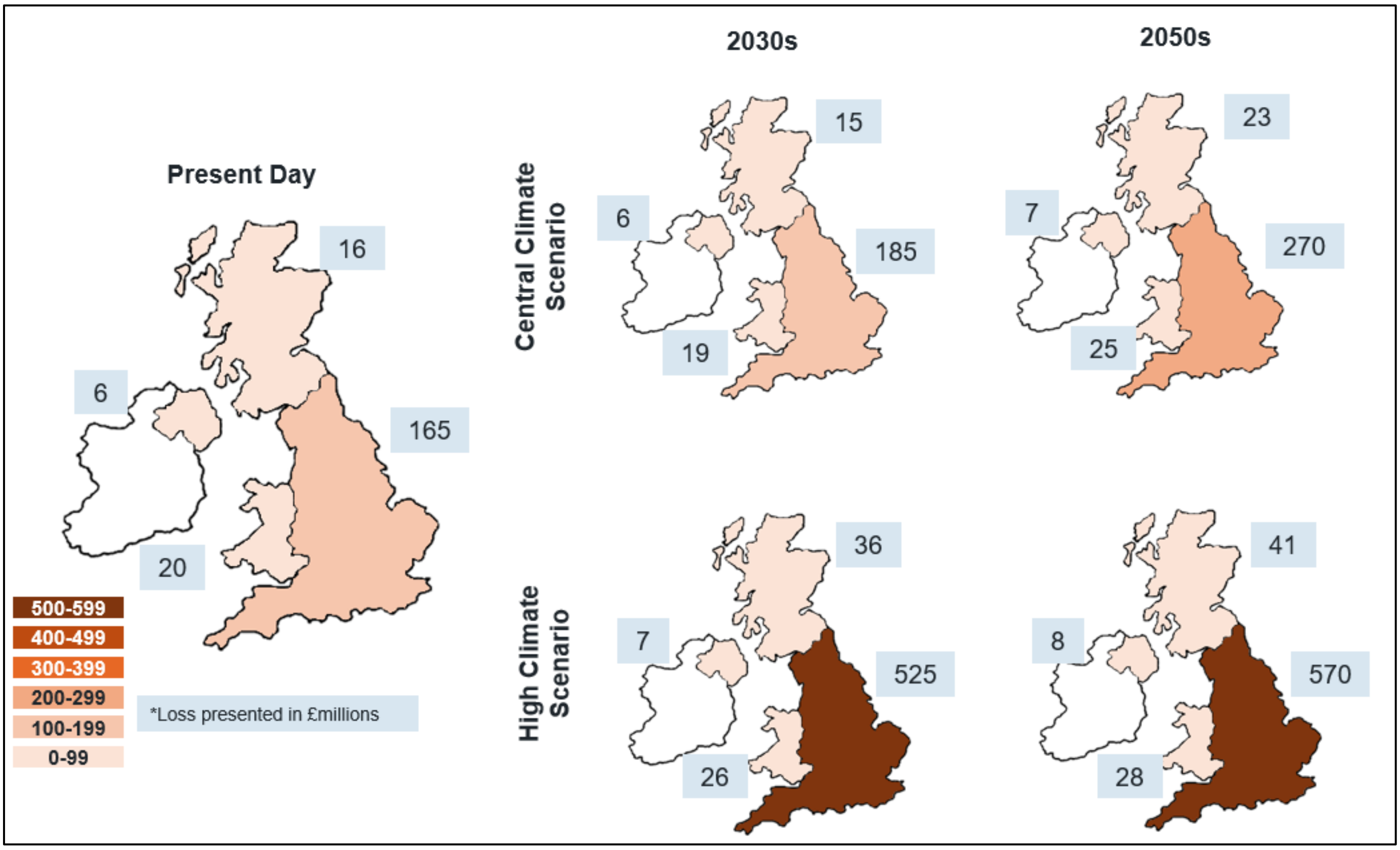
[66] Adapted from Table 2 in Young and Thomson (2023) - https://www.theccc.org.uk/wp-content/uploads/2023/08/Archetypes-representative-of-current-UK-rural-land-use-and-land-management-UKCEH.pdf.

Economic analysis

The economic losses observed in this analysis are a function of four key drivers: the geography of a given region, the specific hazard and impact metrics that are applied, the size of a region in terms of both area and livestock populations, and the relative value of the different products and subproducts produced in that region, both impacting on the economic value of the impacts.

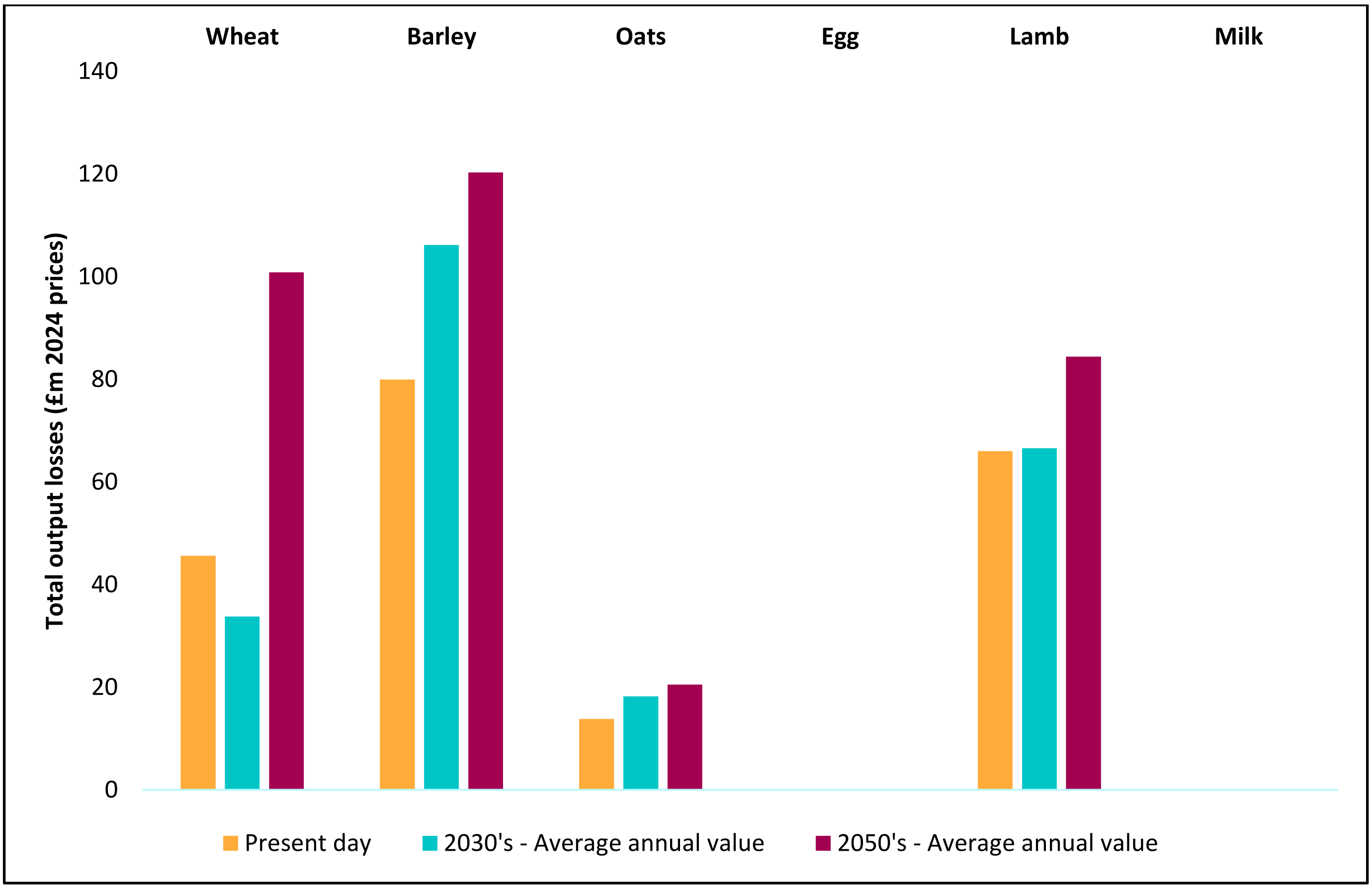
The sum of economic losses across the six assessed agricultural products under the BAU land use scenario are mapped in Figure 12. The analysis shows that specific temperature-related (heat) risks are already causing substantive economic losses across the UK's farmed landscapes. Relatively modest changes are expected in the central climate scenario over the coming decade; while economic losses are expected to be somewhat higher in England compared to today, they will be similar across the devolved administrations. However, the impacts of climate change on the UK's farmed landscapes are much more severe by mid-century; around 57% higher across the modelled components at a UK level, in the central climate scenario. When looking at a future with a greater change in the climate (high climate scenario), impacts are substantially more severe; economic losses across the UK could be more than three times the level experienced today, at £647m per year on average, in the 2050s.

Figure 12. Average annual economic losses from specific temperature-related (heat) risks to select agricultural products (wheat, barley, oats, dairy, eggs, and lambs) under BAU, Central and High Climate scenarios (£millions)



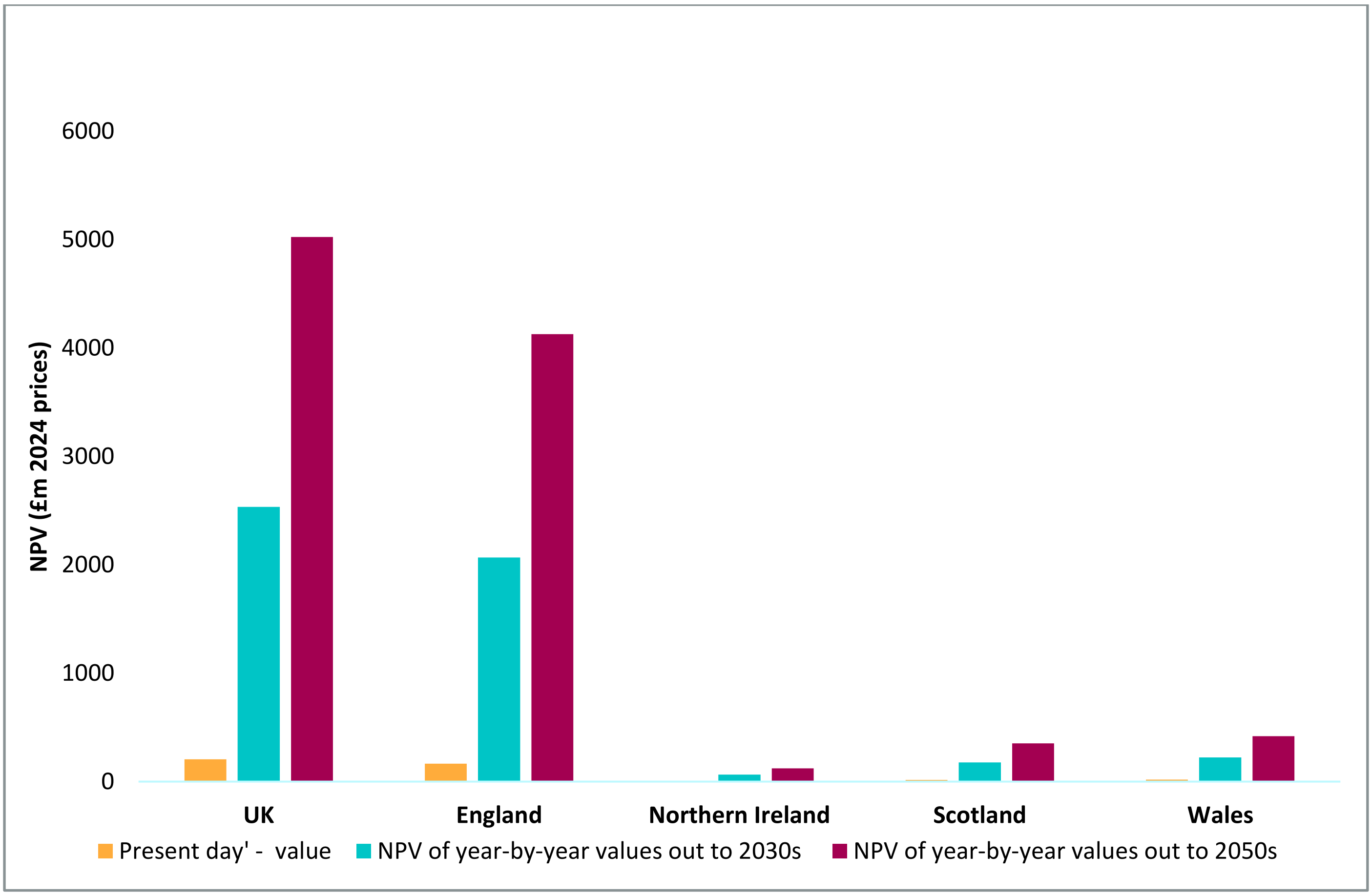
When considering the impacts on individual components, present day losses are dominated by wheat, barley and lamb (see Figure 13). Barley is modelled as having the largest economic losses today, at £80m, and these losses are expected to increase by around half by mid-century to reach £120m on average through the 2050s. While wheat losses today are modelled as less than those experienced in barley or lamb, they are expected to more than double by the 2050s, reaching £100m per year.

Figure 13. Average annual economic losses from specific temperature-related (heat) risks by agriculture sub-component (UK, BAU, central climate scenario)



By contrast, the modelled livestock components are relatively resilient to economic losses from heat stress; noting lambs which are already subject to a substantial risk of parasite infection which leads to present-day damages, and while these losses will increase in the future, the change is limited. More markedly, modelled economic losses from eggs and milk are expected to remain very small in absolute terms. However, livestock are at risk of second-order effects which go beyond the scope of this quantitative analysis, for example fodder crops and pasture are more vulnerable to heat-related climate change impacts, and increased scarcity of animal feed in the future is likely to have a more substantive impact on livestock – with respect to health and productivity in the short term, and population in the long term, linked to their financial viability. In addition, this analysis does not account for higher heat stress thresholds that may result in livestock deaths, and thus further economic losses. Thus, overall, these conclusions should be interpreted with a degree of caution, as they only represent one piece of a much bigger system.

Figure 14. Net Present Value (NPV) of economic losses from specific temperature-related (heat) risks by nation for the six assessed products (wheat, oats, barley, milk, lambs, eggs) in the BAU, central climate scenario.



England dominates the economic losses observed, both currently and in the future, due to its significant role within the UK agricultural sector and its greater exposure to higher temperatures. As shown in Figure 14, England experiences the greatest economic loss in total across each of the six components assessed in terms of Net Present Value (NPV), and as at the UK level, the greatest losses are associated with wheat, lamb and barley. In Scotland and Wales, economic losses are dominated by the costs of treating lambs, although losses associated with barley also contribute (about 20% of the total losses in NPV terms) to the losses in Scotland over the period to the end of the 2050s, but a much smaller role in Wales. Besides losses associated with treating parasite infections in lambs, in Wales, Northern Ireland, and Scotland, there are limited losses across the remaining farmed landscape sub-components.

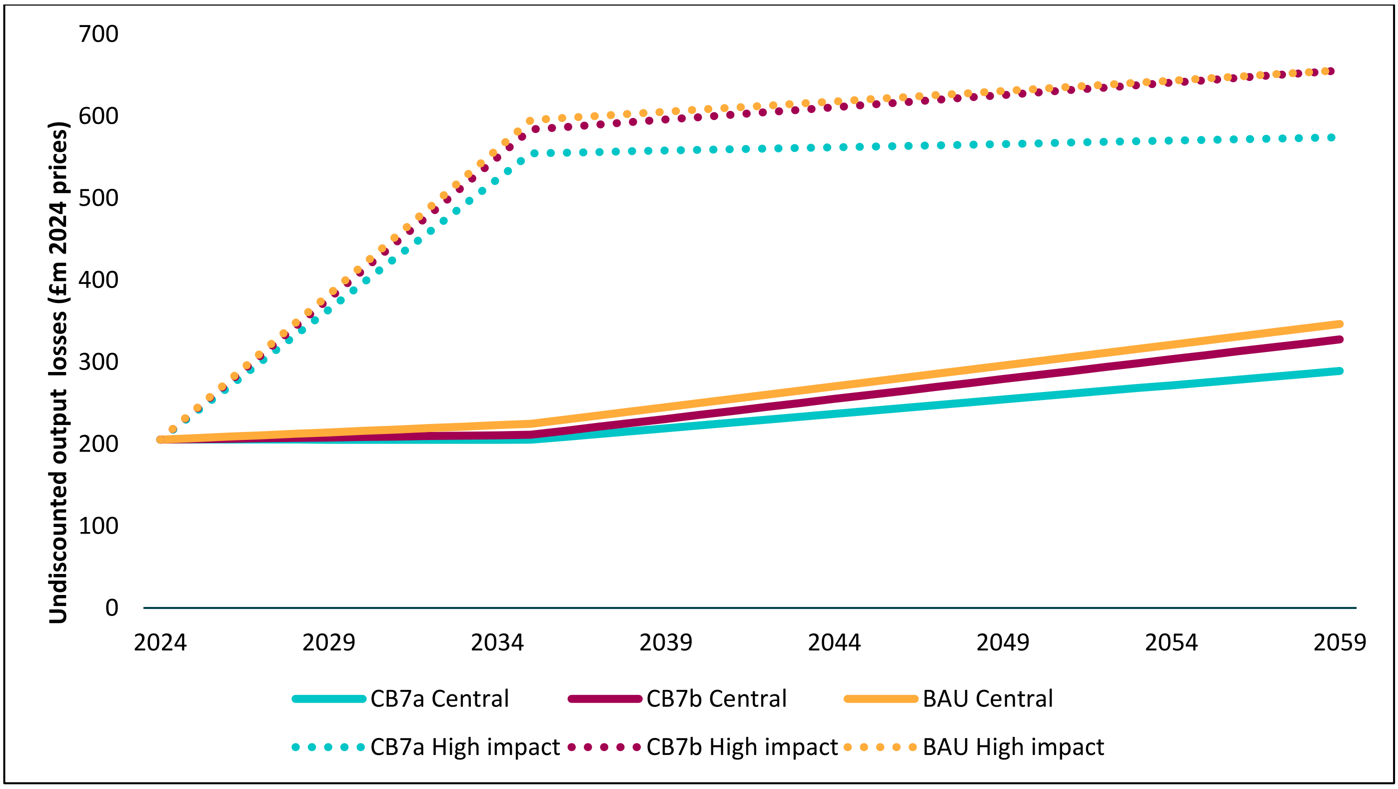
Land Use Scenario Results

This section summarises the results of the climate risk analysis for the other two land use scenarios, CB7a and CB7b, compared to Business as Usual (BAU).

Figure 15 presents the undiscounted annual output losses of all assessed agricultural components in the UK by land use and climate scenario.[67] In the 2050s, damages are 16% smaller in the CB7a land use scenario than in the BAU scenario, reflecting the reduction in agricultural land area and livestock populations occurring over time (Table 14). Under the CB7a and CB7b scenarios, livestock numbers are expected to decline by about one third, driven by dietary shifts – meat consumption per person being projected to fall by roughly one third.

With future projected crop and milk yield increases (per unit area), as modelled in the CB7b scenario, expected economic damages are higher compared to CB7a, as there is more production exposed to climate hazards. However, at the UK level, total output losses remain higher in the BAU scenario than in the CB7b scenario. This is because future total outputs in the BAU scenario are overall slightly higher than in CB7b, due to the reduction in cropped area and numbers of livestock inherent in CB7b, despite the assumed increased in yields under CB7b.

Figure 15. Average annual output losses from specific temperature-related (heat) risks in the UK for the six assessed components (wheat, oats, barley, milk, lambs, eggs) by land use and climate scenario



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[67] Note: The CB7 Balanced Pathway does not model any egg or lamb productivity improvements, and as such, these were not included in the assumptions that informed our CB7b scenario. Thus, the CB7a results (where numbers of livestock decrease over time) were used for these products in the CB7b land use scenario.

Table 14. Average annual UK economic losses in the 2050s for the six modelled components (wheat, oats, barley, milk, lambs, eggs), by land use and climate scenario

Scenario	Central	High
Business-As-Usual (BAU)	£325 million	£647 million
CB7a *(% change compared to BAU)*	£274 million *(-16%)*	£571 million *(-12%)*
CB7b *(% change compared to BAU)*	£316 million *(-3%)*	£643 million *(-1%)*

Figure 16 and Figure 17 present the average annual economic losses by nation in the CB7a and CB7b scenarios, respectively.

Figure 16. Average annual economic losses from specific temperature-related (heat) risks to the six modelled agriculture products (wheat, barley, oats, dairy, eggs, and lambs) under CB7a Central and High Climate scenarios (£millions)

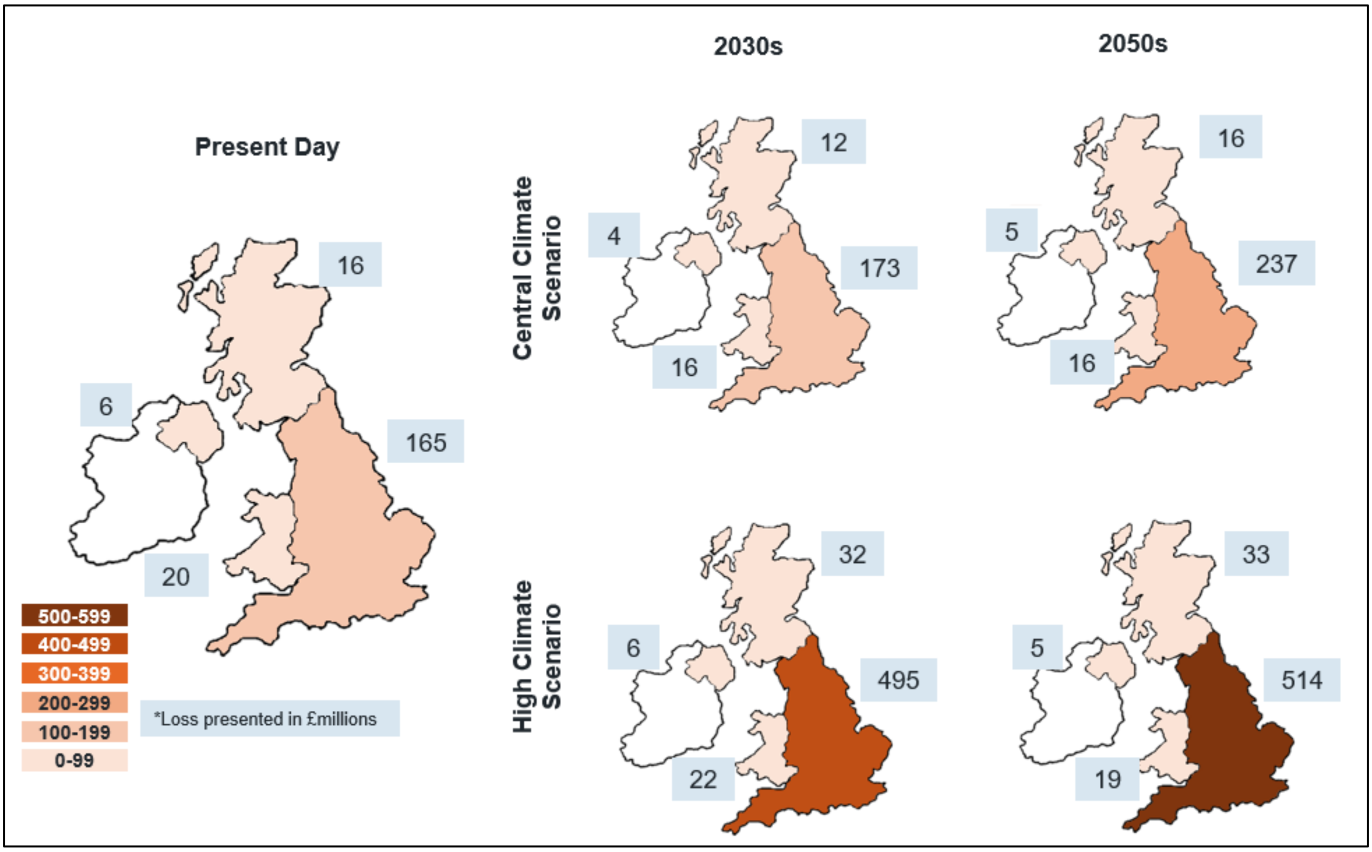
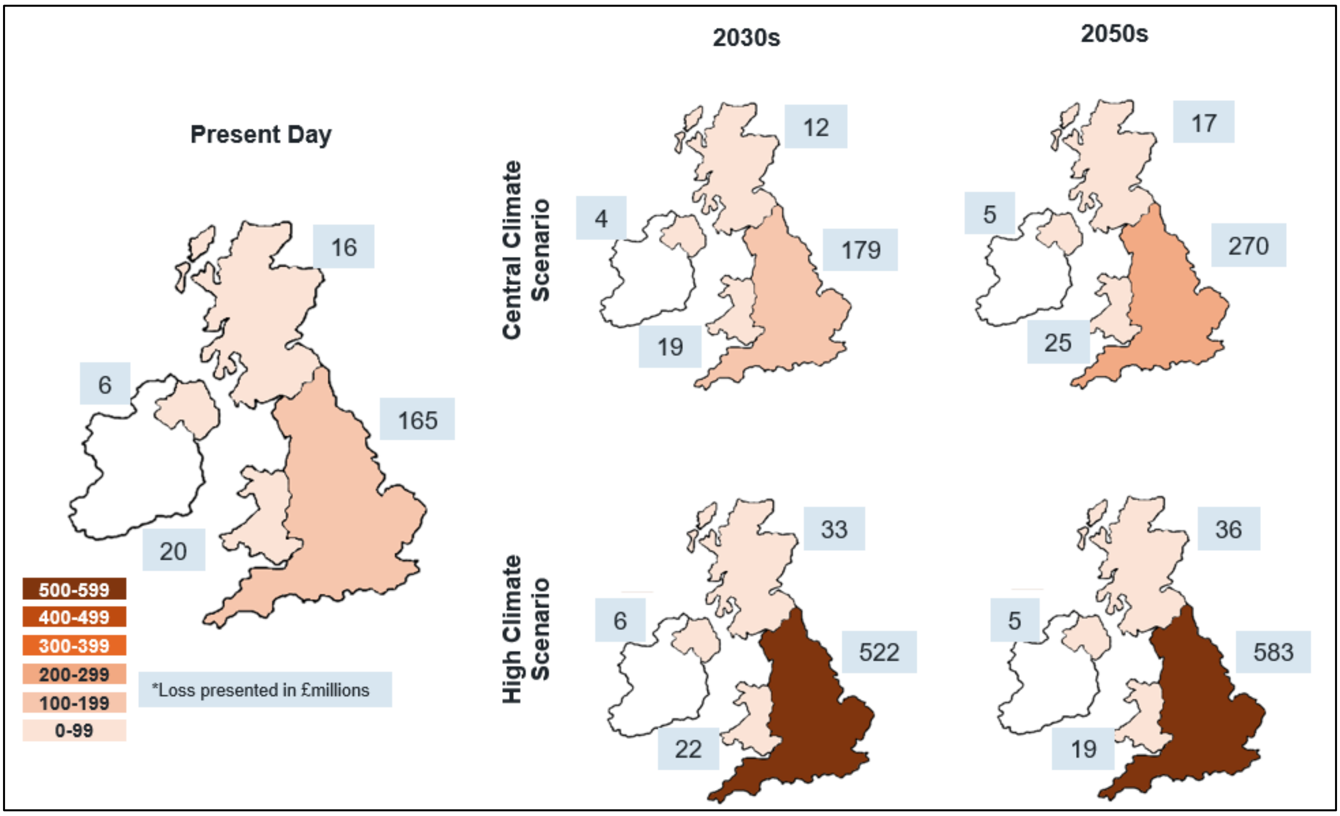


Figure 17**. Average annual economic losses from** specific temperature-related (heat) risks to the six modelled agriculture products (wheat, barley, oats, dairy, eggs, and lambs) under CB7b Central and High Climate scenarios (£millions)



Contextualising the Economic Analysis: Average and Maximum Annual Losses

Overall, modelled average annual economic losses are substantial, especially in England, where total losses could reach from £514 - £583 million per year in the 2050s under the high climate scenario. Nevertheless, since these figures represent averages, actual annual losses could be severe at both farm and national scales. To explore an example of what maximum annual losses from the assessed heat thresholds could look like, the *maximum* projected annual economic losses over each 20-year timeframe (2030s and 2050s; high climate scenario), derived from the risk modelling for the selected model members, were analysed for each agricultural sub-component. These figures are illustrated in Table 15.

Table 15. Maximum projected annual economic losses for the 2030s and 2050s due to specific temperature-related (heat) risks (£millions, also expressed as increase in £millions compared to present day losses)*

Agricultural sub-component	Nation and Timeframe							
	England		Scotland		Wales		Northern Ireland	
	2030s	2050s	2030s	2050s	2030s	2050s	2030s	2050s
Wheat	£1,157.1m (+£682.6m)	£865.7 (+£391m)	£21.4 (+£18.9m)	£21.4 (+£18.9m)	£8.2 (+£5.3m)	£8.2 (+£5.3m)	£0.5m (+£0.5m)	£0.5m (+£0.5m)
Barley	£795.2m (+£326.4m)	£725m (+£256m)	£144.3m (+£119.7m)	£144.3m (+£119.7m)	£19.4m (+£12.6m)	£15.5m (+£8.7m)	£9.3m (+£7.4m)	£9.3m (+£7.4m)
Oats	£136.7m (+£55m)	£128.8m (+£48m)	£16.5m (+£13.8m)	£16.5m (+£13.8m)	**	**	£0.7m (+£0.6m)	£0.7m (+£0.6m)
Lambs	£40.4m (+£3.5m)	£41.6m (+£5m)	£21.1m (+£3.3m)	£19.5m (+£1.7m)	£26.1m (+£2.8m)	£25.6m (+£2.3m)	£8.1m (+£1m)	£7.7m (+£0.6m)
Milk	£1.1m (+£0.8m)	£2m (+£2m)	£0.1m (+£0.1m)	£0.1m (+£0.1m)	£0.3m (+£0.2m)	£0.4m (+£0.3m)	£0.1m (+£0.1m)	£0.1m (+£0.1m)
Eggs	£0.4m (+£0.3m)	£0.7m (+£0.6m)	<£0.1m	<£0.1m	<£0.1m	£0.1m (+£0.1m)	<£0.1m	<£0.1m

* Maximum projected losses for each sub-component over the 2030s and 2050s under the BAU, high climate scenario.

** Data on the planted area of oats in Wales were not available and could therefore not be modelled in this analysis.

All modelled agricultural sub-components, except for eggs, show marked increases in the maximum projected annual losses compared to the present day. Across all agricultural sub-components and nations, the maximum modelled annual loss occurs in England in the 2030s, where high temperatures during anthesis are projected to cause a loss of £1.16 billion for wheat - equivalent to 59% of England's 2024 income from wheat, compared to the modelled annual average loss of £570 million.[68] This equates to £682.6 million more losses compared to the present day, or a 144% increase. In Scotland, the maximum projected annual losses are for barley – up to £144.4 million per year from high temperatures during anthesis, or 40% of the nation's 2024 income from barley.[69] Similarly, the maximum modelled loss for Northern Ireland is also for barley, costing up to £9.3 million per year. This is equivalent to 37% of Northern Ireland's 2023 income from barley.[69] In Wales, the highest losses are associated with parasite infections in lambs, costing the nation £26.1million per year in the 2030s (8% of the 2024 agricultural income from sheep in Wales [69]), a 12% increase from present day losses.

Table 16 compares the projected annual economic losses from the specific temperature-related (heat) risks, both the averages and maximums modelled, against observed annual income variations for all agricultural sub-components in the study. In England, the average £570 million per year modelled loss is equivalent to up to 7% of historical, average annual variation of combined wheat, barley, oat, lamb, dairy, and egg farming income, more than double the modelled losses at present day. However, these losses are within the standard deviation of variability of observed historic income trends, indicating that while significant, they are not unprecedented in the context of long-term variability. When assessing the projected maximum annual losses, all still fall within the standard deviation of historic income trends, except for England. In this case, projected cereal crop losses drive the figure to significantly exceed the standard deviation (maximum projected annual loss of £2.131 billion). Maximum annual losses modelled are also significant in Scotland, equivalent to 15% of the nation's average annual income from cereals, milk, eggs, and lambs combined.

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[68] Department for Environment, Food & Rural Affairs (DEFRA). (2025) Total income from farming in England in 2024. GOV.UK. Available at: https://www.gov.uk/government/statistics/total-income-from-farming-in-england/total-income-from-farming-in-england-in-2024#section-5---about-these-statistics (Accessed: 11 September 2025).

[69] Total income from farming across the devolved administrations, expressed in 2024 prices. Time periods for average figures include 2005-2024 (England and Scotland), 2015-2024 (Wales), 2018-2023 (NI). Sourced from official statistics from Defra, Scottish Government, Welsh Government, and Daera.

Table 16. Projected annual economic losses versus annual income from farming for modelled sub-components, by nation

	England	Scotland	Wales	Northern Ireland
Observed Annual Income				
Average annual income from cereals, milk, eggs and lambs*	£8,035 million	£1,402 million	£1,120 million	£1,234 million
Standard deviation*	£1,424 million	£266 million	£128 million	£216 million
Modelled Losses				
Modelled average annual economic losses from cereals, milk, eggs and lambs (high climate scenario)	*£570 million*	*£41 million*	*£28 million*	*£8 million*
Modelled losses as a percentage of regional output (income)	*7.1%*	*2.9%*	*2.5%*	*0.6%*

**Category classifications differ slightly across the Devolved Administrations. Expressed in 2024 prices. Time periods for average figures include 2005-2024 (England and Scotland), 2015-2024 (Wales), 2018-2023 (NI). Sourced from official statistics from Defra, Scottish Government, Welsh Government, and Daera.*
*** Largest modelled annual losses from present day through the 2050s (BAU, high climate scenario). Assumes modelled thresholds for each sub-component are all breached in one year, thus impacting all components (high temperatures during spring affecting cereal crop yields, overall higher average temperatures affecting parasite outbreaks in lambs, high temperatures throughout the year affecting milk and egg production).*

Overall, uncertainty in future climate trajectories poses a significant risk to the agricultural sector. Risks associated with rising temperatures alone, including plant and animal heat stress and parasite outbreaks, could triple annual economic losses in the UK from the 2030s onwards. This uncertainty makes assessing the appropriate level of adaptation a question of risk management (i.e., balancing probabilities of different outcomes) rather than simply optimizing against a known set of economic losses.

Task 2.2 - Adaptation Options

Overview

The overall approach to collating and considering adaptation measures that could potentially address the heat risks determined in Task 2.1 is outlined below.

1. **Development of a longlist**

   An initial longlist of >80 adaptation options was developed through literature review, specialist input, and consultation with the CCC and the stakeholder group (Appendix C - Adaptation longlist). This list was consolidated to remove duplicate measures and those which did not specifically address heat-related risks (Appendix D - Excluded adaptation options). The consolidated longlist was then filtered to retain measures that could be applied across the whole cohort of heat-impacted sub-components. Measures that could form part of a future national adaptation response, but required location-specific insights, regulatory change, field trials or other enabling activity were excluded from the list, since detailed data on their feasibilities or efficacies were limited. Examples include moving crop cultivation to north-facing (cooler) sites or substitution with alternative crops (Appendix E - Deprioritised adaptation options). The final longlist of 30 measures was passed forward for shortlisting.

2. **Shortlisting via Multi-Criteria Analysis**

   A qualitative multi-criteria analysis (MCA) was conducted to shortlist adaptation options. Core criteria included cost, risk reduction, scale of applicability / implementation potential, potential to support nature / deliver ecosystem service co-benefits, and potential to address climate risks beyond heat (such as drought and waterlogging). The MCA criteria were agreed with the CCC project team and Adaptation Committee, and weighted to favour cost-effective measures – i.e., those considered to have lower costs and higher risk reduction potential.

   The resulting ranked list of measures fell into two groups - those scoring 1.9 and above (22 measures) and those scoring 1.8 and below (8 measures). The latter were retained for narrative discussion (and are listed in Appendix E - Deprioritised adaptation options) but excluded from subsequent quantification and modelling. The ranked measures were shared with the SSG to test whether they reflected their expert understanding, and to consider whether any key measures had been overlooked. Due to a perceived initial bias towards rapidly implementable ‘grey’ or ‘infrastructure’ measures, the measures were also discussed with the CCC’s Adaptation Committee and refined to provide a final shortlist of 18 measures passed forwards for full, quantitative analysis. All excluded measures were retained for narrative discussion.

3. **Appraisal of Costs and Benefits**

   For each shortlisted option, data was collated on capital cost, operational cost, lifetime of measure, time for risk reduction (to commence, following implementation of the measure), the time taken for the adaptation measure to be implemented, risk reduction (i.e., extent to which the measure could reduce the modelled economic losses), consequential losses (such as land taken out of cropping to allow wetland to be created), carbon and nature co-impacts (including carbon emissions / sequestration and ecosystem services). The extent to which any measure was already likely to exist in the landscape (such as hedgerows) and the maximum extent to which any measure was likely to be adopted (uptake) were also captured for subsequent modelling. All assumptions and sources were logged (see Appendix F - Adaptation measure assumptions and data sources).

The full longlist of all considered adaptation measures is provided in Appendix C - Adaptation longlist. The consolidated longlist passed forward for scoring and ranking in the multi-criteria analysis is set out in Table 17.

Table 17. Consolidated longlist of adaptation measures, including the component (of the farmed landscape) and specific hazard they are intended to address, together with a brief description

Component	Hazard	Brief description of adapt option	Source
Cereals	Heat stress	Agroforestry to provide shade for crops (i.e. silvo-arable e.g., alley cropping)	ADAS & Met Office, 2023a[70]
Dairy cattle	Heat stress	Agroforestry to provide shade for livestock (i.e. silvo-pasture) - planting may be linear or grouped	ADAS & Met Office, 2023a[70]
Hens and cattle	Heat stress	Adopt diurnal (daytime) and/or summer housing	ADAS & Met Office, 2023a[70]
Lambs	Temperatures conducive to parasite outbreaks	Increase pest and disease surveillance	ADAS & Met Office, 2023a[70]
Cereals	Heat stress	Increase application of trace elements like calcium	ADAS & Met Office, 2023a[70]
Cereals	Heat stress	Increase diversity of cultivars in terms of maturity and resistance	ADAS & Met Office, 2023a[70]
All livestock	Heat stress	Install in-field shelters/tents (semi-permanent)	ADAS & Met Office, 2023a[70]
Dairy cattle	Heat stress	Use different breeds of livestock that are more resilient to hotter/drier conditions	ADAS & Met Office, 2023a[70]
Cereals	Heat stress	Grow heat tolerant and drought resistant varieties (crops/forage)	ADAS & Met Office, 2023a[70]
Cereals	Heat stress	Use genetically engineered or genetically modified crops	ADAS & Met Office, 2023a[70]
Hens and cattle	Heat stress	Use genetically engineered or genetically modified livestock breeds	ADAS & Met Office, 2023a[70]
Laying hens	Heat stress	Use different breeds of poultry that are more resilient to hotter/drier conditions	ADAS & Met Office, 2023a[70]
Lambs	Temperatures conducive to parasite outbreaks	Alter lambing schedule to benefit from warming temperatures and longer growing season i.e. earlier lambing	ADAS & Met Office, 2023b[71]
Lambs	Temperatures conducive to parasite outbreaks	Increase biosecurity measures in livestock housing to guard against the spread of new diseases	ADAS & Met Office, 2023[71]
Lambs	Temperatures conducive to parasite outbreaks	Vaccinate livestock against new and prevalent diseases	ADAS & Met Office, 2023[71]
Lambs	Temperatures conducive to parasite outbreaks	Manage the grazing behaviour of host livestock to limit parasite spread, for example moving animals to 'safe' grazing areas	Jones et al., 2020[72]

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[70] Defra.gov.uk. (2026). Science Search. [online] Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796

[71] Defra.gov.uk. (2026). Science Search. [online] Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21797

[72] Jones, L., et al (2020). Climate driven threshold effects in the natural environment. Report to the Climate Change Committee. May 2020

Component	Hazard	Brief description of adapt option	Source
Cereals	Heat stress	Conduct transformative adaptation, whereby the land is taken out of cereal production and instead use this for woodland or wetland as a means of carbon storage / nature benefit	Jones et al., 2020[72]
Dairy cattle	Heat stress	House cows inside all year round, include fans and sprinklers	Jones et al., 2020[72]
Dairy cattle	Heat stress	Provide extra forage to stock during cooler times, to help compensate for reduced feeding activity in the heat of the day	AHDB, 2015[73]
Dairy cattle	Heat stress	Offer housing as shade - covering or painting over translucent roof sheets in a shed can dramatically help to reduce the temperature.	AHDB, n.d.[74]
Dairy cattle	Heat stress	Minimise standing time in the parlour - this is where many cows accumulate heat, so splitting milking groups in half will reduce. Increased space and fans in the collecting yard for increased air movement around cows.	AHDB, n.d.[74]
Dairy cattle	Heat stress	Diet adjustments to mitigate impacts of heat stress, increasing fat and decreasing fibre intake	Henry et al., 2018[75]
Dairy cattle	Heat stress	Wet the dairy yard for an hour before cows arrive	Dairy Australia, 2023[76]
Dairy cattle	Heat stress	Sprinkle cows for 30-60 minutes while standing in the dairy yard waiting for afternoon milking	Dairy Australia, 2023[77]
Cereals	Heat stress	Crop insurance	Zhao et al., 2022[78]
Lambs	Temperatures conducive to parasite outbreaks	Launch regional risk forecasting systems to provide advanced warning of *Haemonchus* outbreaks in sheep, giving farmers time to implement treatments	Skuce et al., 2014[79]
Laying hens	Heat stress	Lights can be turned on for an hour or two at midnight and feeders run to encourage hens to eat during a cooler time of day	Hendrix Genetics, 2021[80]
All livestock	Heat stress	Insurance against losses	Howden, 2025[81]
Cereals	Heat stress	The relationship between soil moisture and air temperature means that (in theory) measures to improve soil water holding capacity such as added organic matter may reduce air temperatures above those soils	Petch et al., 2020[82] Liu & Pu, 2019[83]
Cereals and livestock	Heat stress	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits	Ampatzidis, Cintolesi & Kershaw, 2023[84] Froglife, 2022[85]

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[73] AHDB Beef and Lamb (n.d.). Managing cattle and sheep during extreme weather events. Available at: https://projectblue.blob.core.windows.net/media/Default/Imported%20Publica20tion%20Docs/BRP-Managing-cattle-and-sheep-during-extreme-weather-events-1.pdf

[74] AHDB (n.d.). Heat stress and foot health | AHDB. [online] Available at: https://ahdb.org.uk/heat-stress-and-foot-health.

[75] Henry, B.K., Eckard, R.J. and Beauchemin, K.A. (2018). Review: Adaptation of ruminant livestock production systems to climate changes. animal, 12(s2), pp.s445–s456. doi:https://doi.org/10.1017/s1751731118001301.

[76] Dairy Australia (2023). Cool Cows - Strategies for managing heat stress in dairy cows.

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[78] Zhao, J et al. (2022). Priority for climate adaptation measures in European crop production systems. European Journal of Agronomy, 138, p.126516. doi:https://doi.org/10.1016/j.eja.2022.126516.

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Multi-criteria analysis (MCA)

The longlist of adaptation options was ranked using a qualitative MCA (multi-criteria analysis). Criteria and weightings were agreed through discussion with the CCC project team and are listed in Table 18 with the MCA presented in Table 19, and resulting ranked list in Table 20. Stakeholders were consulted on the composition of this list.

Table 18. Ranking criteria, with weightings

Criteria	Weighting (%)	Score (High; Medium; Low)
Cost	30	H = 1; M = 2; L = 3
Risk reduction ("effectiveness")	30	H = 3; M = 2; L = 1
Implementation potential	10	H = 3; M = 2; L = 1
Potential to provide nature co-benefits	20	H = 3; M = 2; L = 1
Potential to address climate impacts other than those caused by heat	10	H = 3; M = 2; L = 1

Table 19. MCA (multi-criteria analysis)

Component	Adaptation Option Description	Cost	Risk Reduction	Implementation potential	Nature	Potential to address other impacts	Final weighted score
Cereals	Silvo-arable approach	Medium	Medium	Medium	High	High	2.3
Dairy cattle	Silvo-pastoral approach	Medium	Medium	Medium	High	High	2.3
Hens and cattle	Daytime (climate controlled) housing	Medium	Medium	Medium	Medium	Low	1.9
Lambs	Increased pest and disease surveillance	Low	Low	High	Low	Medium	1.9
Cereals	Trace element supplementation	High	Low	High	Low	Medium	1.3
Cereals	Increased diversity of cultivars	Low	Medium	High	Medium	High	2.5
All livestock	Install in-field shelters	Medium	High	Medium	Low	Low	2
Dairy cattle	Use tolerant breeds	Medium	High	Medium	Low	Medium	2.1
Cereals	Use tolerant cultivars	Medium	High	High	Low	Medium	2.2
Cereals	Use Genetically Engineered or Genetically Modified crops	High	High	Medium	Low	High	1.9

Component	Adaptation Option Description	Cost	Risk Reduction	Implementation potential	Nature	Potential to address other impacts	Final weighted score
Hens and cattle	Use Genetically Engineered or Genetically Modified livestock breeds	High	High	Medium	Low	High	1.9
Laying hens	Use tolerant breeds	Low	High	Medium	Low	Medium	2.4
Lambs	Earlier lambing	Low	Low	Medium	Medium	Low	1.9
Lambs	Increase biosecurity measures	Medium	Medium	High	Medium	Medium	2.1
Lambs	Vaccinate livestock	Low	High	High	Medium	Medium	2.7
Lambs	Rotational grazing to avoid parasites	Low	Medium	Medium	High	High	2.6
Cereals	Take land out of production and convert for woodland, wetland or wildflowers	High	High	Medium	High	High	2.3
Dairy cattle	House cows inside	High	High	Medium	Low	High	1.9
Dairy cattle	Alter feeding schedules to coincide with cooler times	Medium	Medium	High	Low	Low	1.8
Dairy cattle	Offer housing as shade	Medium	High	Medium	Low	Low	2
Dairy cattle	Minimise standing time in the parlour	Low	Low	High	Low	Low	1.8
Dairy cattle	Adjust diets to mitigate impacts of heat stress	Medium	Medium	High	Low	Low	1.8
Dairy cattle	Wet the dairy yard before cattle arrive	Low	Low	High	Low	Low	1.8
Dairy cattle	Sprinkle cattle while standing in the dairy yard awaiting milking	Low	Low	High	Low	Low	1.8
Cereals	Crop insurance	High	High	High	Low	High	2
Lambs	Launch regional risk forecasting systems to provide advanced warning of parasite outbreaks	Medium	Medium	Medium	Low	Low	1.7
Laying hens	Midnight feeding to address daytime deficiencies	Low	Low	Medium	Low	Low	1.7
All livestock	Insurance against losses	High	High	High	Low	High	2
Cereals	Improve soil water holding characteristics	Medium	Medium	High	High	High	2.4
Cereals and livestock	Re-wet landscapes through installation of ponds, to deliver a cooling effect	High	High	Medium	High	High	2.3

Table 20. Ranked longlist of adaptation measures

Component	Description of adaptation option	Ranking
Lambs	Vaccinate livestock against new and prevalent diseases	1
Lambs	Manage the grazing behaviour of host livestock to limit parasite spread, for example moving animals to ‘safe’ grazing areas	2
Cereals	Increase diversity of cultivars in terms of maturity and resistance	3
Cereals	Increase soil water holding capacity to evaporatively cool air above	4
Laying hens	Use different breeds of poultry that are more resilient to hotter/drier conditions	5
Cereals	Use alley cropping to provide shade for crops (silvo-arable)	6=
Dairy cattle	Plant trees in pasture to provide shade for livestock (silvo-pasture)	6=
Cereals	Conduct transformative adaptation, whereby the land is taken out of cereal production and instead use this for woodland or wetland as a means of carbon storage / nature benefit	6=
Cereals and livestock	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits	6=
Cereals	Grow heat tolerant varieties (crops/forage)	10
All livestock	Use different breeds of livestock that are more resilient to hotter conditions	11=
Lambs	Increase biosecurity measures in livestock housing to guard against the spread of new diseases	11=
All livestock	Install in-field shelters/tents (semi-permanent)	13=
Dairy cattle	Upgrade winter housing to provide summer shading	13=
Cereals	Insurance against losses	13=
All livestock	Insurance against losses	13=
Hens and cattle	Adopt diurnal (daytime) and/or summer housing	17=
Lambs	Increase pest and disease surveillance	17=
Cereals	Use Genetically Engineered or Genetically Modified crops	17=
Hens and cattle	Use Genetically Engineered or Genetically Modified livestock breeds	17=
Lambs	Bring forward lambing dates	17=
Dairy cattle	House cows inside all year round, include fans and sprinklers	17=
Dairy cattle	Provide extra forage to stock during cooler times, to help compensate for reduced feeding activity in the heat of the day	23=
Dairy cattle	Minimise standing time in the parlour, provide more space and install misting fans in the collecting yard	23=
Dairy cattle	Adjust diets to mitigate impacts of heat stress, increasing fat and decreasing fibre intake	23=
Dairy cattle	Wet the collecting yard for an hour before cows arrive	23=
Dairy cattle	Sprinkle cows while standing in the collecting yard ahead of afternoon milking	23=
Lambs	Launch regional risk forecasting systems to provide advanced warning of *Haemonchus* outbreaks in sheep, giving farmers time to implement treatments	28=

Component	Description of adaptation option	Ranking
Laying hens	Implement midnight feeding to encourage feed intake during cooler period of the day	28=
Cereals	Increase application of trace elements such as calcium to enhance heat tolerance	30

Developing a shortlist of adaptation options

Based on the qualitative scorings, lower ranking options from the MCA were excluded from further analysis, as listed in Table 21. Their rankings reflect a combination of factors, including lack of nature-related co-benefits and inapplicability to address other climate impacts.

Table 21. Lower ranking adaptation options

Component	Description of adaptation option
Dairy cattle	Provide extra forage to stock during cooler times, to help compensate for reduced feeding activity in the heat of the day
Dairy cattle	Minimise standing time in the parlour, provide more space and install misting fans in the collecting yard
Dairy cattle	Adjust diets to mitigate impacts of heat stress, increasing fat and decreasing fibre intake
Dairy cattle	Wet the collecting yard for an hour before cows arrive
Dairy cattle	Sprinkle cows while standing in the collecting yard ahead of afternoon milking
Lambs	Launch regional risk forecasting systems to provide advanced warning of *Haemonchus* outbreaks in sheep, giving farmers time to implement treatments
Laying hens	Implement midnight feeding to encourage feed intake during cooler period of the day
Cereals	Increase application of trace elements such as calcium to enhance heat tolerance

Other options were then removed for a range of reasons, as set out in Table 22.

Table 22. Screened options

Component	Description of adaptation option	Reasons for screening
Cereals	Increase diversity of cultivars in terms of maturity and resistance	Lack of confidence in the effectiveness of this measure due to lack of evidence for UK-relevant studies into cereal cultivars capable of tolerating the modelled high temperatures during flowering.
Cereals	Grow heat tolerant varieties (crops/forage)	*ibid*
All livestock	Use different breeds of livestock that are more resilient to hotter conditions	Lack of confidence in the effectiveness of this measure due to lack of evidence for UK-relevant studies into livestock breeds capable of tolerating the modelled high temperatures.
Laying hens	Use different breeds of poultry that are more resilient to hotter/drier conditions	*ibid*
Cereals	Insurance against losses	Insurance is available (to cover losses due to productivity shortfalls or specific climate events)

Component	Description of adaptation option	Reasons for screening
		but in contrast to other adaptation options, insurance does not seek to address the modelled climate risks in the field (or at the landscape scale).
All livestock	Insurance against losses	*ibid*
Lambs	Increase pest and disease surveillance	Surveillance is already in place for *Haemonchus* and other relevant pests. Its practical implementation on farm is represented by the 'biosecurity' measure, which was taken forward for modelling.
Cereals	Use Genetically Engineered or Genetically Modified crops	These are not currently permitted for use in the UK, and there was also a lack of confidence that breeding / engineering programmes were underway that might meet the specific needs of the UK due to the modelled climate impacts. It was considered extremely unlikely that engineered or modified organisms would be available within the 25 year period considered in this project.
Hens and cattle	Use Genetically Engineered or Genetically Modified livestock breeds	*Ibid*
Lambs	Bring forward lambing dates	There is known to be little immunity to *Haemonchus* in lambs (and even sheep are susceptible to high doses), meaning that changes to lambing dates were thought to be extremely unlikely to moderate the modelled risks from this organism.
Dairy cattle	House cows inside all year round, include fans and sprinklers	The landscape focus of the project meant that housed / intensive livestock were out of scope. An option to upgrade winter housing to accommodate cattle during peak summer temperatures was taken forward for modelling.

Finally, 'mirror' options were added to address risks to related components. For example, the use of silvo-pastoral systems to provide shading to grazing dairy cattle had been considered – but not the use of the same system to provide shade to free range hens. Likewise, whilst the shading benefits of trees had been considered, the potential benefits of hedgerows had not. The final agreed shortlist of measures is set out in the next section.

Adaptation Shortlist

The final shortlist of adaptation measures to address modelled climate-related heat risks is set out in Table 23. To allow a final optimised package of measures to be derived from these options, benefit-cost profiles were developed for each (as described in *Task 2.3 - Final Adaptation Package*). The full dataset and accompanying sources and assumptions are provided in Appendix F - Adaptation measure assumptions and data sources, with key datapoints set out in Table 24. Key reference resources included:

- The Andersons Centre (2023). John Nix farm Pocketbook for Farm Management, 2024. 54th edition[86]
- Soil Association (2019). The Agroforestry Handbook[87]
- Organic Research Centre (2023). Agroforestry and Orchards Pilot[88]
- Defra (2024). 30by30 policy papers[89]
- Defra (2025). Enabling a Natural Capital Approach (ENCA)[90]

Table 23. Final shortlist of adaptation measures to address climate-related heat risks

Component	Adaptation measure
Cereals	Alley cropping to provide cooling via shade (silvo-arable)
Cereals	Improve soil water holding capacity through a combination of the following measures: Cover cropping; Min-till; Crop rotation; Controlled Traffic Farming; Organic matter additions
Cereals	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits
Dairy cattle	Silvo-pasture to provide shade for livestock - planting trees
Dairy cattle	Silvo-pasture to provide shade for livestock - planting hedgerows
Dairy cattle	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits
Dairy cattle	House cows inside during hot periods, using winter housing facilities which have been suitably upgraded to deliver required shade and cooling
Dairy cattle	Install in-field shelters (semi-permanent) to provide shade
Laying hens	Silvo-pasture to provide shade for livestock - planting trees
Laying hens	Silvo-pasture to provide shade for livestock - planting hedgerows
Laying hens	House hens inside during hot weather. Upgrade nighttime housing to include fans + high-pressure fogging, and paint roof with reflective paint
Laying hens	Install in-field shelters (semi-permanent) to provide shade

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[86] Superseded by the 55th and 56th Editions. https://theandersonscentre.co.uk/shop/john-nix-pocketbook-56/

[87] Raskin, B. and Osborn, S. eds., (2019). The Agroforestry Handbook: Agroforestry for the UK. [online] FarmPEP. Available at: https://farmpep.net/sites/default/files/2024-01/the-agroforestry-handbook.pdf.

[88] Agroforestry and Orchards Pilot| SUMMARY REPORT -AUGUST 2023. (2023). [online] Organic Research Centre. Available at: https://www.organicresearchcentre.com/wp-content/uploads/2023/12/Agroforestry-and-Orchards-Pilot-Final-Report-V5.pdf.

[89] DEFRA (2024). 30by30 on land in England: confirmed criteria and next steps. [online] GOV.UK. Available at: https://www.gov.uk/government/publications/criteria-for-30by30-on-land-in-england/30by30-on-land-in-england-confirmed-criteria-and-next-steps.

[90] DEFRA (2020). Enabling a Natural Capital Approach (ENCA). [online] GOV.UK. Available at: https://www.gov.uk/guidance/enabling-a-natural-capital-approach-enca

Component	Adaptation measure
Lambs	Increase biosecurity measures on farms to guard against the import and/or spread of *Haemonchus contortus*
Lambs	Vaccinate lambs against *Haemonchus contortus*
Lambs	Deploy rotational grazing with appropriate layoff intervals to ensure demise of *Haemonchus contortus*

Table 24. Key data for economic modelling. The full dataset with assumptions and sources is set out in Appendix F - Adaptation measure assumptions and data sources.

Number	Component	Adaptation Option Description	Capex	Opex	Carbon value	Nature value	Time for risk reduction	Risk Reduction (%)	Lifetime of measure	Maximum Uptake Rate by 2050 (% of impacted component across the UK)
2	Cereals	Alley cropping to provide cooling via shade (silvo-arable)	£1,250 / ha	£75.00 / ha / yr	£272.80 / ha / yr	£66.90 / ha /yr	15 years	10%	50 years	40%
3a	Dairy cattle	Silvo-pasture to provide shade for livestock - planting trees	£875 / cow	£37.50 / cow / yr	£136.40 / cow / yr	£33.45 / cow / yr	15 years	35%	50 years	30%
3b	Dairy cattle	Silvo-pasture to provide shade for livestock - planting hedgerows	£4,500 / cow	£10.00 / cow / yr	£7.92 / cow / yr	£20.90 / cow / yr	5 years	35%	50 years	75%
3c	Hens	Silvo-pasture to provide shade for livestock - planting trees	£0.70 / hen	£0.03 / hen / yr	£0.11 / hen / yr	£0.03 / hen / yr	10 years	35%	50 years	30%
3d	Hens	Silvo-pasture to provide shade for livestock - planting hedgerows	£3.60 / hen	£0.01 / hen / yr	£0.01 / hen / yr	£0.02 / hen / yr	5 years	35%	50 years	75%
7a	Dairy cattle	House cows inside during hot periods, using winter housing facilities which have been suitably upgraded to deliver required shade and cooling	£200 / cow	£30.00 / cow / yr	-£0.62 / cow / yr	£0.00 / cow / yr	Immediate	10%	10 years	50%
7b	Hens	House hens inside during hot weather. Upgrade nighttime housing to include fans and high-pressure fogging, and paint roof with reflective paint	£2.47 / hen	£0.06 / hen / yr	-£0.01 / hen / yr	£0.00 / hen / yr	Immediate	60%	10 years	50%
29a	Dairy cattle	Install in-field shelters (semi-permanent) to provide shade	£770 / cow	£30.00 / cow / yr	-£3.19 / cow / yr	£0.00 / cow / yr	Immediate	10%	10 years	50%
29b	Hens	Install in-field shelters (semi-permanent) to provide shade	£1.00 / hen	£0.10 / cow / yr	£0.00 / hen / yr	£0.00 / hen / yr	Immediate	15%	8 years	50%
70	Lamb	Increase biosecurity measures on farms to guard against the import and/or spread of *Haemonchus contortus*	£5.00 / lamb	£1.00 / lamb / yr	£0.00 / lamb / yr	£0.00 / lamb / yr	Immediate	70%	1 year	90%
71	Lamb	Vaccinate lambs against *Haemonchus contortus*	£10.00 / lamb	£1.80 / lamb / yr	£0.00 / lamb / yr	£0.00 / lamb / yr	Immediate	80%	1 year	40%
74*	Lamb	Deploy rotational grazing with appropriate layoff intervals to ensure demise of *Haemonchus contortus*	£0.00 / lamb	£0.00 / lamb / yr	£1.76 / lamb / yr	£0.00 / lamb / yr	Immediate	60%	1 year	10%

Number	Component	Adaptation Option Description	Capex	Opex	Carbon value	Nature value	Time for risk reduction	Risk Reduction (%)	Lifetime of measure	Maximum Uptake Rate by 2050 (% of impacted component across the UK)
121	Cereals	Improve soil water holding capacity through a combination of the following measures: Cover cropping; Min-till; Crop rotation; Controlled Traffic Farming; Organic matter additions	£110 / ha	£56.00 / ha / yr	£176.00 / ha / yr	£2,195 / ha / yr	5 years	10%	1 year	70%
123A**	Cereals	Re-wet landscapes through installation of ponds, to deliver a cooling effect	£12,500 / ha	£140 / ha / yr	-£132.00 / ha / yr	£501.75 / ha / yr	5 years	15%	50 years	5%
123B**	Dairy cattle	Re-wet landscapes through installation of ponds, to deliver a cooling effect	£6,250 / cow	£70 / ha / yr	-£66.00 / cow / yr	£250.88 / cow / yr	5 years	15%	50 years	5%

*Consequential losses of 50% are also included as an operational cost due to loss of grazing area, required to ensure that lay-off periods are of sufficient duration to attenuate the parasite

**Consequential losses of 12.5% are also included as an operational cost due to loss of cropping / grazing areas, required to ensure that ponds are sufficiently large to deliver a cooling effect

Task 2.3 - Final Adaptation Package

Approach: Calculating Costs and Benefits

Using the shortlisted adaptation options, the team constructed and applied a final adaptation package out to the 2030s and 2050s. This aimed to minimise net costs while both maximising risk reduction and co-benefits. The assessment included model estimates of total adaptation investment required (capital and operational expenditures), residual climate risk impact, and total net benefit for each time period. Spatial variation was analysed and reported by nation.

The final adaptation package was initially conceived as ‘cost-optimal’, comprising only those measures determined to deliver positive benefit-cost ratios (BCRs). This approach was revised as a consequence of the cost-benefit analysis.

A three-step process was used to develop the BCRs for each measure:

1. Collating cost data;
2. Estimating economic benefits; and
3. Estimating carbon and nature-related (ecosystem services) co-benefits.

Step 1 involved first determining the costs for each of the shortlisted adaptation measures, out to 2059. This required, for each adaptation measure:

- The per-unit GBP values for capital expenditure (CAPEX) and operational expenditure (OPEX);
- The lifetime of the adaptation (in years);
- The baseline uptake (% of those hectares or numbers of livestock where climate modelling indicated a loss due to heat impact), reflecting the pre-existence of trees and hedgerows within the current landscape;
- The potential maximum uptake or adoption that could be reached (%);
- The start year of the adaptation; and
- The number of years taken to reach the potential uptake percentage.

These parameters were then used to generate the phasing of CAPEX and OPEX for each adaptation measure for two periods: between 2025 and 2039, and between 2025 and 2059. Once phased, the CAPEX and OPEX values were multiplied by the hectarage value (for cereals) and the number of livestock (for hens, dairy cattle and lambs) for the UK and each nation.

The dataset was then discounted according to HM Treasury Green Book guidelines.[91] The Green Book supplementary guidance recommends that costs and benefits occurring in the first 30 years of a programme, project or policy be discounted at an annual rate of 3.5% and recommends a schedule of

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[91] HM Treasury (2022). The Green Book. [online] GOV.UK. Available at: https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-government/the-green-book-2020

declining discount rates thereafter. To evaluate the impact of the adaptation measure, we assessed costs and benefits over a time-horizon extending to 2059. In line with the Green Book, a standard discount rate of 3.0% has been applied beyond the first 30 years of the programme.

Step 2 calculated the economic benefits of each measure by using the economic loss data to identify GBP losses for each component (across cereals and livestock). These were then disaggregated by land use scenario, climate scenario and geography (UK and nation). The economic losses were then adjusted to account for: the baseline uptake (%), phasing according to the profile of reaching the potential uptake rate (%), and risk reduction (% effectiveness of the adaptation measure). These varied according to the characteristics of each adaptation measure and yielded the dataset for the reduction in economic losses. The effectiveness of each adaptation measure in reducing the modelled economic losses was used to determine the economic benefit of that measure (i.e. the economic benefits are avoided losses).

Step 3 involved determining both carbon and nature-related benefits. Ecosystem services associated with each adaptation measure were set out. Assumptions were applied to derive the co-benefits on a ‘per hectare’ basis. Ecosystem services were then linked to monetary values. To derive climate mitigation / carbon co-benefits, monetary values were derived by calculating carbon dioxide sequestered (or emitted) per year and carbon market values. To derive nature-related co-benefits, the ecosystem services were mapped and then valued (in £ per unit) by drawing on multiple data sources (see Appendix F - Adaptation measure assumptions and data sources for detail).

A profile for aggregated economic benefits (losses avoided) and climate- and nature-related co-benefits was then generated, noting the phasing of when benefits are realised during each period (2025-2039, and 2025-2059). The phasing of benefits and co-benefits was determined by the time taken to implement the adaptation, the time taken for the risk reduction to be achieved, and the year when the potential uptake percentage is fully reached. Finally, the dataset for benefits and co-benefits was discounted according to HM Treasury Green Book guidelines, as above.

Having derived cost and benefit data series for each adaptation measure, benefit-cost ratios were calculated. A series of further refinements was then implemented to develop a final package of measures that was inputted into the full cost-benefit analysis model used to calculate NPVs (Net Present Value) and other key outputs. These are set out in the following sections.

Assumptions and Limitations

In order to build and run the model, numerous assumptions had to be made. The critical assumptions related to the functionality and results of the modelling are captured here.

Costs and Benefits of Each Adaptation Measure and Related Phasing

Per-unit costs and benefits were held constant across the UK and devolved administrations, and across scenarios. More detailed modelling would account for regional variations in per-unit monetary costs and benefits. However, variation in total costs and benefits per measure varied by nation, simply reflecting the extent of the impacted hectarage/impacted livestock in each area.

The phasing of CAPEX costs per adaptation measure is a function of the lifetime of the adaptation measure. If the lifetime of the adaptation measure comes to an end within the 2025-2059 time period, the

CAPEX cost is incurred again in the first year after the lifetime of the measure has ended. For the following adaptation measures this occurs every year:

- Adaptation 70: Increase biosecurity measures on sheep farms to guard against the import and/or spread of *Haemonchus contortus* outbreaks in lambs;
- Adaptation 71: Vaccinate lambs against *Haemonchus contortus*; and
- Adaptation 121: Use a combination of practices to improve soil water holding capacity (and quality) to provide a cooling effect.

The benefit of economic losses avoided per adaptation measure varies by scenario in line with the modelled economic loss data – the ‘effectiveness’ of each measure being a fixed percentage by which the economic losses are reduced. The nature- and carbon-related co-benefits begin in the same year as the effectiveness begins. The co-benefits “switch on” immediately at a defined point for each measure in the model, rather than accumulating as they mature – reflecting the core economic approach. For example, hedgerows are considered to become effective five years after establishment, while trees (for shading cattle) are considered to become effective after 15 years. In these instances the co-benefits ‘switch on’ after five and fifteen years, respectively.

Uptake rates

Baseline uptake rates and maximum potential uptake rates, meaning the percentage of affected animals or crop hectarage that would benefit from adoption of the adaptation measures, were estimated for each measure using available data and expert judgement. Annual potential uptake rates were calculated based on the uptake rate from the preceding year and the rate was increased until reaching the estimated maximum potential uptake.

Consequential losses

For some adaptation measures, consequential losses were considered in terms of the opportunity cost of land initially occupied by the agricultural component (cereals and/or livestock) now being used for other purposes under additional adaptation measures, or more of an existing adaptation measure being implemented. This was factored in as part of the calculation of economic losses avoided per adaptation measure.

It was assumed that the proportion of land occupied by trees and hedgerows would not have a negative effect on underlying productivity from that land due to the anticipated improved growing conditions as a result of introduction of the measure. No consequential losses were assumed for these measures. By contrast, a consequential loss value was applied to ponds installed to provide a cooling effect. This reflects the significant area required for these ponds and the resulting area taken out of production.

Effectiveness of risk reduction

The degree to which the adaptation measures reduce the hazard identified and modelled in project Task 2.1 could not be established from primary data, since specific quantifiable studies on the causal effectiveness of adaptations are rare. Most of the data relied on studies of relative reduction of the symptoms of “heat stress” to be used as a proxy for risk reduction in this analysis. In addition, while significant effort was made to identify UK (or UK-relevant) field studies, some of the input data were derived from in-field trials in other geographies, laboratory experiments or computational models.

Risk reduction was also considered to be cumulative, with the adaptation measures designed to be stacked. This means that the same modelled area accommodates multiple adaptations if impacted crops or livestock are present in that geographic area. Thus, the effectiveness of the measures is assumed to be additive. However, even in aggregate, the combined effectiveness of risk reduction for any crop or livestock type does not reach 100% due to the relative efficacy of the individual measures. It is also noteworthy that the risk reduction rate is fixed regardless of uptake rate or devolved administration.

Converting between livestock numbers and land area

In many cases, it was necessary to convert units between areas and livestock numbers, to ensure internal modelling consistency and to facilitate like-for-like comparisons between adaptation measures. To facilitate this, livestock / area conversion factors were used, as listed in Table 25.

Table 25. Area to livestock conversion assumptions

Component	Number per hectare	Source
Dairy Cattle	2	Natural England[92]
Hens	2,500	Animal and Plant Health Agency[93]
Lambs	15	Department of Agriculture, Environment and Rural Affairs[94]

Approach: Calculating Carbon and Nature-Related (Ecosystem Service) Co-Benefits

The following section provides detail on specific aspects of the applied methodology underlying the calculation of ecosystem services (and carbon) co-benefits as a proxy for ‘nature’. The objective was to identify the key ecosystem service benefits provided by each of the shortlisted adaptation measures, quantify them using nationally applicable biophysical proxy values (expressed on a per-hectare or per-year basis), and, where possible, assign corresponding monetary values in accordance with HM Treasury’s Green Book and Defra’s Enabling a Natural Capital Approach (ENCA) guidance.[95]

Given the national scale of assessment and the absence of site-specific data (such as the spatial extent of habitats, linear features, or management intensity), the analysis is indicative in nature and provides relative comparisons of ecosystem service materiality rather than absolute financial valuations. The approach is consistent with Defra’s ENCA principles, which encourage the use of nationally available proxy data to inform strategic decision-making in the absence of detailed spatial evidence.

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[92] Natural England Research Report NERR030| Grazing livestock in the lowlands Context. (n.d.). Available at: https://publications.naturalengland.org.uk/file/62085

[93] EMR01 Guidance on legislation covering the marketing of eggs. (2025). [online] Animal and Plant Health Agency. Available at: https://assets.publishing.service.gov.uk/media/684ff1b99d538361ad2da713/EMR01_Guidance_on_legislation_covering_the_marketing_of_eggs.pdf.

[94] Suggests up to 15 ewes per hectare, substituted with lambs for modelling purposes. https://www.daera-ni.gov.uk/news/boosting-flock-performance

[95] DEFRA (2020). Enabling a Natural Capital Approach (ENCA). [online] GOV.UK. Available at: https://www.gov.uk/guidance/enabling-a-natural-capital-approach-enca.

The analytical process follows the structure of the UK's natural capital accounting framework as adopted by the Office for National Statistics (ONS) and Defra. It proceeds through a series of logical steps linking land management interventions to natural capital assets, ecosystem service flows, and their potential economic values. The key steps to calculating these co-benefits are as follows:

1. Identification of Adaptation Measure and Associated Habitat Type
2. Mapping of Ecosystem Services
3. Selection of Biophysical Proxies
4. Application of Monetary Valuation

In Step 1, each adaptation measure was first linked to the most representative habitat or natural capital asset type based on its dominant biophysical characteristics. These associations provide the baseline for linking measures to relevant ecosystem service flows as defined under ENCA. The biophysical and monetary values applied in this assessment are derived from recognised national datasets and peer-reviewed literature and are representative of individual habitat types rather than mixed or transitional land-use systems. This approach ensures that the values used reflect the intrinsic ecosystem service delivery capacity of each habitat type (e.g., broadleaved woodland, wetland, grassland, or scrub) as defined under ENCA's framework. It also maintains consistency with the valuation evidence base published by the Office for National Statistics (ONS), Defra, and Forest Research, which typically report ecosystem service flows and economic values by habitat class.

Where an adaptation measure involves multiple habitat types or land covers, such as an agroforestry system, the associated ecosystem service benefits should therefore be interpreted as representative of the natural capital contribution of the relevant habitat element (e.g., woodland strips or hedgerows) rather than the total area of managed farmland. This distinction avoids double-counting of services and ensures that the proxy values remain aligned with the Green Book principle of proportional and evidence-based valuation.

In Step 2, Ecosystem services were selected from Defra's ENCA typology. From the full ENCA service list, a subset of ecosystem services (a maximum of 7) were scoped in for appraisal, based on: relevance to agricultural land management and climate adaptation functions; strength and consistency of available evidence linking each habitat to a measurable or monetisable service; coverage within national datasets (e.g., ONS, Defra, Forest Research); and materiality in terms of potential contribution to resilience, productivity, and public goods. The ecosystem services for appraisal therefore included:

- Carbon sequestration and storage;
- Flood regulation;
- Soil erosion control;
- Air quality regulation;
- Water regulation (infiltration and retention); and
- Water quality (nutrient and sediment retention).

In Step 3, typical annual biophysical values were assigned to each service using national-scale datasets and peer-reviewed literature. These included, for example, tonnes of carbon dioxide equivalent (tCO_2e) sequestered per hectare per year, cubic metres of water retained per hectare per event, and estimated soil loss avoided per hectare per year. The selected proxies represent average conditions for the relevant habitat types and are suitable for strategic appraisal.

Finally, in Step 4, biophysical values were translated into indicative monetary terms where nationally recognised valuation data were available. Data and sources are set out in Appendix G - Ecosystem services mapping).

Assumptions and Limitations

The analysis is based on several assumptions. First, all values are normalised to a per-hectare, per-year basis to enable comparison between adaptation measures. Habitat typologies are treated as representative averages for the relevant measure and are not site-specific. Biophysical and monetary values are assumed to represent steady-state annual conditions and do not incorporate temporal lag effects associated with habitat establishment or maturation. Ecosystem service values are treated as additive for scoping purposes, although in practice there may be overlaps between co-benefits (for example, between soil retention and carbon storage). All biophysical and monetary data are derived from UK-based studies and are considered nationally applicable, but they do not account for regional variations in soil type, rainfall, or management regime.

The modelling of co-benefits also comes with several limitations. The absence of spatial data prevents calculation of total ecosystem service benefits at site or regional level. Local variations in land management, soil structure, vegetation age, and hydrology can significantly influence actual service delivery. The synergies or trade-offs between adaptation measures are not explicitly modelled. Finally, monetary values are sensitive to future updates in carbon pricing and other economic assumptions published by BEIS and Defra.

Ecosystem services provide the carbon and nature-proxy co-benefits that are quantified as inputs in the model. The economic value of these co-benefits is estimated on a per hectare basis, in line with available datasets. The data was derived from land uses, such as woodland and wetland, which indirectly describe some of the proposed adaptation measures. Given than the adaptation measures will, with the exception of the transformation measures, not result in the complete conversion of impacted farmland to (for example) woodland or wetland, it was therefore necessary to convert the per hectare ecosystem services values to "per unit of measure" values. It was agreed, with expert input, that ecosystem services values could be used in this way for a project of this nature. For example, a proportion of a field planted with rows of trees as an alley cropping measure could be aggregated as a "woodland" and the values applied proportionately to the tree areas. The conversion figures are based on data presented in Table 26 and Table 27:

- Silvo-arable: Multiply area-based value by 15% to provide the measure-based value
- Hedgerows: Multiply area-based value by 5% to provide the measure-based value
- Cooling ponds: Multiply area-based value by 12.5% to provide the measure-based value

For co-benefits, each monetary value for carbon and ecosystem services was further adjusted depending on whether the adaptation related to cereals, lambs, cattle and hens. The assumptions made to standardise these units were: 2 cows per hectare; 15 lambs per hectare; and 2,500 hens per hectare (as set out in Table 25).

Table 26. Field occupation % compared to tree spacing

Tree Row Spacing: silvo-arable	Tree Row Width (assumed)	% of Field Occupied by Trees	Source
10 m spacing	4 m	40%	Agroforestry Research Trust[96]
20 m spacing	4 m	20%	DeepRoots Agroforestry[97]
24 m spacing	4 m	16.70%	Woodland Trust[98]
30 m spacing	4 m	13.30%	Forest Research[99]

Table 27. Field occupation % compared to tree layout

Tree Layout / Spacing: silvo-pastoral	% of Field Occupied by Trees	Source
10 × 10 m grid spacing	10%	Agroforestry Research Trust[100]
Cluster planting or scattered trees	Variable (10-35%) depending on density and canopy cover	Forest Research[99]
Maximum sustainable canopy cover	35% (beyond which forage production declines)	Agroforestry Research Trust[100]

Table 28 presents the maximum crop hectarage / number of impacted livestock in the UK and in each of the devolved areas. These data from the climate risk modelling represent the areas which should benefit from adaptation (once livestock numbers are converted to an area basis – see Table 25).

Table 28. Maximum impacted areas of cereals and impacted numbers of livestock at UK and DA levels (high climate scenario). DA numbers may not sum at UK level, due to rounding

Devolved Authority	Component	**Number of impacted livestock/ hectarage** (rounded)
UK	Cereals	1,350,000
UK	Lambs	16,640,000
UK	Dairy Cattle	1,900,000
UK	Hens	30,100,000
England	Cereals	1,240,000

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[96] Agroforestry UK (n.d.). Silvoarable – The Agroforestry Research Trust. [online] Available at: https://www.agroforestry.co.uk/about-agroforestry/silvoarable/

[97] DeepRoots. (2019). Agroforestry knowledge hub. [online] Available at: https://www.deeproots.ag/learn.

[98] Woodlandtrust.org.uk. (2025). Silvoarable systems. [online] Available at: https://www.woodlandtrust.org.uk/plant-trees/agroforestry-benefits/silvoarable-systems/.

[99] Forest Research. (2025). Agroforestry - Forest Research. [online] Available at: https://www.forestresearch.gov.uk/climate-change/carbon/agroforestry/.

[100] Forest Reasearch. (n.d.). Silvopasture – The Agroforestry Research Trust. [online] Available at: https://www.agroforestry.co.uk/about-agroforestry/silvopasture/.

Devolved Authority	**Component**	**Number of impacted livestock/ hectarage** (rounded)
England	Lambs	7,300,000
England	Dairy Cattle	1,070,000
England	Hens	17,940,000
Wales	Cereals	14,100
Wales	Lambs	4,590,000
Wales	Dairy Cattle	300,000
Wales	Hens	2,590,000
Scotland	Cereals	87,300
Scotland	Lambs	3,350,000
Scotland	Dairy Cattle	202,000
Scotland	Hens	3,420,000
NI	Cereals	3,700
NI	Lambs	1,400,000
NI	Dairy Cattle	325,000
NI	Hens	6,440,000

The final adaptation package

Using the approaches described in the previous sections, the Benefit-Cost Ratios were calculated for each of the shortlisted adaptation measures, at Devolved Administration and UK level, for each of the three land use scenarios, both Central and High climate scenarios, and both time periods (2025 to 2039 and 2025 to 2059). Results for the UK under the BAU: high climate scenario between 2025 and 2059 are shown in Table 29. Two versions of the BCRs are shown, one which includes the economic benefits only (i.e., the avoided losses from implementation of each measure) and one which combines the carbon and ecosystem service values with the avoided loss values.

Table 29. Shortlisted adaptation measures including benefit-cost ratios (BCRs). Derived from a UK-level analysis under the BAU: High climate scenario out to the 2050s, using discounted economic data

Sub-Component	**Adaptation measure**	**BCR (economic benefits only)**	**BCR (carbon + ecosystem + economic benefits)**
Cereals	Alley cropping to provide cooling via shade (silvo-arable)	0.11	1.07
Cereals	This measure improves soil water holding capacity to provide a cooling effect and combines: Cover cropping; Min-till; Crop rotation; Controlled Traffic Farming; Organic matter additions	0.18	11.2

Sub-Component	Adaptation measure	BCR (economic benefits only)	BCR (carbon + ecosystem + economic benefits)
Cereals	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits	0.05	0.40
Lambs	Increase biosecurity measures on farms to guard against the import and/or spread of *Haemonchus contortus*	0.29	0.29
Lambs	Vaccinate lambs against *Haemonchus contortus*	0.33	0.33
Lambs	Deploy rotational grazing with appropriate layoff intervals to ensure demise of *Haemonchus contortus*	0.00	0.01
Dairy cattle	Silvo-pasture to provide shade for cattle – planting trees	0.00	0.80
Dairy cattle	Silvo-pasture to provide shade for cattle – planting hedgerows	0.00	0.08
Dairy cattle	House cows inside during hot periods, using winter housing facilities which have been suitably upgraded to deliver required shade and cooling	0.18	-1.47
Dairy cattle	Install in-field shelters/tents (semi-permanent) to provide shade	0.00	-0.03
Dairy cattle	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits	0.00	0.32
Laying hens	Silvo-pasture to provide shade for hens – planting trees	0.01	1.10
Laying hens	Silvo-pasture to provide shade for hens – planting hedgerows	0.00	0.08
Laying hens	House hens inside during hot weather. Upgrade nighttime housing to include fans + high-pressure fogging, and paint roof with reflective paint	0.00	0.00
Laying hens	Install in-field shelters/tents (semi-permanent) for free range hens to provide shade	0.00	0.00

Unless the values for carbon and ecosystem services are included, no measure returns a BCR >1. Once carbon and ecosystem service values are included, then a small number of measures return a BCR >1 (alley cropping for cereals, planting trees for hens and soil water holding measures for cereals). This combination of three measures would (strictly) comprise a ‘cost-optimal’ package of measures. However, this would omit any measures for risk reduction in dairy cattle and lambs. In discussion with the CCC team, the ‘nature-neutral’ options (temporary field shelters and indoor housing) were omitted, as were the particularly poorly performing rotational grazing approach to *Haemonchus* control, along with measures relying on hedgerows for shading / cooling. This produced a final compromise package of eight measures which explore the use of trees (to shade crops, dairy cattle and free range hens), the use of large ponds to provide cooling for cereals and dairy cattle, biosecurity and vaccination for lambs – and a combination of measures to improve soil water holding capacity (also to deliver a cooling effect) (Table 30).

Table 30. The final package of adaptation measures

Sub-Component	**Adaptation measure**
Cereals	Alley cropping to provide cooling via shade (silvo-arable)
Cereals	This measure improves soil water holding capacity to provide a cooling effect and combines: Cover cropping; Min-till; Crop rotation; Controlled Traffic Farming; Organic matter additions
Cereals	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits
Lambs	Increase biosecurity measures on farms to guard against the import and/or spread of *Haemonchus contortus*
Lambs	Vaccinate lambs against *Haemonchus contortus*
Dairy cattle	Silvo-pasture to provide shade for cattle – planting trees
Dairy cattle	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits
Laying hens	Silvo-pasture to provide shade for hens – planting trees

The performance of this package was modelled across six distinct land-use and climate scenarios[101]:

- BAU – Central
- BAU – High
- CB7a – Central
- CB7a – High
- CB7b – Central
- CB7b – High

Each scenario was assessed over three timeframes: Present Day (~2024), the 2030s, and the 2050s – with an additional average value calculated across the periods. Various model parameters were then altered to explore a series of 'sensitivity' analyses (see *Task 2.4 - Sensitivity Analysis).*

Results

As described above, the performance of the adaptation package was modelled across six land-use and climate scenarios and timeframes. The results consider the economic loss from the modelled heat-related climate hazards, and the residual loss remaining after adaptation. They also consider the total economic

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[101] Detail on the assumptions behind BAU, CB7a and CB7b is set out in *Land use scenarios*, while detail on the assumptions behind Central and High is set out in *Climate scenarios*

costs and net benefits of adaptation. All calculations represented in the figures are based on undiscounted costs and benefits unless noted as Net Present Values (NPV).

Economic Losses Without Adaptation (also referred to as no additional adaptation)

Across all scenarios, the economic losses in the absence of adaptation measures are substantial and increase over time. In the BAU: Central scenario, losses increase from the Present Day through the 2030s and into the 2050s, reflecting the escalating impact of climate hazards. The BAU: High scenario shows an even steeper increase, indicating that higher climate hazard assumptions significantly amplify economic vulnerability. Similar patterns are evident under the other land use scenarios (Table 31).

These findings confirm that without intervention, economic losses due to climate hazards will continue to grow, placing increasing strain on the UK’s agricultural sector.

Table 31. Annual average economic losses (undiscounted) under different land use and climate scenarios

Scenario	2024 (Present day)	2030s	2050s
BAU: Central	£168,297,451	£188,772,059	£274,613,635
BAU: High	£168,297,451	£491,620,215	£586,565,379
CB7a: Central	£168,297,451	£176,613,401	£240,632,721
CB7a: High	£168,297,451	£462,500,935	£529,178,514
CB7b: Central	£168,297,451	£182,952,284	£272,068,525
CB7b: High	£168,297,451	£489,004,110	£598,731,462

Economic Losses with Adaptation

When adaptation measures are implemented, the economic losses are notably reduced across all scenarios and timeframes. Table 32 sets out the annual average losses following the implementation of the adaptation package, while the calculated reduction in economics losses due to the adaptation package are listed in Table 33. These are the ‘economic benefits’. Initially there is no benefit, as the adaptations have not been implemented in 2024, but benefits increase over time as the nature-based adaptation measures become effective. For example, under the BAU: Central scenario, the adaptation package delivers an annual average benefit of £16.9 million in the 2030s, but this increases to £52.4 million in the 2050s. Likewise under the CB7b: High scenario the adaptation package delivers an annual average benefit of £24.1 million in the 2030s, increasing to £70.1 million in the 2050s.

Table 32. Annual average economic losses (undiscounted) under different land use and climate scenarios – following adaptation

Scenario	2024 (Present day)	2030s	2050s
BAU: Central	£168,297,451	£171,838,620	£222,174,849

Scenario	2024 (Present day)	2030s	2050s
BAU: High	£168,297,451	£464,801,288	£507,085,734
CB7a: Central	£168,297,451	£162,322,076	£201,760,280
CB7a: High	£168,297,451	£439,117,769	£465,156,129
CB7b: Central	£168,297,451	£168,478,867	£230,429,635
CB7b: High	£168,297,451	£464,903,606	£528,588,131

Table 33. Calculated reductions in losses as a result of the adaptation package (annual averages: undiscounted)

Scenario	2024 (Present day)	2030s	2050s
BAU: Central	£0	£16,933,439	£52,438,786
BAU: High	£0	£26,818,927	£79,479,645
CB7a: Central	£0	£14,291,325	£38,872,441
CB7a: High	£0	£23,383,166	£64,022,385
CB7b: Central	£0	£14,473,417	£41,638,890
CB7b: High	£0	£24,100,504	£70,143,332

Overall, the data illustrates that adaptation measures are partly effective at curbing economic losses, particularly when implemented early and maintained over time. However, significant residual risk will remain.

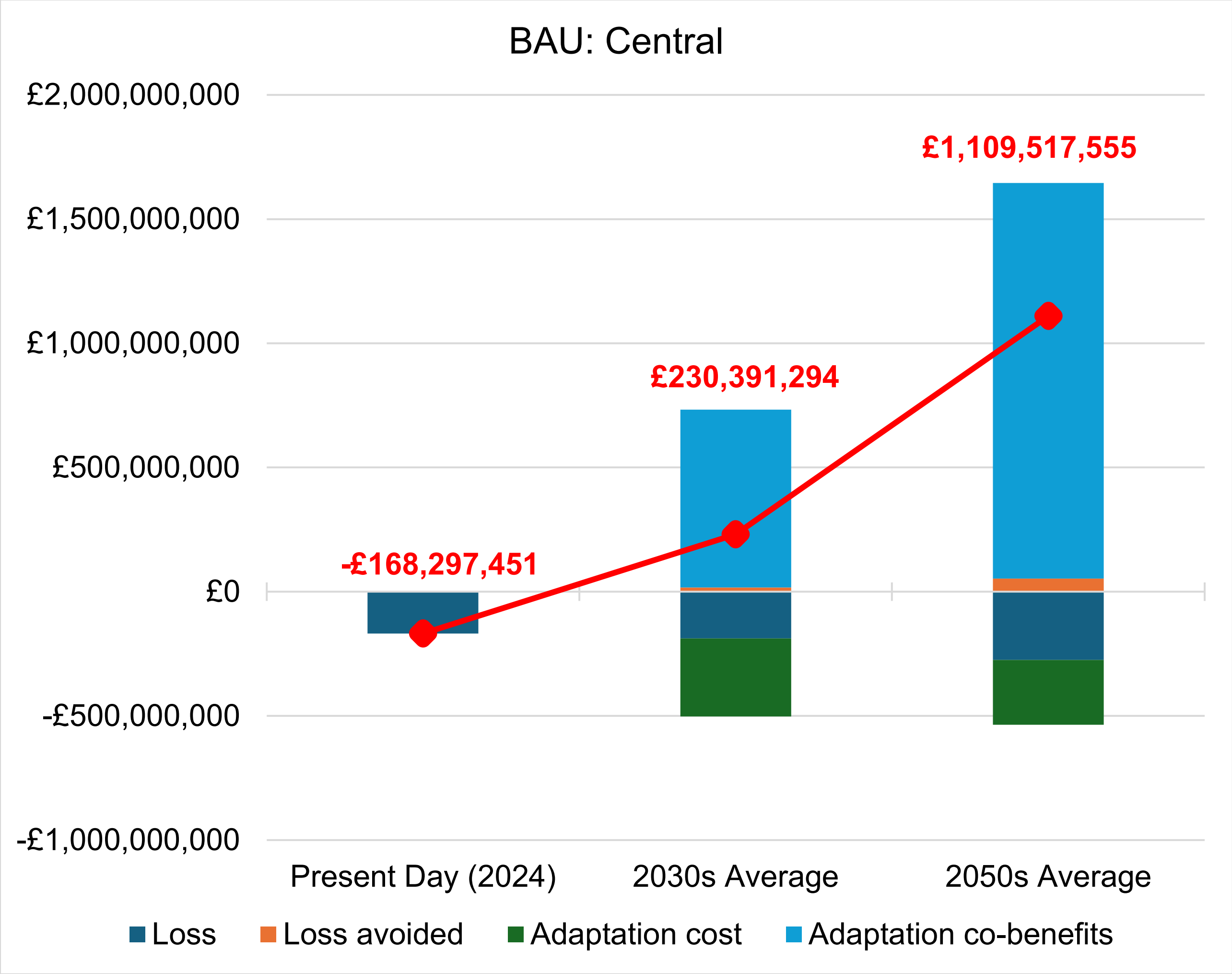
Total Costs and Benefits

Including the adaptation costs (CAPEX and OPEX) provides a more nuanced view of the financial implications of adaptation. The analysis included assessment of:

- Total Costs: Defined as the sum of average annual monetised economic loss and the Totex (CAPEX and OPEX) cost of adaptation;
- Net Benefits: Calculated as the sum of reduced economic loss following adaptation; and
- Total Net Benefits: The difference between total costs and total benefits including co-benefits from ecosystem services.

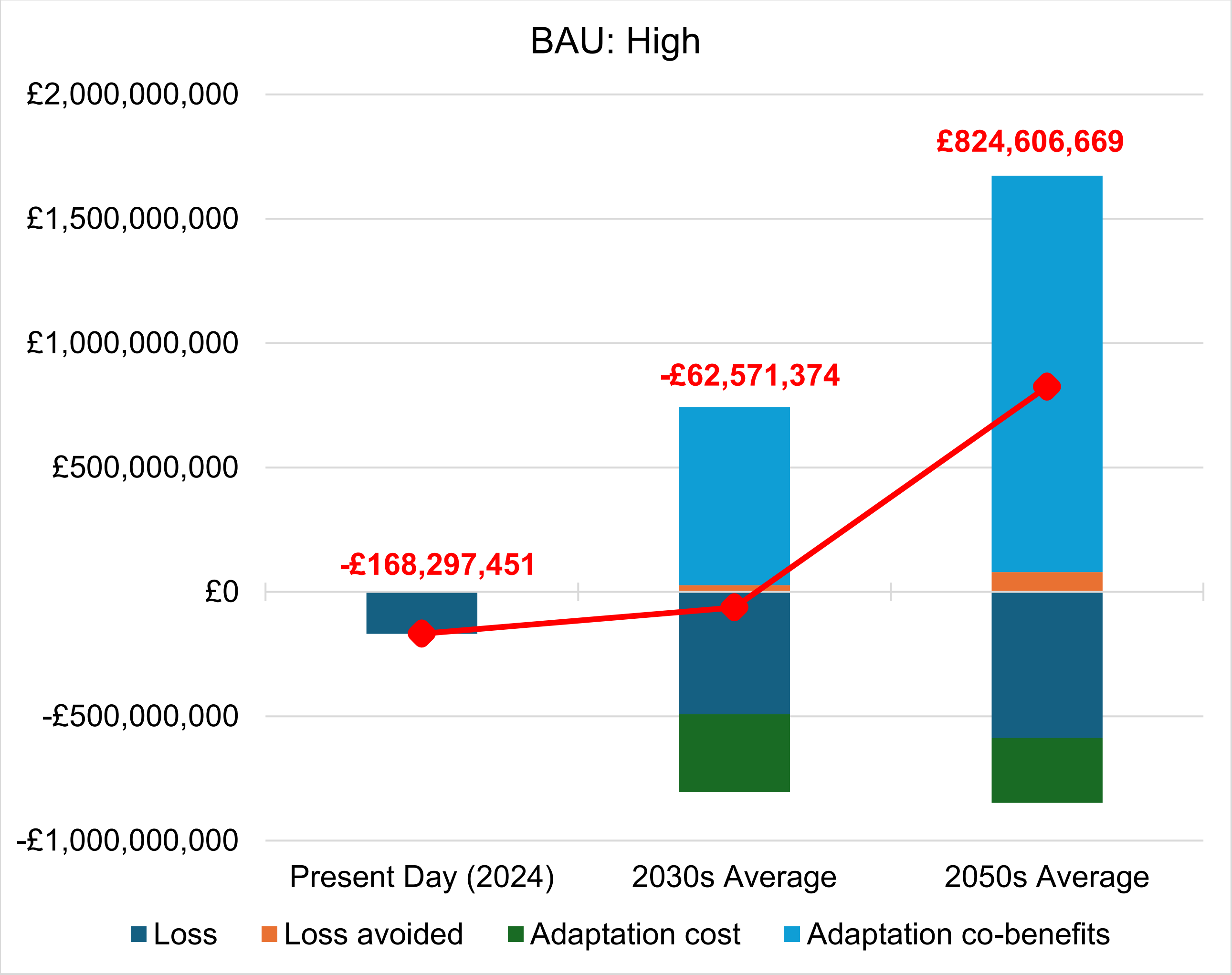
These different contributing factors are combined in Figure 18 and Figure 19, which capture the modelled economic losses, the costs of implementing the adaptation package to address those losses, the extent of the loss mitigation – and the co-benefits of adaptation in terms of carbon and ecosystem services. Overall, the economic losses due to the modelled heat impacts increase over time as the climate risks increase (dark blue bars). The costs of adaptation are greater in the 2030s than 2050s, since trees need to be planted in the 2030s (and 2040s) to 'become effective' at providing their adaptation services by the end of the 2050s (green bars). This need to await tree maturity is also responsible for the increased economic benefit over time due to adaptation (orange bars) – and underpins the increased carbon and ecosystem service benefits over time (light blue bars).

Figure 18. Annual average totals for Present Day, 2030s and 2050s under the BAU: Central scenario, combining modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦



When aggregated under the BAU: Central scenario, this means that the financial position moves from an initial annual loss of £168 million to an annual benefit of £230 million by the 2030s. This benefit increases to £1.1 billion by the 2050s. However, the driver behind these benefits is not the mitigated economic loss – it is the carbon and ecosystem service co-benefits (Figure 18). The same pattern is evident under the BAU: High scenario, but in this case the increased economic losses (due to higher climate risk) are not fully compensated for by the co-benefits in the 2030s – and not compensated for to such a degree by the 2050s (Figure 19).

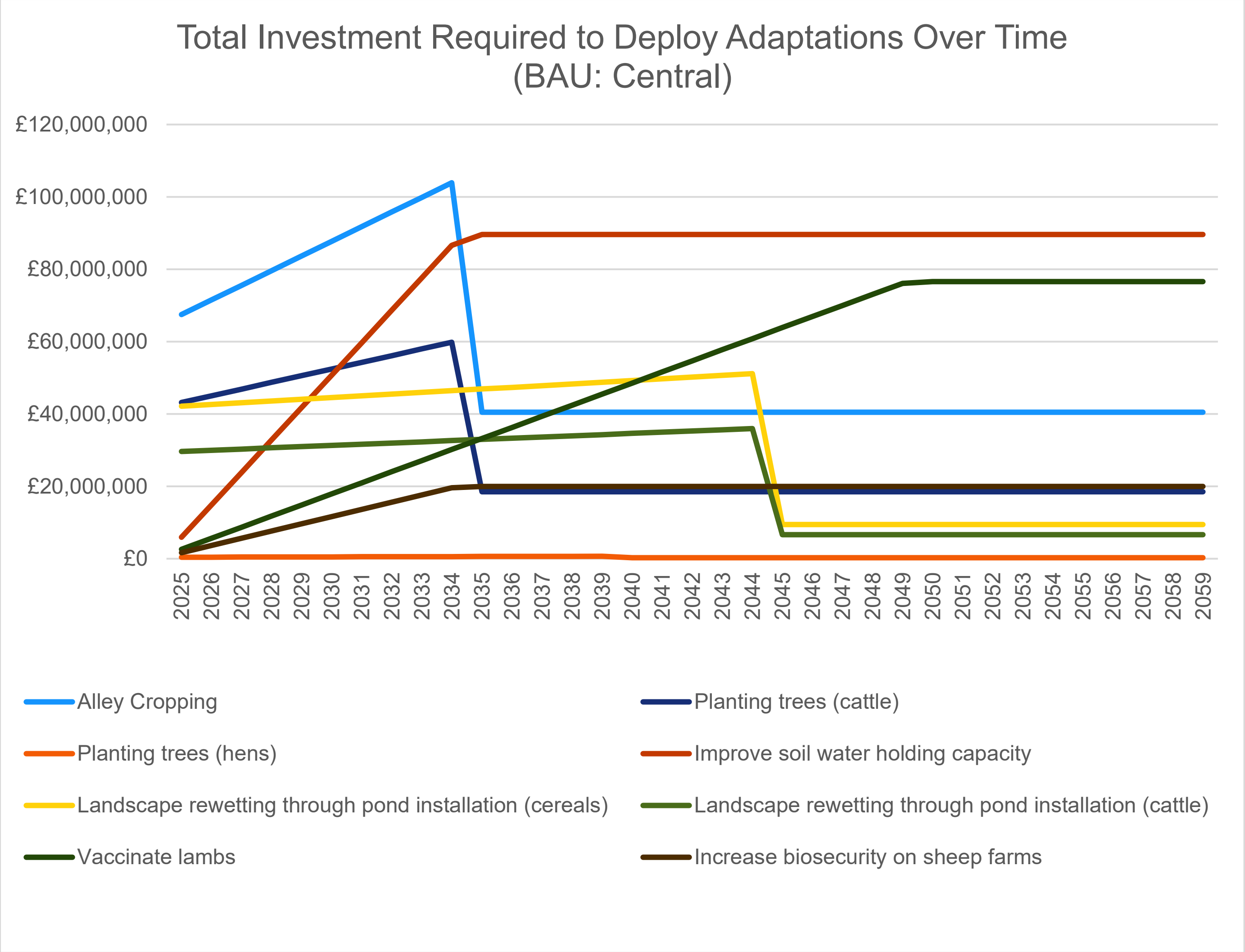
Figure 19. Annual average totals for Present Day, 2030s and 2050s under the BAU: High scenario, combining modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦



Adaptation contributions to the package of measures

The total investment required for each individual adaptation measure varies significantly over the period to 2059. Some measures, such as tree planting and pond installation, reach their maximum potential uptake and then have a relatively long lifetime. This means that once implemented, they require no further capital expenditure, leading to a substantial decline in costs. This can be seen in Figure 20 as sharp declines in total investment for some adaptation measures between 2034 and 2035, and 2044 and 2045. In contrast, other measures, such as enhancing biosecurity on sheep farms, vaccinating sheep, and improving soil water holding capacity, have a lifetime of measure equal to only one year – i.e. they require annual capital investment year-on-year. Their costs scale up until the modelled 'realistic' uptake of the measure is reached, after which they plateau.

Figure 20. Total Investment Required to Deploy Adaptations Over Time Across the UK (BAU: Central)



As for economic losses avoided (i.e. economic benefits), lamb vaccinations deliver the greatest risk reduction (80%) and deliver benefits immediately upon implementation. As shown in Figure 21, this measure generates the greatest annual avoided losses through to 2059. By 2059, the alley cropping measure also contributes significantly to avoided losses.

Figure 21. Avoided Cost of Climate Risk Over Time Across the UK (BAU: Central)

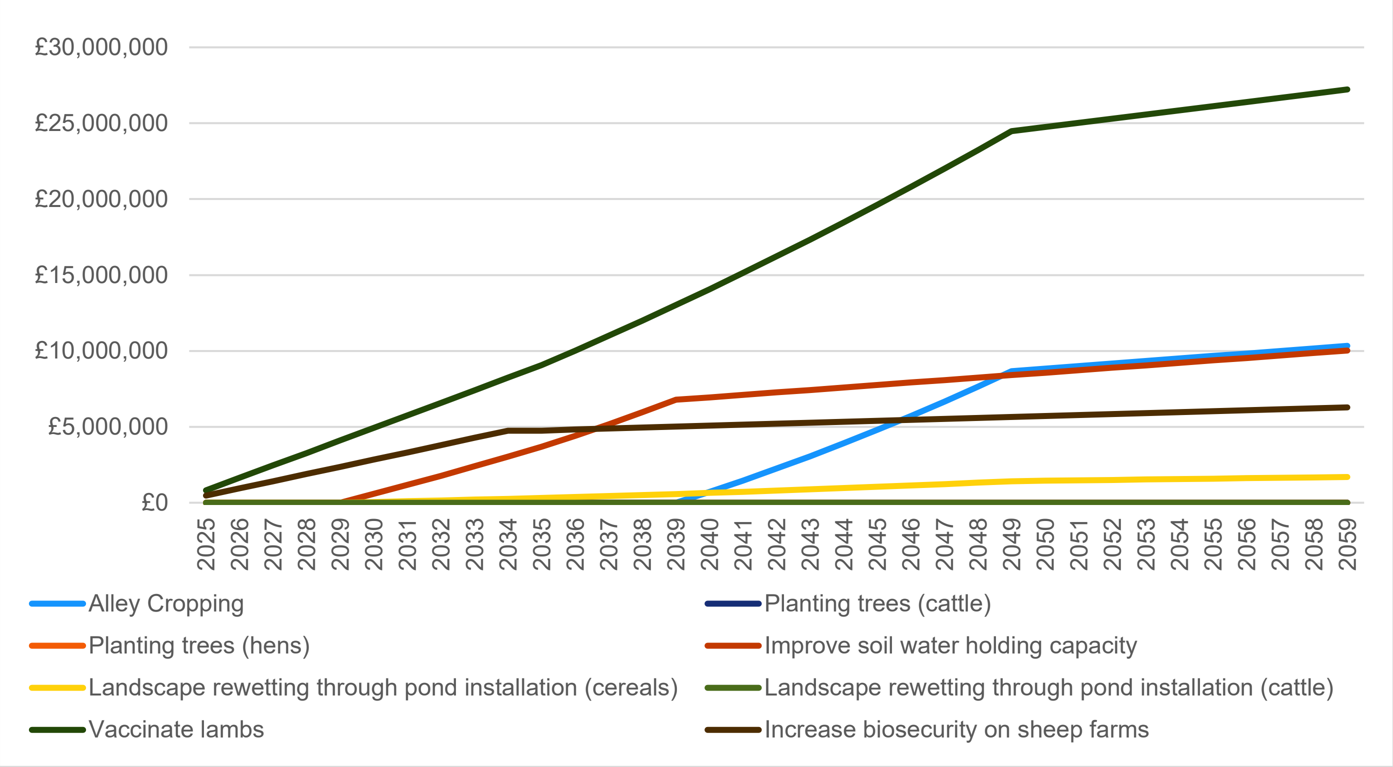


Figure 22 presents the total benefit from adaptation (avoided losses coupled with carbon and ecosystem services) for each adaptation measure over time. The benefits in this instance are dominated by the carbon and ecosystem services provided by the measure which improves soil water holding capacity, so the data for this measure have been excluded from Figure 23 to provide insights into the performance of the other measures. Notably, the monetary values of co-benefits associated with each adaptation are considerably larger than the direct losses avoided through the adaptations themselves, so the lamb vaccination measure (which delivers the largest avoided loss) does not deliver the largest overall benefit since it has no associated carbon or ecosystem service value (Appendix F - Adaptation measure assumptions and data sources). In terms of overall benefit, the measure focussed on soil water holding capacity dominates the results, followed by silvo-arable and silvo-pastoral measures.

Figure 22. Total benefit from each adaptation measure over time across the UK (includes avoided losses + co-benefits (carbon and ecosystem services; BAU: Central))

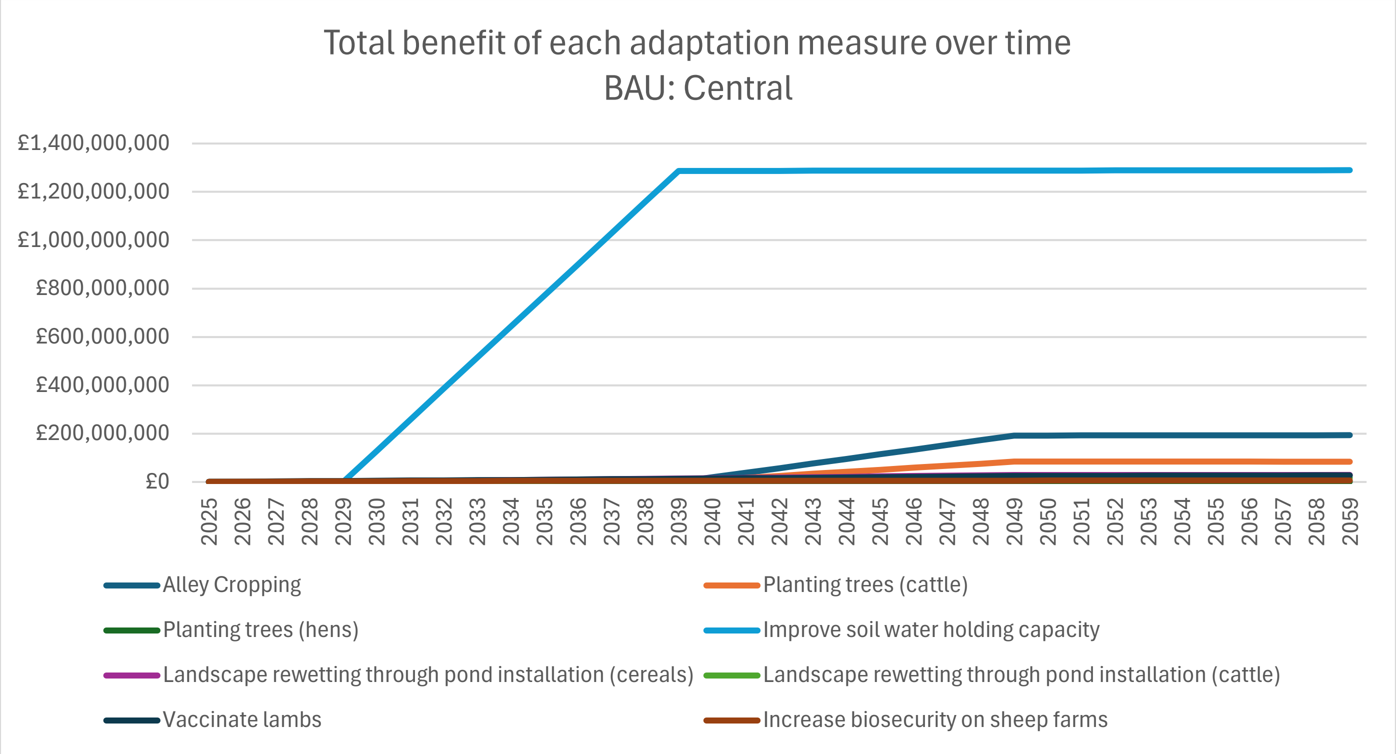
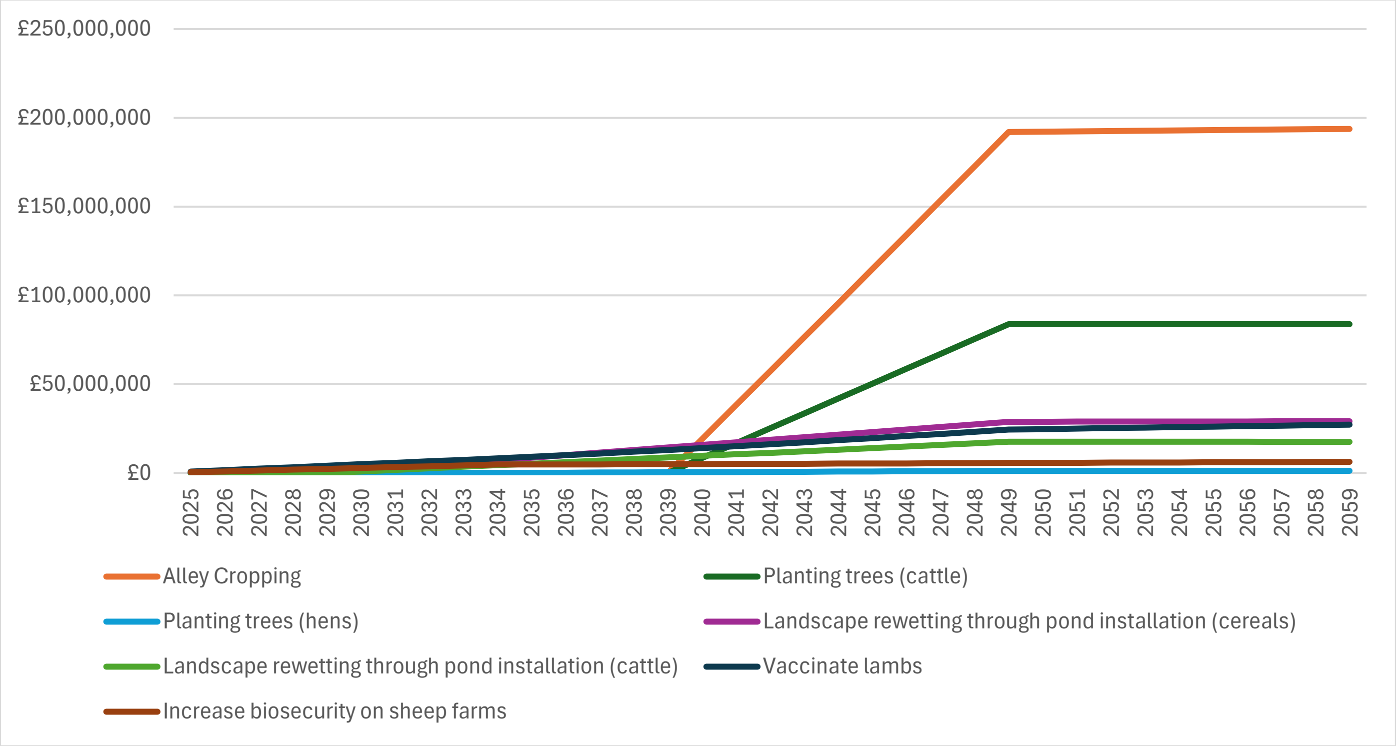


Figure 23. Total benefit from each adaptation measure over time across the UK (includes avoided losses + co-benefits (carbon and ecosystem services)). Excluding the measure focussed on soil water holding capacity (BAU: Central).



Contextualising the adaptation package results

In considering the annual Totex costs of the adaptation package, it is useful to contextualise the values relative to current schemes and sector output. For reference, the annual (average) adaptation costs across all land use and climate scenarios are the same (Table 34).

Table 34. Cost to implement the adaptation package (annual average basis: undiscounted UK data). Costs have been rounded, for clarity

Time period	Annual average cost
2024 (present day)	£0
2030s	£314 million
2050s	£262 million

The budget allocated to agri-environment schemes is shown in Table 35. Payments over this period represent a transitional phase between prior CAP (Common Agricultural Policy) funding and new UK schemes – agri-environment data for 2024 are aggregated for the UK at £1,121 million.[102] Compared with current agri-environment spend, the indicative adaptation costs are in the same order of magnitude.

Table 35. Spend on agri-environment schemes across England and the DAs between 2020 and 2023 (at current prices)

Year	England	Scotland	Wales	Northern Ireland	Source
2020	£136m	£12m	£44m	£4m	Farming in the UK 2020[103]
2021	£281m	£37m	£33m	£5m	Farming in the UK 2021[104]
2022	£286m	£24m	£41m	£6m	Farming in the UK 2022[105]
2023	£553m	£33m	£75m	£5m	Farming in the UK 2023[106]

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[102] DEFRA (2025). Agriculture in the United Kingdom 2024. [online] Available at: https://assets.publishing.service.gov.uk/media/6881de3ff47abf78ca1d35b0/agriculture-in-the-uk-2024.pdf.

[103] DEFRA (2021). Department for Environment, Food and Rural Affairs Department of Agriculture, Environment and Rural Affairs (Northern Ireland) Welsh Government, Knowledge and Analytical Services The Scottish Government, Rural and Environment Science and Analytical Services. [online] Available at: https://assets.publishing.service.gov.uk/media/6215ff49e90e0710b9a8bdff/AUK2020_22feb22.pdf.

[104] DEFRA (2021). Agriculture in the United Kingdom 2021.

[105] DEFRA (2022). Agriculture in the United Kingdom 2022. [online] Available at: https://assets.publishing.service.gov.uk/media/6548e4bc59b9f5000d85a2cc/auk-2022-13jul23ii.pdf.

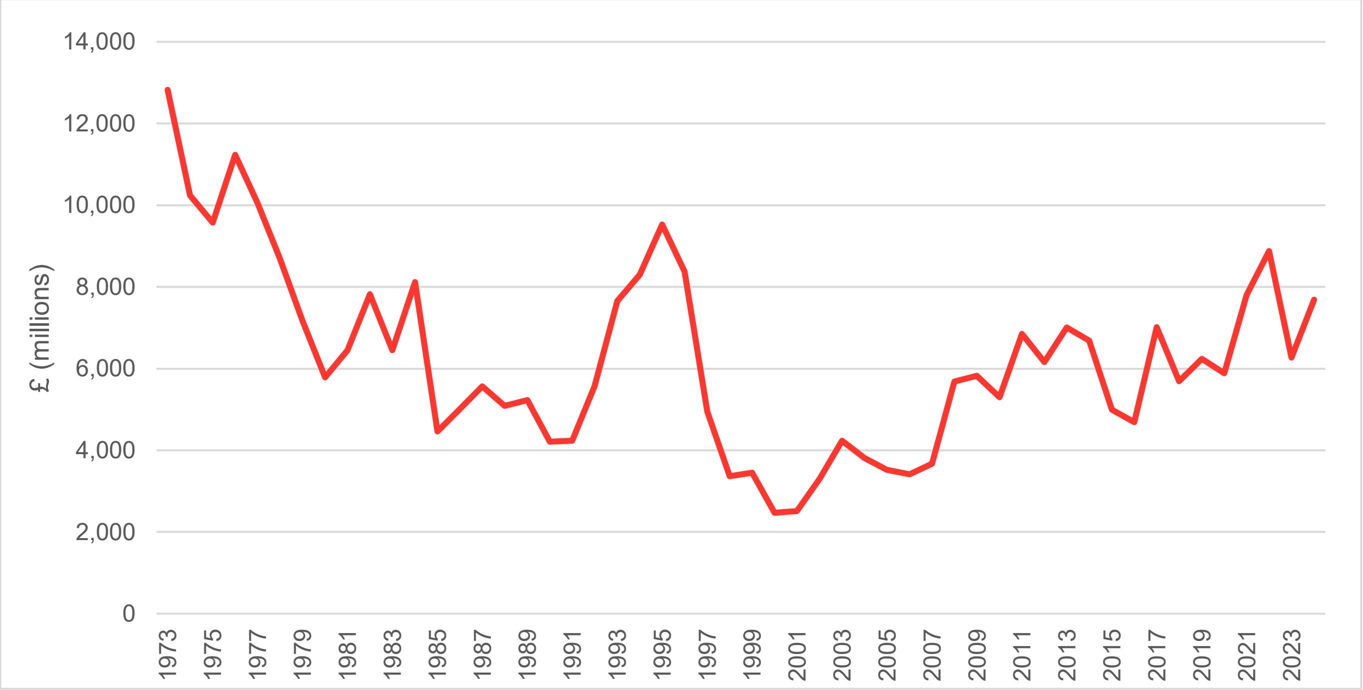
[106] DEFRA (2023). Agriculture in the United Kingdom 2023 . [online] Available at: https://assets.publishing.service.gov.uk/media/669e4777ab418ab055592a2c/auk-2023-06jun24iii.pdf.

The total income from farming (TIFF), including the full time series from 1973 to 2024, is provided in Figure 24. TIFF in 2024 was £7.69 billion. 2024 income data are not yet available for Northern Ireland, but 2023 TIFF for each DA are listed in Table 36. An indicative annual cost to adapt to the modelled, heat-impacted components is well within current agri-environment spend and would represent less than 4% of total income from farming.

Table 36. Total Income from Farming (TIFF) across Devolved Administrations for 2023 (corrected for 2024 pricing, and rounded)

Devolved Administration	2023 TIFF	Source
England	£4,500 million	Defra[107]
Scotland	£920 million	Scottish Government[108]
Wales	£450 million	Welsh Government[109]
Northern Ireland	£350 million	Daera[110]

Figure 24. Total Income from Farming in the UK (data in 2024 prices)



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[107] DEFRA (2019). Total income from farming in England. [online] GOV.UK. Available at: https://www.gov.uk/government/statistics/total-income-from-farming-in-england.

[108] The Scottish Government (2025). Total income from farming estimates: 2018-2024. [online] Gov.scot. Available at: https://www.gov.scot/publications/total-income-from-farming-estimates-2018-2024/documents/.

[109] Government of Wales (2025). Aggregate agricultural output and income: 2024 . [online] GOV.WALES. Available at: https://www.gov.wales/aggregate-agricultural-output-and-income-2024-html.

[110] DAERA (2023). Aggregate Agricultural Account 1981 onwards. [online] Department of Agriculture, Environment and Rural Affairs. Available at: https://www.daera-ni.gov.uk/publications/aggregate-agricultural-account-1981-onwards.

Land Use Scenario Results

The various contributing cost and benefit factors are combined in Figure 25 for the CB7a land use scenario under Central and High climate futures. Corresponding data for the CB7b land use scenario are captured in Figure 26. Overall, these show similar trends to the BAU (Business-as-Usual) scenarios in the core analysis described above.

Losses are higher in the 2050s than the 2030s due to higher heat-related climate impacts. These losses are marginally higher in the 2050s for the CB7b: High scenario when compared with the BAU: High scenario (average annual losses of £529 million as against £507 million), although this is not evident in the 2030s (£465 million in both cases), demonstrating the higher climate impact within a system that has a reduced productive land area – even though productivity within that area has increased. Side-by-side comparisons are facilitated by the data in Table 31.

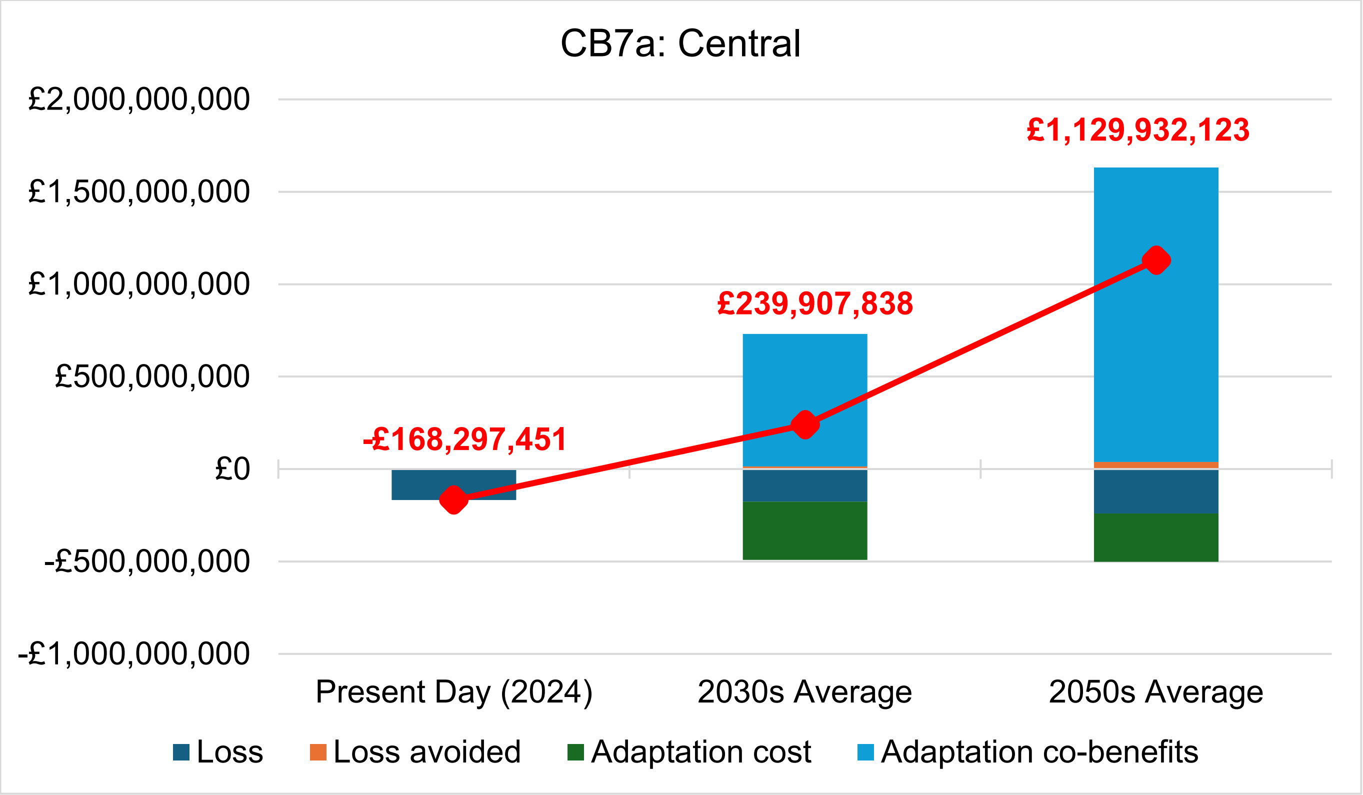
Under both CB7a and CB7b scenarios, costs of adaptation decline over time – reflecting the significant upfront investment in tree planting and other measures for which capital costs are not then re-incurred during the modelled timespan. Total costs and co-benefits (carbon and ecosystem services) are the same under all land use and climate scenarios, but the avoided losses change in line with the underlying losses. These are set out in Table 32 and Table 33 and summarised here (on an annual average basis for the UK, undiscounted):

- Economic losses in the 2030s and 2050s under the CB7a: Central scenario are £162 million and £202 million, respectively. Avoided losses due to adaptation are £14 million and £39 million
- Economics losses in the 2030s and 2050s under the CB7a: High scenario are £439 million and £465 million, respectively. Avoided losses due to adaptation are £23 million and £64 million
- Economic losses in the 2030s and 2050s under the CB7b: Central scenario are £169 million and £230 million, respectively. Avoided losses due to adaptation are £15 million and £42 million.
- Economics losses in the 2030s and 2050s under the CB7b: High scenario are £465 million and £529 million, respectively. Avoided losses due to adaptation are £24 million and £70 million

As with the BAU scenarios, the driver behind the overall benefits (Figure 25 and Figure 26) is not the mitigated economic loss – it is the carbon and ecosystem service co-benefits.

These results underscore the importance of scenario-specific planning. While the adaptation package delivers risk reduction in every scenario, the timing and magnitude of the avoided losses and value of the co-benefits depend heavily on the underlying climate assumptions and the nature of the adaptation measure.

Figure 25. Total costs, net benefits and total net benefits across the CB7a land use, Central and High climate scenarios for Present Day, the average for the 2030s and the average for the 2050s. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦



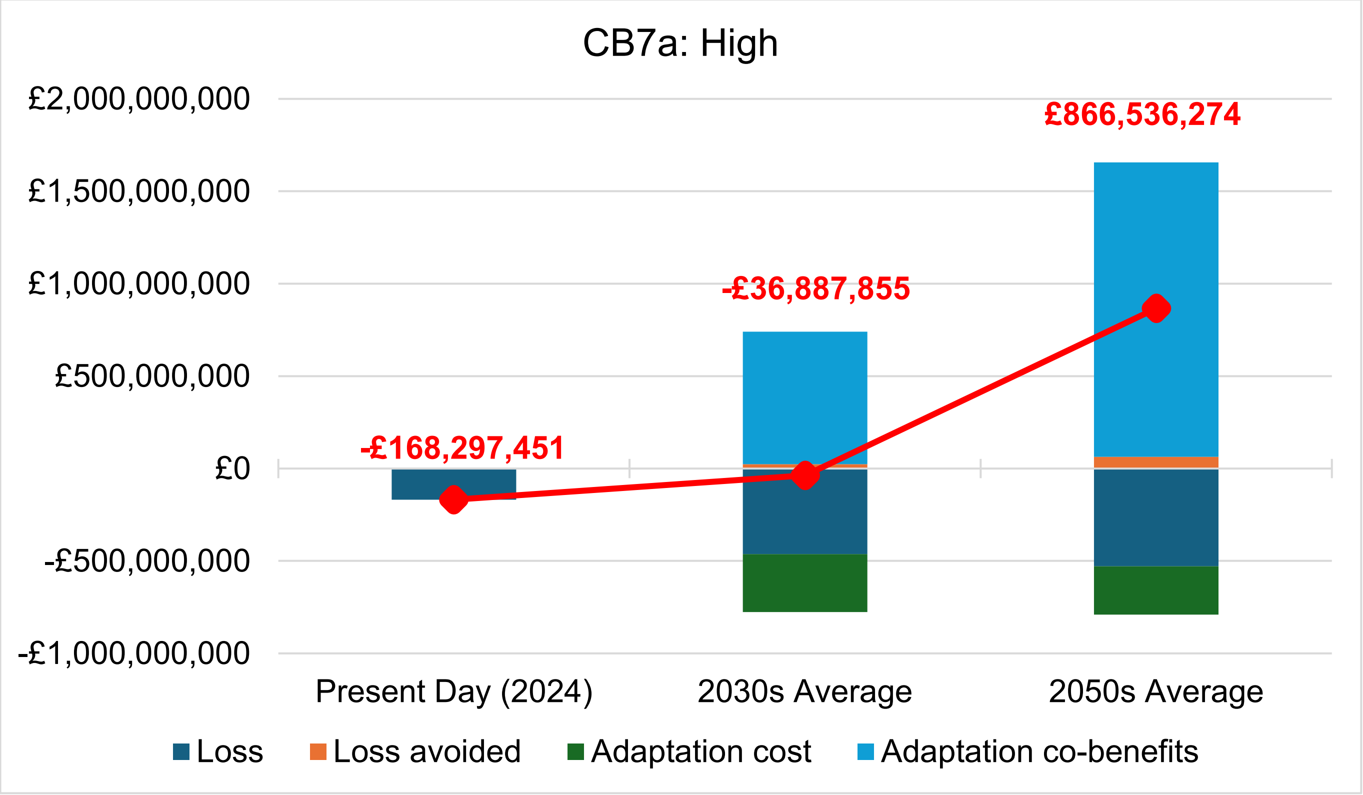
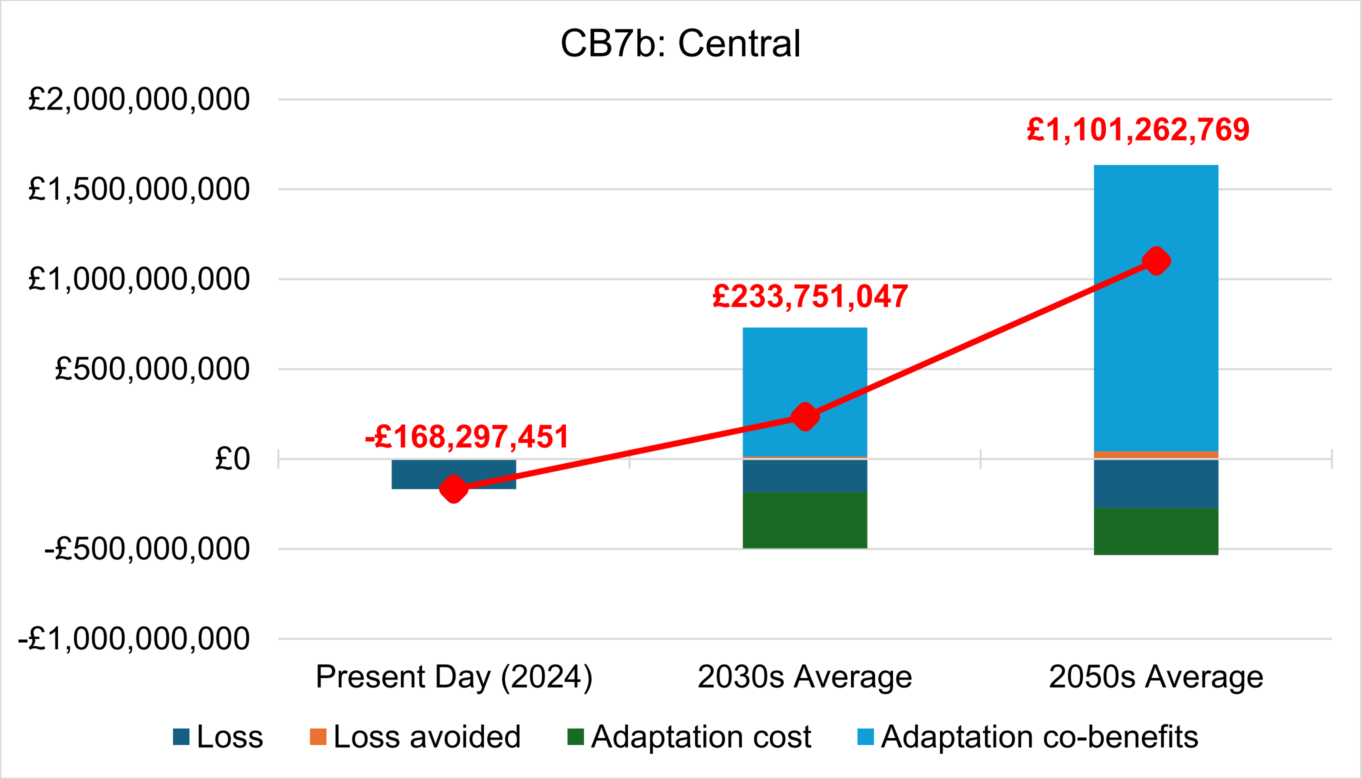
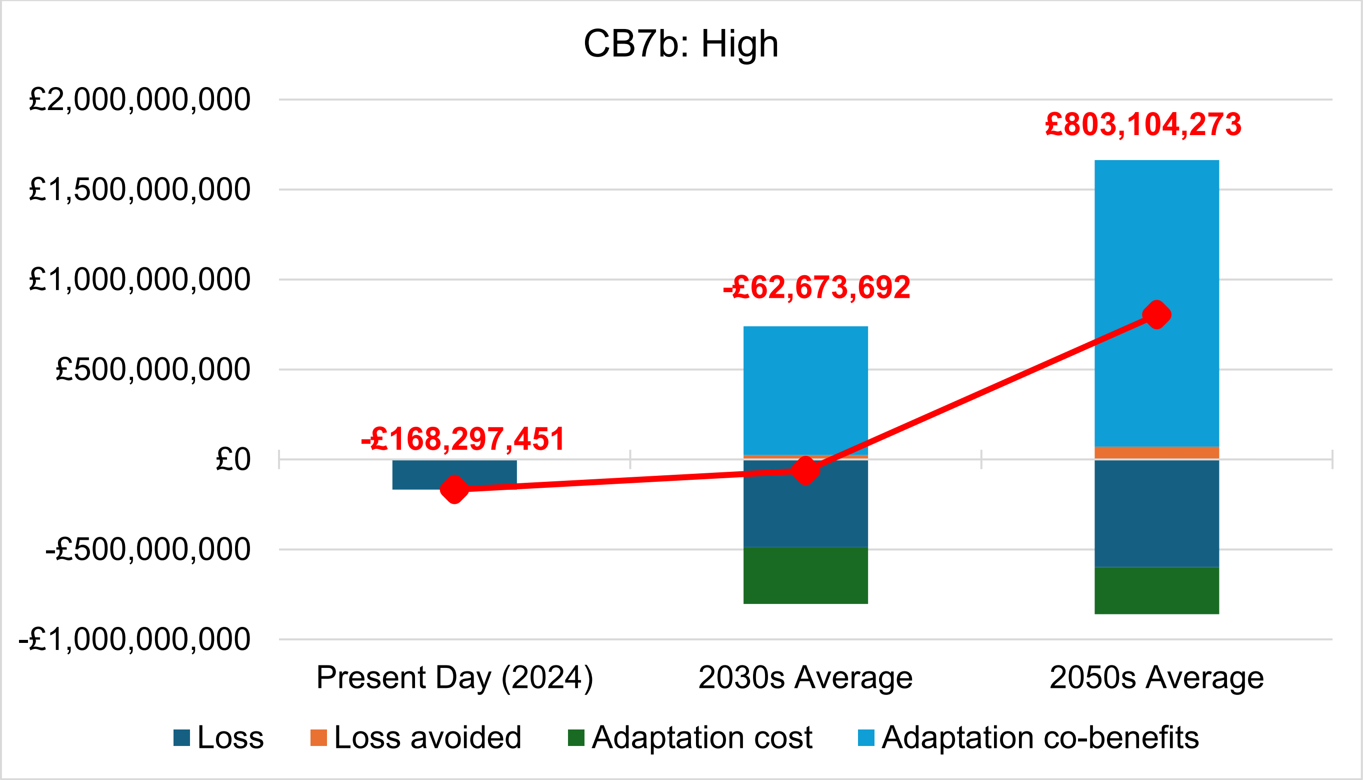


Figure 26. Total costs, net benefits and total net benefits across the CB7b land use, Central and High climate scenarios for Present Day, the average for the 2030s and the average for the 2050s. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦





Conclusions and constraints

The analysis of the final adaptation package reveals several important insights. Firstly, while the measures implemented do contribute to risk reduction (avoided loss), their overall effectiveness remains modest. Even when combined, there are still notable losses (residual risks). This suggests that these adaptation measures alone cannot fully eliminate the impacts of the specific climate hazard thresholds being reached, and that some level of loss will persist. This residual risk highlights the limitations of these adaptation measures that could be modelled throughout the analysis, and suggests that complementary strategies, such as emergency response planning, insurance mechanisms, and financial diversification, are necessary in addition to the field interventions. It is important to recognise that adaptation is a critical component of risk management, but not a standalone solution.

In the Business-As-Usual (BAU) central scenario for the 2030s, the residual annual average loss is only approximately 10% lower than it would be without any adaptation. By the 2050s, this figure improves to ~20% reduction. This trend indicates that the efficacy of adaptation measures increases over time, both due to the maturation of the interventions and the increasing trend in the climate risk – specifically, the number of days or geographic area by which hazard thresholds are exceeded, and thus more risk is reduced as adaptations take effect. This pattern of increasing effectiveness over time is consistent across all modelled scenarios, including CB7a and CB7b, under both central and high climate conditions. However, the degree of efficacy is slightly diminished in the high scenario compared to the central one, reflecting the greater challenges posed by more extreme climate conditions (16% under BAU: High compared to 24% under BAU: Central. The same pattern is also evident in the CB7 scenarios).

The effectiveness of adaptations varies considerably across different climate scenarios. In high climate scenarios, the economic losses are more severe, and the benefits of adaptation take longer to materialise. This sensitivity to scenario assumptions means that adaptation planning must be tailored to the specific risk profile of each region or component of the analysis.

When the costs of adaptation are considered in relation to the average annual economic losses, the analysis shows a clear economic justification for investment. In the BAU, central climate scenario, by the 2030s, adaptations yield a net benefit of approximately £230 million per year (including both avoided losses and carbon / ecosystem service benefits). This benefit grows substantially to £1.1 billion annually by the 2050s, demonstrating the long-term financial value of proactive adaptation. Similar trends are observed in the CB7a and CB7b scenarios (Figure 18). In CB7a, the net benefit is slightly lower (Figure 25), while CB7b shows a higher benefit in the 2030s but a slight reduction by the 2050s (Figure 26). In contrast, the high climate scenario does not produce a net economic benefit in the 2030s; benefits only begin to emerge by the 2050s. This delay is largely attributable to the severity of climate impacts and the time required for certain measures, such as tree planting, to reach maturity. The model assumes that trees, for example, take approximately 15 years to deliver both risk reduction and co-benefits in this analysis.

The data shows that adaptation measures implemented in the Present Day or early 2030s result in significantly higher net benefits by the 2050s. This finding underscores the value of early and proactive investment in climate resilience. Delaying adaptation not only increases exposure to risk but also reduces the financial efficiency of the measures. Early action allows time for interventions to mature and deliver their full benefits, particularly for measures with long lead times such as tree planting. Therefore, early implementation of adaptation should be prioritised to maximise returns and minimise future losses.

Despite this delay, even in the 2030s, the total net co-benefits nearly offset the combined costs, including economic losses and the total expenditure associated with adaptation. As adaptation measures mature and are maintained over time, the residual risk associated with climate hazards tends to decline. This trend is evident across all scenarios analysed, with greater reductions in economic loss observed in the 2050s compared to the 2030s. The findings suggest that sustained investment in adaptation not only delivers immediate benefits but also contributes to long-term resilience. This reinforces the importance of continuity in adaptation programmes and the need for ongoing monitoring and evaluation to track progress and adjust strategies as necessary.

Beyond direct risk reduction, adaptation measures generate additional economic and environmental benefits, referred to as co-benefits. These may include carbon sequestration and a range of ecosystem services. When these co-benefits are included in the analysis, the total value of adaptation increases significantly. This broader perspective is essential for making informed investment decisions. It also strengthens the case for adaptation by demonstrating that its benefits extend beyond climate resilience to encompass wider societal gains. It must also be considered that several of the adaptation measures in the final package can be expected to deliver benefit beyond the simple mitigations of heat modelled in this analysis:

- Silvo-arable and silvo-pastoral measures increase resilience to excess precipitation, by facilitating infiltration (and evapotranspiration during the growing season). They also provide habitat for a range of species, and depending on the type of tree planted may also provide additional revenue from fruit or timber;
- Soil measures also increase resilience to excess precipitation through improved infiltration. Attention to the water holding capacity of soils also provides resilience under drought conditions, reducing the need for irrigation – while increases in soil organic matter (SOM) are a key indicator for soil health and a core component of regenerative farming practice that is increasingly specified by farm customers (such as multi-national food and beverage organisations);
- Re-wetting of landscapes through installation of large ponds will provide important wetland habitat with a wide range of wildlife benefits. It can also improve flood resilience by slowing the flow into watercourses following rainfall. Large ponds also deliver amenity value and may also provide additional revenue opportunities.

Even without these further tangible benefits, the annual costs of implementing the measures considered in this simplified analysis are well within prior agri-environment budgets.

Whilst ‘transformational’ options are considered in *Exploring transformational measures* (specifically, scenarios in which cropped land is converted to woodland, wetland or wildflowers), opportunities to swap to different types of crop or other agricultural land use have not been considered, such as conversion to vineyards or planting soybeans. Such options were the subject of a recent study which explored the future suitability of more than 160 crops for the UK and showed that warming increases suitability for many, including some not typically or widely grown here today such as sunflowers, soybeans and chickpeas.[111] Experimental plantings of warm-season crops such as chickpeas and rice have already taken place.[112]

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[111] Soci.org. (2025). Climate change and farming: The surprising impact on the UK’s crops. [online] Available at: https://www.soci.org/news/2025/1/climate-change-and-farming-the-impact-on-the-uks-crops.

[112] Speare-Cole, R. (2025). UK harvest on course for near record low after drought hits crops – analysis. [online] The Independent. Available at: https://www.independent.co.uk/climate-change/news/met-office-b2812587.html.

Similarly, okra and outdoor aubergine might become more viable in the far south. The study highlights that the southwest of England and Scottish Borders could see the greatest increases in suitability for cropping later in the century.[113] This suggests an opportunity for those regions to expand horticultural output – e.g., Scottish growers might grow more field vegetables or even fruits that were once confined to southern England. Such transpositions are already starting to be visible – while there has been a significant expansion of viticulture in the south of England (which now produces ~10+ million bottles of wine a year, from around 3,500ha of vines – a tenfold increase in two decades[114]), a number have been established as far north as Yorkshire. These shifts could contribute to resilience by spreading production more evenly across the country, although land type and topography in southwest England and Wales could constrain future expansion.[113] The cost-benefit model assumes that adaptation measures are universally applied to all areas of heat-impacted cereals and livestock. We consider this reasonable for vaccination, tree planting and other measures in the package. It would not be reasonable for crop substitutions or other substantive changes, which could only be implemented based on site / soil and farm-business specific circumstances. This report is not intended to provide farm-level insights or guidance, although the structure of the cost-benefit analysis could readily be adapted for application at this scale. Finally, the substitution of current crop cultivars with those adapted to peaks of heat during the flowering period has not been modelled. This reflects the state of evidence in the UK context. For example, trials to rank the drought tolerance of wheat cultivars have already taken place[115], whilst other trials are ongoing[116]. Investigations into heat tolerance during anthesis (the risk under scrutiny in this study) have taken place in heat-prone areas such as Australia[117,118] and Sub-Saharan Africa[119], while there is increasing recognition of this risk elsewhere in Europe[120]. In principle, crop varieties with appropriate resilience traits could be substituted directly for current varieties on farm.

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[113] Speare-Cole, R. (2025). UK harvest on course for near record low after drought hits crops – analysis. [online] The Independent. Available at: https://www.independent.co.uk/climate-change/news/met-office-b2812587.html.
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[120] Nóia-Júnior, et al (2025). Wheat breeding trials will lose climate relevance in Europe. Environmental Research Letters, 20(11), p.114092. doi:https://doi.org/10.1088/1748-9326/ae0e38

Task 2.4 - Sensitivity Analysis

Introduction

This section presents the findings from a range of sensitivity tests concerning the adaptation package, primarily tested using the BAU: Central and BAU: High scenarios. As with Task 2.3, each scenario was assessed over three timeframes: Present Day (2024), the 2030s, and the 2050s – with an additional average value calculated across the periods. The results consider economic losses from the modelled heat-related impacts and the residual loss remaining after adaptation. They also consider the total economic costs and net benefits of adaptation. The sensitivity analyses take into account changes to different parameters in the economic model, and how this impacts results. These sensitivities effectively stress-test various scenarios as part of a theoretical exercise and model quality assurance (QA) – they do not seek to explore specific drivers behind core modelling outcomes, as these have been considered in previous sections: the prevalence of (heat-impacted) cereal crops in England, the relative ineffectiveness of the adaptation measures at reducing economic losses, the importance of carbon and ecosystem service values in delivering supportive Benefit-Cost Ratios, and the particular benefits associated with soil and tree-related measures when deployed to address climate-related heat risks to cereal crops.

Exploring ‘peak’ losses

This section presents findings for the BAU: High scenario in the UK, focusing on the *maximum* projected annual losses discussed in *Task 2.1 - Climate Risk Analysis*. In the core analysis, average annual economic losses are modelled out to 2059 along with their corresponding adaptation responses. In this ‘peak’ analysis it has been assumed that in 2035 and 2055 only, the economic losses are substituted for the *maximum annual modelled* losses from the hazards across all sub-components, which occur in any given year over the 2030s, and then the 2050s. Although the year in which these losses were modelled to occur differs across each specific sub-component, they are grouped together and considered to all occur in one year for the purposes of this peak analysis. Peak loss could be driven by either more days over the established threshold, a wider geographic area experiencing days over the established threshold, or both. In addition, it is acknowledged that the likelihood of all the hazard thresholds across all sub-components peaking at the same is unlikely.

The ‘peak’ data are set out in Table 15, with maximum losses of wheat in England during the 2030s and 2050s due to the modelled heat impacts being £1.16 billion and £0.87 billion respectively. Peak losses of wheat for the UK in aggregate were modelled to be £1.19 billion and £0.90 billion for the 2030s and 2050s respectively. In contrast, the average annual UK losses for what in the same scenario were modelled as £0.034 billion and £0.101 billion for the 2030s and 2050s respectively (Figure 13).

Results for the ‘peak’ analysis are presented in Figure 27, with corresponding results for the core analysis (without peaks) presented in Figure 28.

The overall trajectories are similar – once carbon and ecosystem service values are combined with the avoided losses and offset against adaptation costs (and residual losses), there remain net economic losses in the 2030s. However, due to the peaks, this aggregate (annual) loss increases from £63 million to £233 million in the 2030s. The aggregate (annual) benefit in the 2050s decreases from £825 million in the core analysis to £703 million in the peak analysis. These patterns are direct reflections of the additional losses imposed under the peak model – the extent, costs, benefits and co-benefits of adaptation remain the same in both core and peak approaches (the package does not change in any way). Since the adaptation effectiveness operates on a % basis, the greater level of modelled losses in 2035 and 2055 are reflected in greater modelled adaptation benefits (from £26.8 million and £79.5 million in core analysis to £31.7 million and £91.7 million in the peak analysis).

Overall, the data illustrates that adaptation measures are somewhat effective in curbing economic losses, particularly when implemented early and maintained over time. However, significant residual risk will remain. These findings confirm that without intervention and where there are extreme climate events in any given year, economic losses due to climate hazards will continue to grow, placing increasing strain on the agricultural sector.

Figure 27. Annual average totals for Present Day, 2030s and 2050s under the BAU: High scenario, with peak loss events in 2035 and 2055. The chart combines modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦

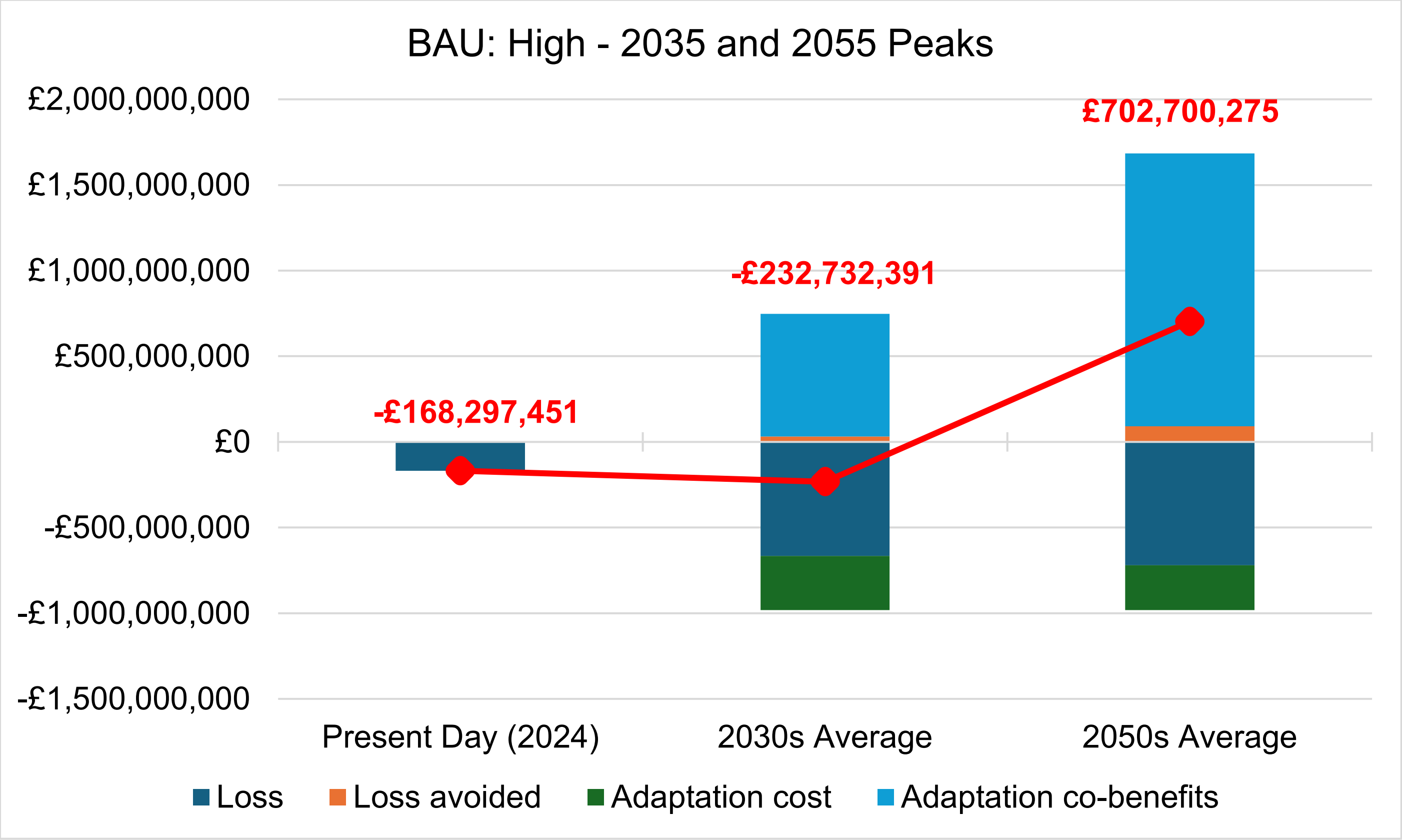
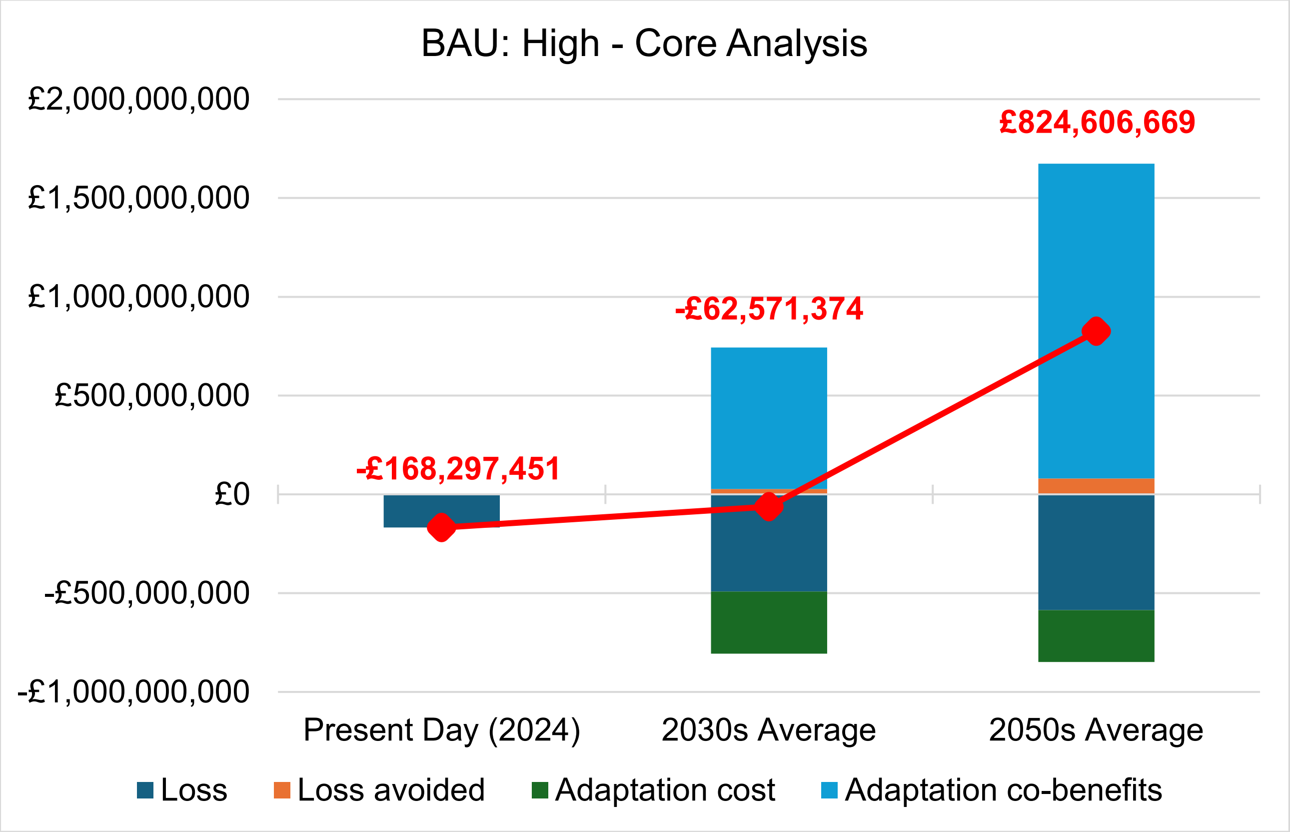


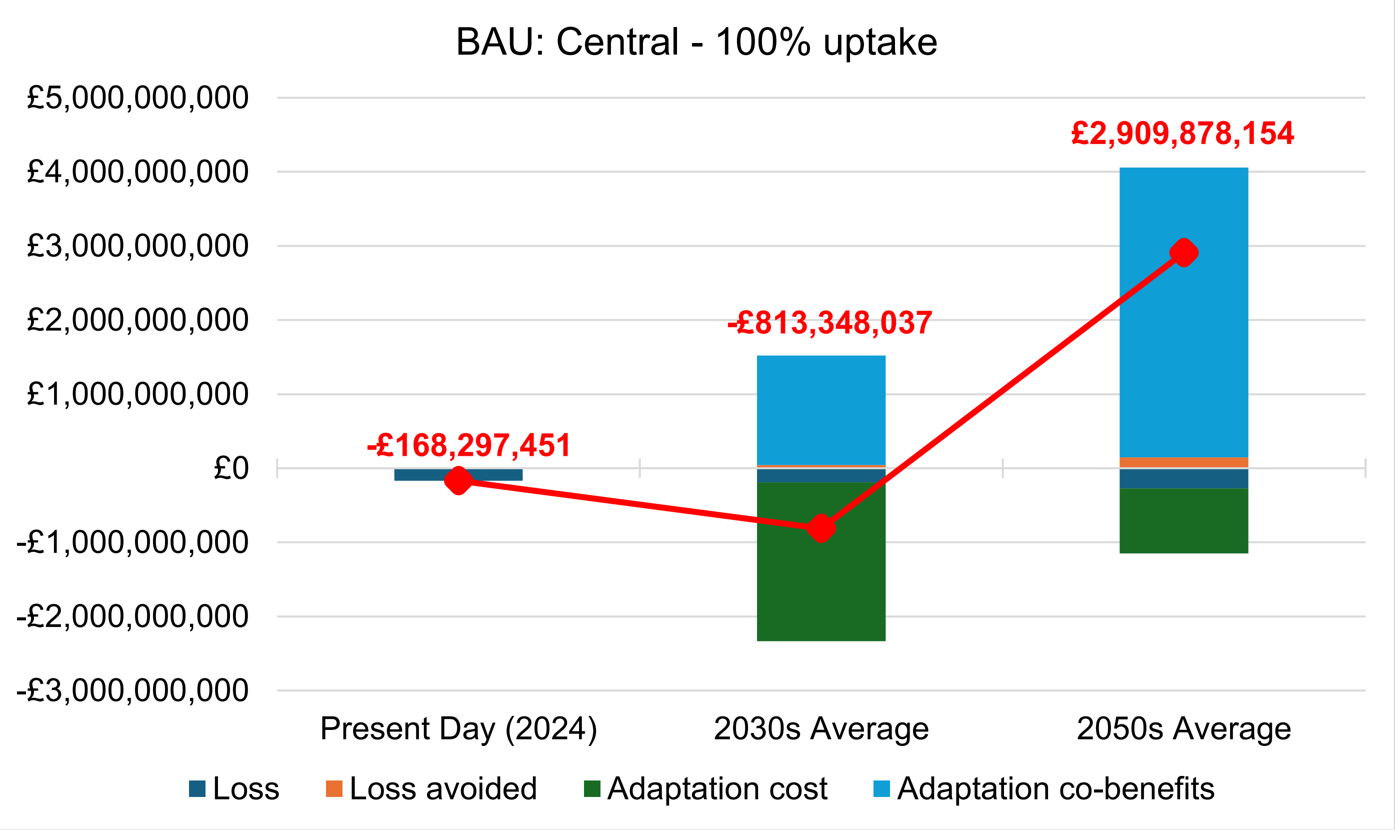
Figure 28. Annual average totals for Present Day, 2030s and 2050s under the BAU: High scenario (core analysis). The chart combines modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦. Note that this figure is a duplicate of Figure 19



Exploring 100% uptake of the adaptation package

This section presents findings for the BAU: Central and BAU: High scenarios, under the assumption that each adaptation in the package of measures will be implemented across 100% of the (modelled) heat-impacted hectarage or livestock. Both scenarios were assessed over three timeframes: Present Day (~2024), the 2030s, and the 2050s – with an additional average value calculated across the periods. Data for economic losses, avoided losses, adaptation costs and adaptation co-benefits are summarised in Figure 29 for the BAU: Central scenario and Figure 30 for the BAU: High scenario (in both of which adaptation uptake is set at 100%). These charts should be compared with their counterparts which capture the core analysis (which assumes 'realistic' uptake of adaptations): Figure 18 and Figure 19.

Figure 29. Annual average totals for Present Day, 2030s and 2050s under the BAU Central scenario, where the adaptation package is implemented across 100% of the impacted crop and livestock area. The chart combines modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦

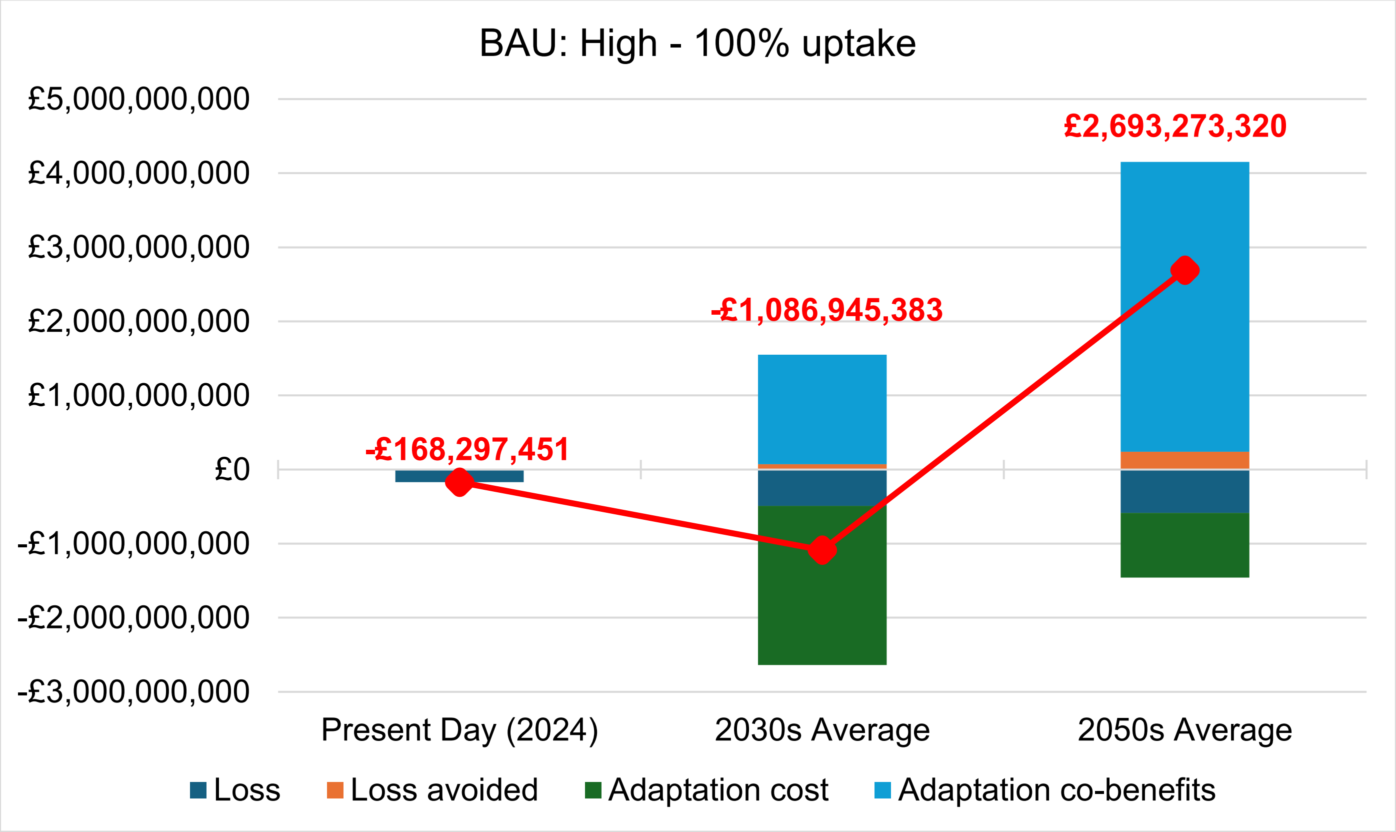


Across the scenarios and as with the uptake measures in the core 'realistic' analysis, the economic losses in the absence of adaptation are substantial and increase over time. In the BAU: Central and BAU: High scenarios, in the absence of adaptation losses increase from the Present Day through the 2030s and into the 2050s, reflecting the escalating impact of climate hazards (Table 37). The BAU: High scenario shows an even steeper increase until the 2050s, indicating that higher climate hazard assumptions significantly amplify economic vulnerability.

Table 37. Annual average economic losses due to modelled heat impacts on aggregated agricultural components (cereals, lambs, milk and eggs) at a UK level. Undiscounted values

Economic losses	Present Day (2024)	2030s Average	2050s Average
BAU: Central	£168,297,451	£188,772,059	£274,613,635
BAU: High	£168,297,451	£491,620,215	£586,565,379

Figure 30. Annual average totals for Present Day, 2030s and 2050s under the BAU High scenario, where the adaptation package is implemented across 100% of the impacted crop and livestock area. The chart combines modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦



When adaptation measures are implemented, the economic losses are notably reduced across all scenarios and timeframes. In the BAU: Central scenario, adaptation leads to a marked decline in losses by the 2030s and a significantly larger reduction by the 2050s (reflecting the delayed effectiveness of the silvo-arable and silvo-pastoral measures). In the BAU: High scenario, while still showing significant losses overall by the 2050s, there is an increase in economic losses following adaptation between the Present Day and the 2030s. This is mainly due to the phasing of CAPEX which is greater given the increased hectarage and livestock that is determined as impacted by the 2030s. However, the benefits from adaptation still cause a visible downward shift in the loss curve by the 2050s. Overall, the data illustrates that adaptation measures are effective in curbing some economic losses, particularly when implemented early and maintained over time.

Similar trends are observed across both the BAU: Central and High scenarios under 100% uptake. In the Central scenario, there are some residual losses in 2030, but the overall trajectory shows a strong positive return, with total net benefits at £2.9 billion by the 2050s. Meanwhile, the BAU: High scenario reflects a larger but delayed positive return, also materialising in the 2050s, though lower than the Central scenario, at £2.7 billion (Table 38). These results highlight the long-term value of adaptation measures, even when initial benefits are modest or delayed. However, the investment required to deliver the 100% uptake of adaptation measures is extremely high.

Table 38. Net annual benefits under BAU: Central and BAU: High scenarios when the adaptation package is implemented at 'realistic' and 100% uptake rates at a UK level. Undiscounted values

Net benefits	Present Day (2024)	2030s Average	2050s Average
BAU: Central (realistic uptake)	-£168,297,451	£230,391,294	£1,109,517,555
BAU: High (realistic uptake)	-£168,297,451	-£62,571,374	£824,606,669
BAU: Central (100% uptake)	-£168,297,451	-£813,348,037	£2,909,878,154
BAU: High (100% uptake)	-£168,297,451	-£1,086,945,383	£2,693,273,320

Adaptation costs at 100% uptake are (inevitably) far higher than under the core ‘realistic’ uptake (Table 39). The key driver for this is the substantial difference in uptake of costly adaptation measures, such as the re-wetting of landscapes through installation of ponds for both cereals and cattle, which increases from a ‘realistic’ maximum uptake of 5% to 100% by the 2050s.

Table 39. Annual average costs of implementing the adaptation package at 'realistic' and 100% uptake rates at a UK level. Undiscounted values

Adaptation costs	Present Day (2024)	2030s Average	2050s Average
BAU: Central and High (realistic uptake)	£0	£314,162,619	£261,510,434
BAU: Central and High (100% uptake)	£0	£2,145,079,234	£873,380,219

Exploring cost increases across the adaptation package

This section presents findings for the BAU: Central scenario, under the assumption that the unit costs (both CAPEX and OPEX) of each measure in the adaptation package are 40% higher than modelled in the core analysis. Scenarios were assessed over three timeframes: Present Day (~2024), the 2030s, and the 2050s – with an additional average value calculated across the periods.

Figure 31 presents the total costs, net benefits and total net benefits across the BAU: Central scenario for Present Day, the average for the 2030s and the average for the 2050s, whilst Figure 32 covers BAU: high. The impacts of the price differentials can be seen in Table 40, while the impacts that these have on the net benefits are set out in Table 41.

Table 40. Annual average costs of implementing the adaptation package at core and 40% higher prices for all measures in the package, at a UK level. Undiscounted values

Adaptation costs	Present Day (2024)	2030s Average	2050s Average
BAU: Central and High (core cost)	£0	£314,162,619	£261,510,434
BAU: Central and High (40% cost uplift)	£0	£439,827,667	£366,114,608

Table 41. Net annual benefits under BAU: Central and BAU: High scenarios when the adaptation package is costed at core and 40% higher prices, at a UK level. Undiscounted values

Net benefits	Present Day (2024)	2030s Average	2050s Average
BAU: Central (core cost)	-£168,297,451	£230,391,294	£1,109,517,555
BAU: Central (40% cost uplift)	-£168,297,451	£104,726,246	£1,004,913,381
BAU: High (core cost)	-£168,297,451	-£62,571,374	£824,606,669
BAU: High (40% cost uplift)	-£168,297,451	-£188,236,422	£720,002,496

Overall, total net benefits are lower in the 2030s and 2050s for both BAU: Central and BAU: High scenarios when adaptation costs are increased. This translates into a greater loss for the 2030s under the BAU: High scenario (£188 million, as compared with £63 million). However, net benefits are still high under both scenarios in the 2050s.

Figure 31. Annual average totals for Present Day, 2030s and 2050s under the BAU Central scenario, where the costs (capital and operational) for all adaptation measures are increased by 40%. The chart combines modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦

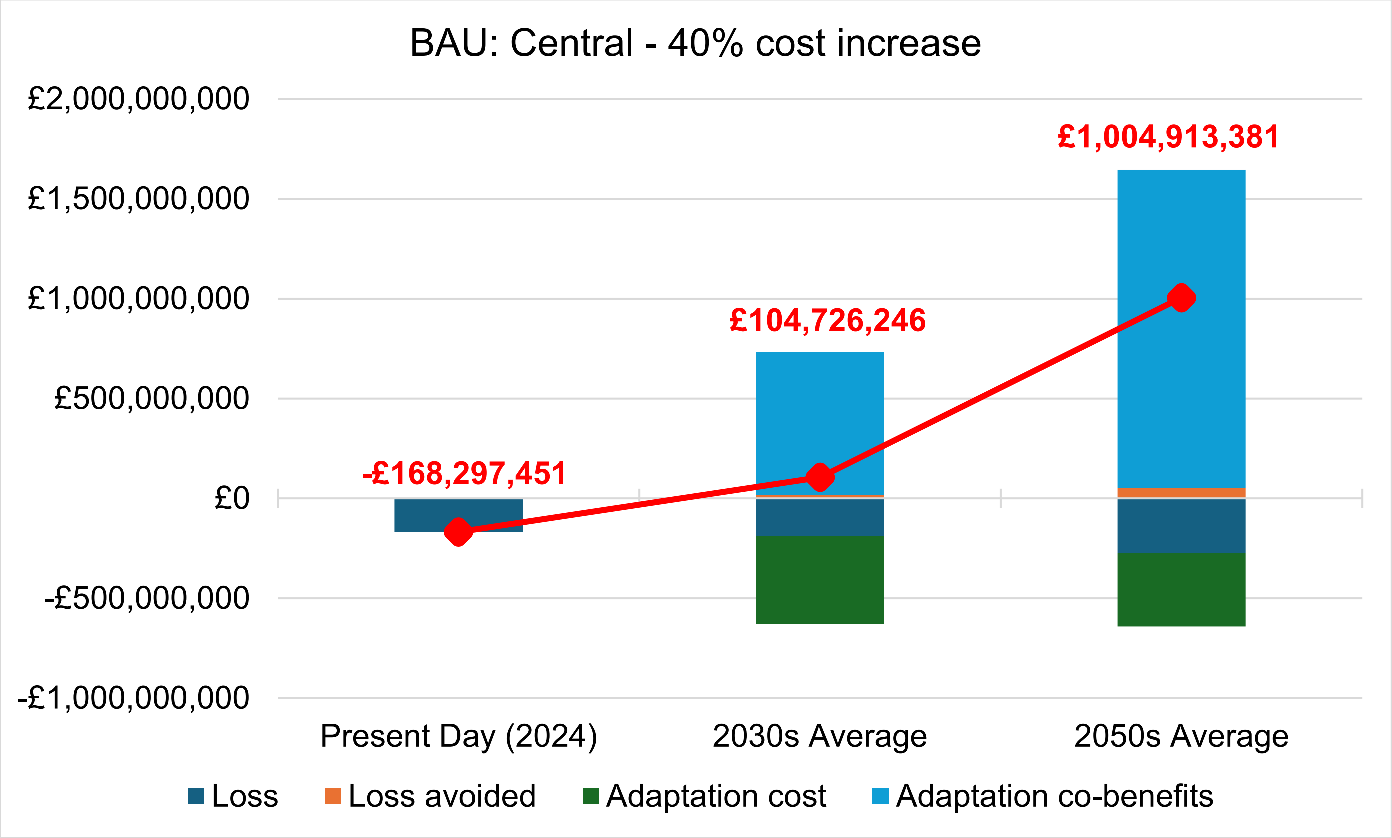
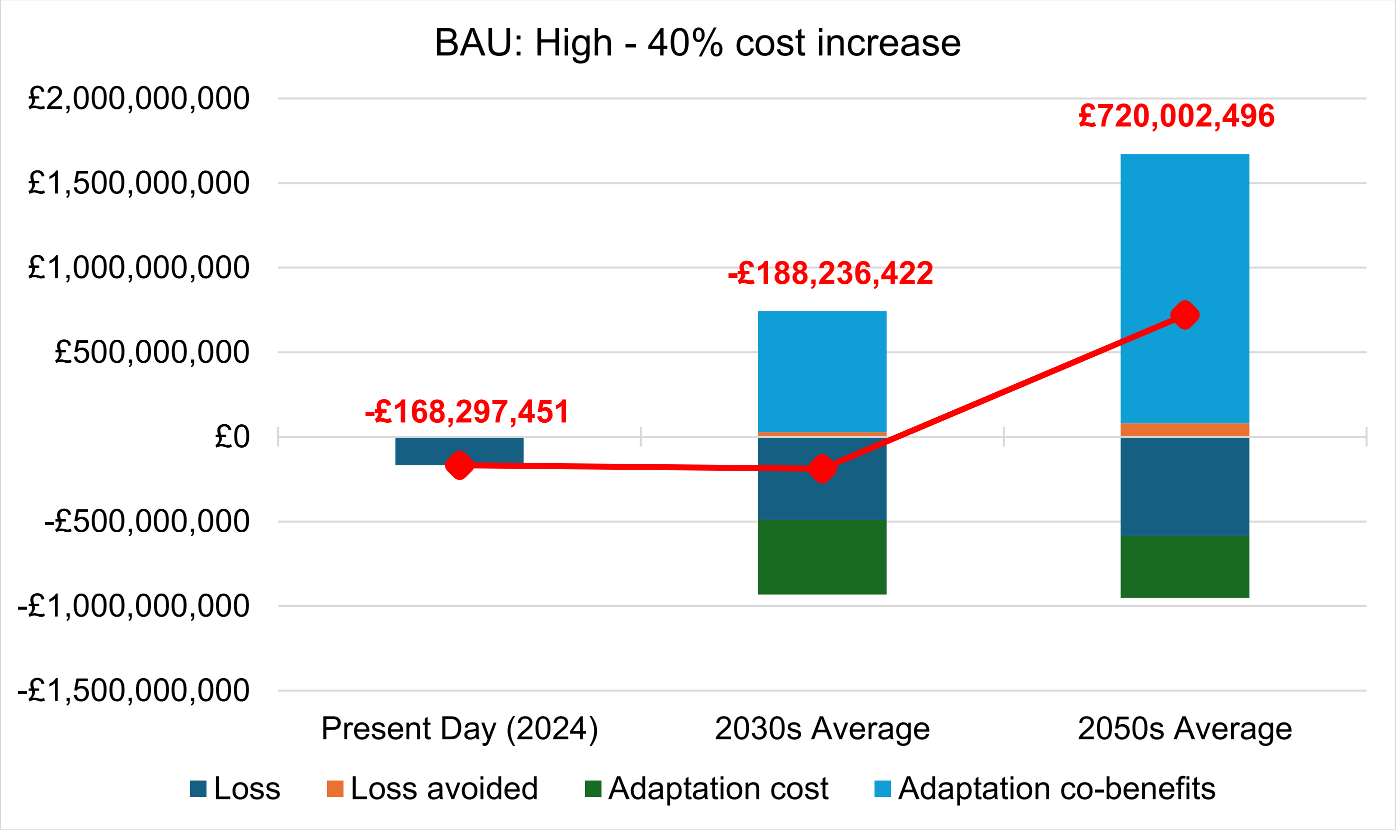


Figure 32. Annual average totals for Present Day, 2030s and 2050s under the BAU High scenario, where the costs (capital and operational) for all adaptation measures are increased by 40%. The chart combines modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦



Exploring cost decreases across the adaptation package

This section presents findings for the BAU: Central scenario, under the assumption that the unit costs (both CAPEX and OPEX) of each measure in the adaptation package are 40% lower than modelled in the core analysis. Scenarios were assessed over three timeframes: Present Day (~2024), the 2030s, and the 2050s – with an additional average value calculated across the periods.

Figure 33 presents the total costs, net benefits and total net benefits across the BAU: Central scenario for Present Day, the average for the 2030s and the average for the 2050s, whilst Figure 34 covers BAU: high. The impacts of the price differentials can be seen in Table 42, while the impacts that these have on the net benefits are set out in Table 43.

Table 42. Annual average costs of implementing the adaptation package at core and 40% lower prices for all measures in the package, at a UK level. Undiscounted values

Adaptation costs	Present Day (2024)	2030s Average	2050s Average
BAU: Central and High (core cost)	£0	£314,162,619	£261,510,434
BAU: Central and High (40% cost drop)	£0	£188,497,571	£156,906,261

Table 43. Net annual benefits under BAU: Central and BAU: High scenarios when the adaptation package is costed at core and 40% lower prices, at a UK level. Undiscounted values

Net benefits	Present Day (2024)	2030s Average	2050s Average
BAU: Central (core cost)	-£168,297,451	£230,391,294	£1,109,517,555
BAU: Central (40% cost drop)	-£168,297,451	£356,056,342	£1,214,121,728
BAU: High (core cost)	-£168,297,451	-£62,571,374	£824,606,669
BAU: High (40% cost drop)	-£168,297,451	£63,093,673	£929,210,843

Overall, total net benefits are higher in the 2030s and 2050s for both BAU: Central and BAU: High scenarios when adaptation costs are decreased. This translates into a positive net benefit in the 2030s under the BAU: High scenario (£63 million benefit, as compared with £63 million loss), with net benefits being higher under both scenarios in the 2050s.

Figure 33. Annual average totals for Present Day, 2030s and 2050s under the BAU Central scenario, where the costs (capital and operational) for all adaptation measures are decreased by 40%. The chart combines modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦

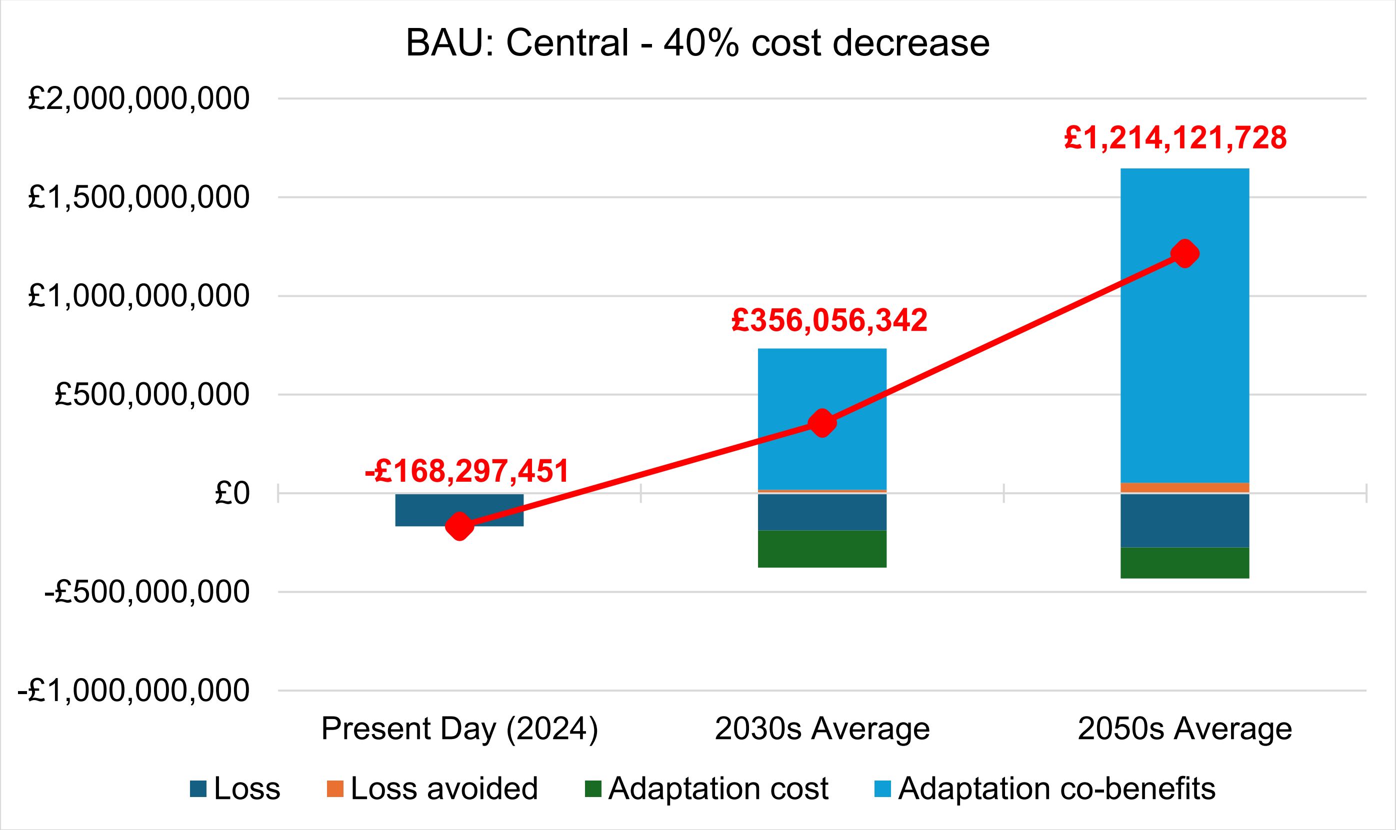
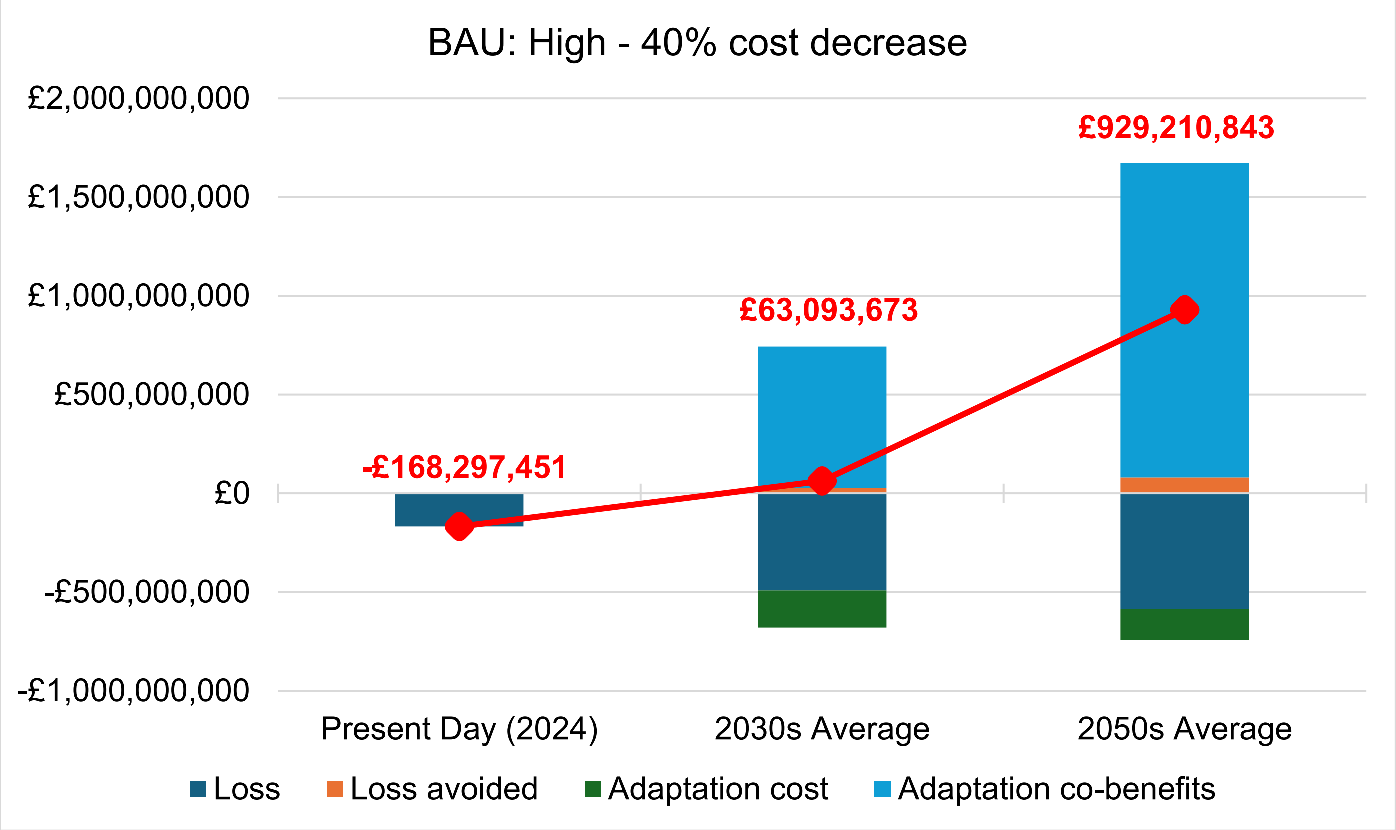


Figure 34. Annual average totals for Present Day, 2030s and 2050s under the BAU High scenario, where the costs (capital and operational) for all adaptation measures are decreased by 40%. The chart combines modelled heat-related losses, adaptation responses (and associated avoided losses) and adaptation co-benefits. Undiscounted data. The net costs (negative £ values) or benefits (positive £ values) in 2024 prices are stated as column headings and marked as ♦



Exploring transformational measures

For the transformational measures, an assessment was undertaken to estimate the costs / benefits of converting the modelled heat impacted area of cereals (see Table 28) to either woodland, wetland or wildflower meadow. This change would forego revenue from cereals formerly produced on this land, but the analysis was intended to explore whether this financial loss might be offset by co-benefits (carbon and ecosystem services). The core CBA model was updated to reflect the revenue foregone – estimated at £1,200 per hectare[121].

Overall financial implications for such transformations are summarised in Table 44. In the case of woodland and wildflowers, modelling resulted in a benefit-cost ratio of below one, meaning the resultant co-benefits do not outweigh the costs associated with the transformation. For wetlands, however, co-benefits surpass lost revenues, strengthening the case for this transformational approach.

Table 44. Financial impacts of converting arable land to woodland, wetland or wildflower meadow. Benefit-cost ratio output for the UK out to 2030 and 2050, using discounted figures. The BCRs apply to all land use and climate scenarios

New land use	Applicable period	NPV of total cost (capex + opex + non-avoided loss)	NPV of total benefit (avoided loss + carbon + ecosystem services)	Benefit Cost Ratio
Woodland	2025 to 2039	£8,906,667,609	£877,371,411	0.10
	2025 to 2059	£27,504,409,173	£2,830,442,552	0.10
Wetland	2025 to 2039	£4,238,072,116	£4,950,464,745	1.17
	2025 to 2059	£9,254,542,635	£15,970,438,404	1.73
Wildflowers	2025 to 2039	£2,018,796,803	£433,646,389	0.21
	2025 to 2059	£6,125,576,326	£1,398,964,200	0.23

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[121] Based on prices listed in the Nix Farm Management Pocketbook 2024 Edition (published by The Andersons Centre)

Summary

Net benefits for the various sensitivity analyses are summarised in Table 45. In all cases the present day (2024) benefit is actually an economic loss – due to modelled heat-related climate risks under a 1.1°C GWL scenario. This becomes a net benefit by the 2030s in the core analysis and where the costs of adaptation significantly increase or decrease, but the losses become more severe by the 2030s where the rate of adaptation is unconstrained in a 100% uptake world. The counterpoint to this is that by the 2050s, the net benefit from the unconstrained world is nearly three times higher than delivered under the 'realistic' uptake assumptions in the core analysis – reflecting the enormous ecosystem service and carbon benefits associated with wetlands and other nature-focussed adaptation measures. Similar patterns are evident in the High climate scenarios. Peak losses in 2035 and 2055 have impacts on the annual average net benefit, although this is far less evident by the 2050s (when tree-based measures are fully effective) than the 2030s. The co-benefits associated with wetlands are also evident in our exploration of land use transformation – more than compensating for the loss of revenue from cereals.

Table 45. Net benefits for the sensitivity scenarios, based on undiscounted data for the UK

Net benefits	Present Day (2024)	2030s Average	2050s Average
BAU: Central (core analysis)	-£168,297,451	£230,391,294	£1,109,517,555
BAU: Central (100% uptake)	-£168,297,451	-£813,348,037	£2,909,878,154
BAU: Central (40% cost uplift)	-£168,297,451	£104,726,246	£1,004,913,381
BAU: Central (40% cost drop)	-£168,297,451	£356,056,342	£1,214,121,728
BAU: High (core analysis)	-£168,297,451	-£62,571,374	£824,606,669
BAU: High (100% uptake)	-£168,297,451	-£1,086,945,383	£2,693,273,320
BAU: High (40% cost uplift)	-£168,297,451	-£188,236,422	£720,002,496
BAU: High (40% cost drop)	-£168,297,451	£63,093,673	£929,210,843
BAU: High (peak losses in 2035 and 2055)	-£168,297,451	-£232,732,391	£702,700,275

Conclusions

Conclusions

This assessment has delivered a quantitative assessment of specific temperature-related (heat) risks and an adaptation package for six agricultural products: wheat, barley, oats, lambs, milk and eggs. Initially conceived as a quantitative analysis of future acute and chronic temperature and precipitation events as applied to both agricultural productivity and nature within the UK's farmed landscapes, evidence from both literature and expert stakeholders indicated that our ability to attribute quantified climatic events to causational impacts would be limited, meaning that a holistic analysis across all aspects of the UK farmed landscape was not feasible with available data. Intended as an exploratory, experimental approach to quantification of risks and adaptation costs, the extent of feasible quantification as developed for this study inevitably considers a fraction of the climate risks facing UK farmed landscapes and the adaptations needed to address them. To support the quantification, several significant assumptions have been required, meaning that the results should be used with caution. Key data gaps include climate risk thresholds relevant to UK farming and thresholds for nature within farmed landscapes.

Using climate scenarios based on UKCP18 Local projections and land use pathways aligned with the CCC's Seventh Carbon Budget, the study modelled the impacts of heat-related impact thresholds on crop yields, livestock health and productivity. Results indicate that high temperatures during anthesis will increasingly reduce annual yields of cereals, especially in the East of England, the Midlands, and the South East, with barley and oats facing losses up to 29.9% and 36.2% respectively by the 2050s. Lamb productivity is projected to be impacted due to additional parasite infections from *Haemonchus contortus*, particularly in Scotland and Wales, while milk and egg production show relatively minor direct losses from the modelled heat-related thresholds. The spatial analysis aligns these impacts with rural land use archetypes, highlighting the vulnerability of regions where these farming activities are concentrated.

Economically, the analysis estimates that annual losses from the modelled heat-related risks could reach £647 million by the 2050s under a high climate scenario in the UK, more than triple current levels. England is expected to bear the greatest share of these losses due to its high amount of agricultural activity (area and volume) and geographic exposure to higher temperatures. Sensitivity analyses using alternative (CB7-aligned) land use scenarios suggest that reducing agricultural land and livestock numbers could mitigate damages through reduced exposures, while productivity improvements may slightly offset modelled losses but still leave substantial risk. The study concludes that heat-related risks to UK agriculture will increase due to climate change. The findings underscore the need for robust and wide-ranging adaptation strategies and risk management to safeguard agricultural productivity and rural livelihoods in the face of uncertain future climate trajectories.

Modelling demonstrated that without adaptation, economic losses from heat-related risks will rise over time, placing increasing strain on the sector. Adaptation measures such as silvo-pastoral (shade trees in pasture), silvo-arable (alley trees in arable fields), large ponds and improved soil water holding capacity all provide cooling effects via shading and/or evaporative processes whilst lamb vaccination and enhanced biosecurity measures help to address parasite risks. In combination, these measures reduce economic losses from heat-related risks – especially when implemented early and maintained over time. However, residual risks will remain within adapted landscapes, indicating that on-farm interventions alone cannot fully eliminate or address predicted economic losses. The effectiveness of nature-focussed adaptation measures increases over time – particularly as trees grow and mature, and soil conditions improve – and the net benefits of the package of measures grow from approximately £230 million per year in the 2030s to £1.1 billion annually by the 2050s in the central climate scenario. The timing and magnitude of benefits depend heavily on the underlying climate assumptions and the phasing and uptake of the adaptation, with early action delivering higher returns. The findings emphasise the importance of early implementation, particularly in measures that require time to become effective. Planning must account for these lags to avoid underinvestment and ensure benefits are realised when most needed.

The analysis also highlights the importance of co-benefits, such as carbon sequestration and ecosystem services, which substantially increase the total value of adaptation beyond direct heat risk reduction. Sensitivity analyses reveal that adaptation remains cost-beneficial even under extreme (‘peak’) scenarios, higher or lower uptake rates, and varying cost assumptions because of these co-benefits, though the degree of benefit varies by region and scenario. Transformative adaptation options, such as converting arable land to woodland, wetland, or wildflower meadow, show that only wetland conversion yields a benefit-cost ratio above one, illustrating that the ecosystem service benefits outweigh the costs of conversion (notwithstanding that this simple analysis excludes system impacts such as the need to replace lost grain production from elsewhere). Overall, the findings underscore that while field-scale adaptation is essential for climate resilience against heat-related hazards, it must be complemented by broader risk management strategies, and early, sustained investment is crucial for maximising long-term benefits and minimising future losses.

Strategic prioritisation is vital and adaptation measures should be selected based on their return on investment, capacity to address heat (and other climate) risks, and alignment with broader policy objectives. Commercial resilience, often overlooked in economic analyses, must also be considered. Approaches like regenerative agriculture, which prioritise biodiversity, soil health, and integration of livestock with cropping, may reduce short-term productivity but improve long-term profitability and resilience when considered at a system level.

Two critical conclusions emerge from this study:

1. Quantitative analysis must evolve with better data, refined models, and clearer estimates of cost-effectiveness. Research and enhanced modelling and evaluation across farming and the natural environment will be required.
2. Resilience arises from ecologically functional, diversified, and adaptable systems. Many such measures are undervalued by conventional metrics due to their distributed, multi-purpose benefits realised over time.

This study, including considerations beyond the deep dive methodology, also highlights the value of systems thinking in adaptation planning, recognising that resilience emerges from diversified, ecologically functional landscapes. Technical solutions alone may not suffice; instead, integrated approaches that combine nature-focussed interventions, stakeholder engagement, and policy alignment are essential. Adaptation should be embedded within broader agricultural and environmental frameworks, with support for farmers through advisory services, financial incentives, and flexible scheme design. These wider considerations enhance financial resilience by reducing volatility, protecting productive capacity, and enabling profitable, lower-input farming. They also align climate adaptation with decarbonisation and nature recovery goals, particularly when viewed through the lens of land use. For example, agroforestry could prioritise native tree species. Measures such as diversified rotations, agroforestry, hedgerows, and restored blue-green infrastructure increase adaptive capacity by maintaining optionality and enhancing the effectiveness of technological solutions.

In terms of suggestions for future research, several key data gaps were identified throughout this study, including:

- Quantified climate risk (hazard and impact) thresholds relevant to UK agricultural products;
- Quantified climate risk (hazard and impact) thresholds to nature (i.e., habitats or specific species) within the UK's farmed landscapes;
- Quantified effectiveness of adaptation in addressing specific climate hazards and impacts;
- Costs of adaptation measures; and
- Approaches to integration of different types of impacts and adaptation measures at a system level.

Among all of these, a lack of quantified data on the effectiveness, or risk reduction, provided by adaptation measures is particularly notable. However, future research that explicitly links quantified climate hazard thresholds to attributable, quantified impacts (including for multiple and compounding climate hazards, like combined heatwave and drought events) will be beneficial for future quantitative risk studies. Finally, future research should consider the overlapping of adaptation options, such as integrating pest surveillance and biosecurity, and seek to build them into an adaptation pathways approach.

Additionally, innovation is needed to value ecosystem services and natural capital in future quantitative climate risk assessments. Spatial data mapping of soils, habitats, and hydrological functions could be overlaid with climate risk and production maps to prioritise investment where marginal benefits are highest. This supports co-funding models and enables monitoring of change over time. Future studies should identify priority zones for nature-based buffers, irrigation storage, and shade investments. Partnerships with devolved evidence programmes and supply chain actors can accelerate this work. Consumer-facing measures, such as acceptance of more flexible product specifications, can transform climate-induced variability into an acceptable expression of natural production.

Quantitative analysis remains an essential – yet developing – area for reliable assessment of climate risk. While data related to attribution, causation, impact and effectiveness are still lacking, they are required to support the future prioritisation of risks, ranking of adaptation options, and estimation of costs and benefits in building the business case for proactive management of climate-related risks. This project's scope, limited to linear, quantifiable metrics, precluded broader systemic challenges and opportunities, such as risks from combined heat and drought or other climate events. These gaps underscore the need for expanded research, monitoring, and evaluation to support future adaptation planning, as outlined above.

Despite these limitations, the study quantitively assessed heat-related risks and developed an adaptation package that, while not significantly reducing economic losses, delivers substantial co-benefits including carbon sequestration, improved soil health, and enhanced ecosystem services. In conclusion, building climate resilience in UK farmed landscapes requires a holistic, evidence-based approach that accounts for the complexity of agricultural systems and the interdependencies between productivity, nature, and society. By advancing both quantitative and qualitative understanding, and fostering collaboration across sectors, the UK can develop robust strategies to safeguard its agricultural future in the face of climate change.

Going beyond the deep dive method

Going Beyond the Deep Dive Method

Quantitative analysis is essential for climate risk assessment, offering structured insights into adaptation priorities and cost-benefit trade-offs. However, such methods are inherently reductive, often omitting systemic complexities and qualitative dimensions. This section complements the quantitative findings with a broader exploration of: challenges to farmed landscapes from waterlogged soils; climate change vulnerabilities and adaptation opportunities in the UK horticulture sector; and combined heat / drought events. Key drivers of adaptation potential are also considered. The section concludes with observations on the value of a ‘systems’ approach to landscape-scale challenges, and how this could be conceptualised.

Waterlogging and compound weather events
Waterlogging, driven by heavy rainfall and poor drainage, already causes widespread crop failure and disruption to livestock production. Case studies show that both infrastructure upgrades (e.g., drainage systems) and adaptive practices (e.g., switching to alternative cropping regimes) are essential. Compound heat / drought events have already led to reduced crop yields, early culling of livestock, and increased operational costs. These might be mitigated through enhanced water storage / management capacity – including a greater focus on soil health and quality.

Climate change and UK horticulture
Though occupying just 150,000 hectares, UK horticulture contributes 20% of agricultural output value. The sector is highly climate-sensitive, with key crops like field vegetables and soft fruits vulnerable to extreme heat, drought, waterlogging, and storms. Regional concentration in the East and Southeast heightens exposure. Despite these risks, the sector holds potential for expansion and resilience through targeted adaptation.

Effective measures include:

- Efficient irrigation and water storage to mitigate against drought
- Enhanced drainage to mitigate against waterlogging
- Focus on soil health to optimise water management characteristics and rooting environment
- Implementation of frost protection techniques to safeguard orchard crops
- Selection of climate-resilient varieties
- Increase in protected cropping of higher value vegetables and fruits, within sufficiently robust cropping structures

Introduction

Quantitative analysis is a foundational component of credible climate risk assessment. It enables decision-makers to prioritise risks, rank adaptation options, estimate costs and benefits, and identify interventions that appear cost-optimal across a range of projected futures. However, by necessity, these approaches are reductive. They simplify complex systems, focus on measurable endpoints, and rely on structured, comparable datasets. As a result, they offer a valuable – but inherently partial – view of the risks posed by climate change and the adaptations required to build robust future resilience.

Throughout this deep-dive project, limitations in both methodology and data availability have underscored that the assessment represents only a narrow segment of the agricultural and horticultural sectors – and an even smaller portion of land use archetypes. The analysis was constrained to linear, quantifiable metrics, excluding broader systemic challenges and opportunities that fall outside the scope the CCC's prescribed methodology. Yet, understanding these excluded dimensions is essential. Exploring risks and adaptation needs beyond the quantitative scope helps contextualise the findings, while also revealing methodological gaps and data limitations that shape the assessment's boundaries.

This chapter draws on available literature, expert input and stakeholder engagement to explore:

1. Aspects of climate change beyond specific heat events – particularly the impacts of and ability to adapt to waterlogging, in addition to the impacts of, and ability to, adapt from combined heat and drought events – such as those witnessed across parts of the UK in 2025;
2. The value of, impacts on and adaptation potential within the UK horticulture sector; and
3. The need to apply systems' thinking to a 'wicked' problem of this kind.

This content is intended to enrich, rather than diminish, the value of the quantitative findings set out in the main report – and is supported by a series of appendices in which a sub-set of these topics are explored in greater detail.

Waterlogging: impacts and adaptation options[122]

Overview

Agriculture and horticulture in the UK are highly sensitive to waterlogging (irrespective of cause), whether through its direct impacts on crop production and livestock health, or its indirect impacts on soil quality and resilience. Excess water can lead to reduced oxygen supply, root rot, and nutrient deficiencies whilst also hindering livestock movement, reducing forage quality and increasing disease risk ultimately resulting in lower harvests and economic losses for farmers.[123] Livestock activity can damage wet soils through poaching, but avoiding this by housing livestock during wet periods can have implications for fodder costs. This section examines the impacts of waterlogging on UK crop and livestock farming, reviews historical occurrences and explores how waterlogging may evolve in the future.

The exceptionally wet winter of 2023/24 highlighted the vulnerability of farming systems, with widespread financial impacts. Looking ahead, high-rainfall periods capable of saturating soils could occur more frequently – although this may take place within a context of drier and warmer summers which depress soil moisture and underlying groundwater levels, reducing subsequent waterlogging risks. Nonetheless, proactive adaptation will be essential, drawing on measures such as improved drainage, optimised irrigation, tolerant crops and robust flood defences, to mitigate waterlogging impacts and support sustainable management of the UK's farmed landscapes.

Causes of waterlogging

Waterlogging is complex, dynamic, and difficult to predict, resulting from interactions within the soil-plant-atmosphere continuum.[124] Waterlogging occurs as a result of numerous factors linked to climate, including

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[122] Note that further information on this topic is provided in 0

[123] Striker, G.G. (2012). Time is on our side: the importance of considering a recovery period when assessing flooding tolerance in plants. Ecological Research, 27(5), pp.983–987. doi:https://doi.org/10.1007/s11284-012-0978-9.

[124] Liu, K., Harrison, M. T., Shabala, S., Meinke, H., Ahmed, I., Zhang, Y., ... & Zhou, M. (2020). The state of the art in modelling waterlogging impacts on plants: what do we know and what do we need to know. *Earth's Future*, *8*(12), e2020EF001801.

geography, soil type, lateral ground water flows, and rising or perched water tables. As a result, identifying the direct cause of waterlogging is often not straightforward, due to poor reproducibility in field trials, high soil variability (e.g., clay content, layering structure, mineral content, etc.), and the unique nature of each waterlogging event.

The most common forms of waterlogging in the UK are seasonal waterlogging and subsoil waterlogging,[128] which frequently impact agricultural areas due to heavy rainfall, high groundwater levels, inadequate drainage, and poor irrigation and farming practices. This is often dependent on the soil type and management regime. For example, soils with high clay content or those that have become densely compacted from repeated machinery traffic often exhibit inadequate drainage, thereby increasing the likelihood of waterlogging events.[125,126,127] Riverine waterlogging is also a significant factor, especially in floodplain areas that experience flooding during heavy rainfall events.[128]

Analysis of prior waterlogging events

There have been two recent notable historical instances of waterlogging in the UK: the 2013/2014 winter flood event and the extended wet period of 2023/2024. These exemplify both acute and chronic waterlogging impacts.

October 2022 to March 2024 Event

The United Kingdom recorded its wettest 18-month period from October 2022 to March 2024. Notably, the autumn of 2023 and the following winter (2023 - 2024) saw rainfall totals that were twice the monthly averages for 1991-2020, leading to considerable flooding across the region. According to the EA's summary report of the Water Situation for February 2024.[129] All river catchments in England received above average rainfall, resulting in wetter than expected soils, particularly in the North East, East, and South East regions – while mean river flows increased at two-thirds of indicator sites. All indicator sites saw a rise in groundwater levels. Rainfall for February was exceptionally high for the time of year in 75% of catchments, notably high in 8%, and above normal in 12%. Six river monitoring sites broke records for their highest February flow, including the Rivers Yare, Gipping, Nene, Avon at Evesham, Upper Brue, and Exe.

This heavy rainfall adversely impacted domestic production of broccoli and other vegetables, including carrots, parsnips, cauliflower, and potatoes.[130] It also hindered farmers across many regions from planting key crops such as potatoes, wheat, and vegetables during the spring season of 2024 and negatively affected the quality of those already sown. Crop reports[131] from 2024 indicate that wheat production decreased by 15%, the largest reduction observed since 2020. Similarly, winter barley production experienced a decline of 22%, also the most substantial drop since 2020.

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[125] Tian, L. X., Zhang, Y. C., Chen, P. L., Zhang, F. F., Li, J., Yan, F., Dong, Y., & Feng, B. L. (2021). How Does the Waterlogging Regime Affect Crop Yield? A Global Meta-Analysis. *Frontiers in plant science*, *12*, 634898. https://doi.org/10.3389/fpls.2021.634898

[126] Najeeb U., Bange M., Tan D., Atwell B. (2015). Consequences of waterlogging in cotton and opportunities for mitigation of yield losses. AoB Plants 7:plv080. 10.1093/aobpla/plv080

[127] Ploschuk R. A., Miralles D. J., Colmer T. D., Ploschuk E. L., Striker G. G. (2018). Waterlogging of winter crops at early and late stages: impacts on leaf physiology, growth and yield. Front. Plant Sci. 9:1863. 10.3389/fpls.2018.01863

[128] Evans, D. E., & Gladish, D. K. (2017). Plant responses to waterlogging. *Encyclopedia of applied plant sciences*, *1*, 36-39.

[129] EA (2025) Research Analysis Water Situation: February 2024 Summary [online] Available at: https://www.gov.uk/government/publications/water-situation-national-monthly-reports-for-england-2024/water-situation-february-2024-summary

[130] Newson, N. (2025) In Focus: Climate change: Supporting farmers and growers, in House of Lords Library [online] Available at: https://lordslibrary.parliament.uk/climate-change-supporting-farmers-and-growers/#fn-4

[131] Defra (2025) Accredited official statistics: Cereal and oilseed production in the United Kingdom 2024 [online] Available at: https://www.gov.uk/government/statistics/cereal-and-oilseed-rape-production/cereal-and-oilseed-production-in-the-united-kingdom-2024

In 2024, UK farmers incurred losses exceeding £1 billion in arable crop income, primarily due to persistently wet winter conditions.[132] Official statistics show that crop output fell by £0.6 billion in 2023[133], with challenging weather during planting and declining prices for cereals and oilseeds exacerbating the situation. Despite these setbacks, the total contribution of agriculture to the UK economy reached £14.6 billion in 2024, an increase of £1.6 billion over 2023. This growth was mainly attributed to higher overall livestock output, accompanied by rising prices for eggs, beef, and milk.[129]

2013 - 2014 Winter Flood Event

The winter 2013/2014 flooding was caused by the succession of deep Atlantic depressions and North Sea storm surges.[134] Widespread coastal flooding and prolonged rainfall was attributed to an unusual configuration within the jet stream. The winter was distinctive for the occurrence of multiple types of flooding. Pluvial, fluvial, groundwater and coastal flooding all affected the UK, sometimes simultaneously, although the relative importance of these varied geographically and over the course of the winter.[135]

The western UK saw coastal flooding intensified by storm surge, swell waves, storm waves, and high spring tides, with river flooding exacerbated by tidal blocking.[136] In the southeast, rainfall at 250% of the long-term average overwhelmed already saturated catchments, causing the River Thames and its tributaries to flood large areas.[137] Economic damages from the floods reached £1,300 million in England and Wales, with agriculture facing £19 million in losses, primarily affecting arable crops (£6.9m), grassland (£1.7m), and livestock (£4.1m).[135] Whilst Flood defences protected 250,000 hectares of farmland, compared to 45,000 hectares that flooded (40,259 ha of cattle grazing, 51,267 ha of sheep and lamb grazing and 11,911 ha of pig paddock), saving an estimated £106.25 million in agricultural damages.[138]

According to a 2014 ADAS report, a total of 44,405 ha of crop land was affected, with 40,259 ha of cattle grazing, 51,267 ha of sheep and lamb grazing and 11,911 ha of pig paddock. For fields waterlogged for <15 days, the estimated average yield loss for winter wheat was 20% and winter oilseed rape was 15%. For fields waterlogged >15 days, losses of winter wheat, winter oilseed rape and winter field beans were all estimated at 100%. Additionally, stakeholder consultation in Somerset highlighted that 50% of land planted with winter cereals (1,336 ha) and oilseed rape (155 ha) was rendered unviable, while 75% of the 50 ha of winter field beans (50 ha) was rendered unviable. 100% of spring cereal planting was delayed, while failed winter cropland could not be re-drilled in a timely fashion, leading to further yield impacts (estimated at 10%).

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[132] https://www.fwi.co.uk/news/weather/farmers-lost-1bn-to-extreme-weather-in-2024-defra-says

[133] Defra (2025) Accredited official statistics: Total income from farming in the UK in 2024 [online] Available at: https://www.gov.uk/government/statistics/total-income-from-farming-in-the-uk/total-income-from-farming-in-the-uk-in-2024

[134] Kendon, M., & McCarthy, M. (2015). The UK's wet and stormy winter of 2013/2014. *Weather (00431656)*, *70*(2)

[135] ADAS UK Ltd on behalf of Defra (2014) Impact of 2014 Winter Floods on Agriculture in England [online] Available at: https://assets.publishing.service.gov.uk/media/5a74a46d40f0b61df47774b1/RFI7086_Flood_Impacts_Report__2_.pdf

[136] Sibley, A., Cox, D., & Titley, H. (2015). Coastal flooding in England and Wales from Atlantic and North Sea storms during the 2013/2014 winter. *Weather (00431656)*, *70*(2)

[137] EA (2014) February 2014 Flooding [online] Available at: ITEM%205a%20ii%20Annexe%205b%20-%20Environment%20Agency%20Briefing%20Note.pdf

[138] Chatterton, J. et al (2016). The costs and impacts of the winter 2013 to 2014 floods -Non-technical report - SC140025/R2. GOV.UK.

Future potential for wet periods

A 2024 study found that climate change had increased both the frequency and intensity of heavy rainfall during autumn and winter storms in the UK and Ireland from October 2023 to March 2024.[139] It found that, in a pre-industrial climate, rainfall from storms as intense as the 2023-24 season would have had an estimated 50-year return period. In today's climate, with 1.2°C of warming, these events are expected to occur once every 5 years and be 20% more intense compared to pre-industrial times. In a 2°C world, storm events of this magnitude could occur once every 3 years and be an additional 4% more intense compared to today's climate (1.2°C of warming).

Similarly, for wet periods such as the October 2023-March 2024 season, the estimated return period in a pre-industrial climate was once in 80 years. In today's climate, such an event is at least four times more likely to occur. Scientists estimate that climate change has increased total rainfall by about 15%. If global warming reaches 2°C, similar periods of rainfall – capable of saturating soils and causing significant agricultural losses – are expected to become much more frequent, occurring roughly every 13 years.[139]

Potential adaptation strategies

Effective prevention and management strategies are crucial to mitigate waterlogging. Below are some examples of measures that can improve the resilience of agriculture to waterlogging.

- **Soil Management Practices:** Deploy a combination of soil management measures to improve soil structure and water holding capacity (including cover cropping; minimum tillage; crop rotation; maintained surface cover, increases soil organic matter; reduced machinery traffic). Improvements to root health can also support heat tolerance and other co-benefits such as improving soil shear strength and reducing susceptibility to erosion.
- **Crop selection:** Select crop varieties with high tolerance to waterlogging conditions (e.g., early maturing cereals), noting that this may require trade-offs between tolerance and yield / quality. A number of tree species are tolerant / moderately tolerant to waterlogging and may contribute to alternative land use strategies. These include several willow (*Salix*) and alder (*Alnus)* species, as well as Bird Cherry (*Prunus padus*) and Pedunculate Oak (*Quercus robur*).[140]
- **Drainage:** Effective drainage techniques play a crucial role in mitigating waterlogging. Already wet weather and low crop prices in the UK have prompted an increase in drainage operations on arable land, resulting in yield increases of up to 35%.[141] Problems such as delayed drainage of flooding and waterlogging may occur when conventional subsurface drainage is used alone, whether through pipe drains, mole drains or tile drains. Ditches, outfalls and pipes should be regularly cleared and periodic jetting of the drainage network may be necessary to optimise water flows. Costs to install new drainage systems may range between £2,500 and £3,500 per hectare, comprising perforated plastic pipe installed at a depth of around 0.8m in a trench that is normally backfilled with aggregate to maintain permeability.[142]
- **Bio drainage:** removes excess soil water by relying on evapotranspiration by deep-rooted fast-growing trees such as willow and poplar. Plant water consumption can vary between 6500 and 28

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[139] Met Office (2024) Climate change drives increase in storm rainfall [online] Available at: Climate change drives increase in storm rainfall - Met Office

[140] Broome, A., Beauchamp, K., Breeze, T. & Staton, T. (2024). Tree Species Guide for UK Agroforestry Systems [online]. Available at: https://www.forestresearch.gov.uk/publications/tree-species-guide/

[141] Farmers Weekly (2016) How to tackle poor drainage to raise crop yields [online] Available at: https://www.fwi.co.uk/arable/land-reparation/soils/tackle-poor-drainage-raise-crop-yields

[142] Redman, G. (2023). John Nix Pocketbook for Farm Management For 2024. Fifty-fourth edition, published by Agro Business Consultants Ltd

000 m^3 ha^{-1} yr^{-1} and an ideal tree plantation can lower groundwater levels by 1-2 m over 3-5 years.[143] Evapotranspiration rates will be lower in winter (or nil for deciduous species).

- **Flood defence:** Raise riverbanks to reduce river overtopping onto land.
- **Irrigation systems:** Drip irrigation reduces evaporation and prevents waterlogging, allowing plants to receive exactly the amount of water they need, instead of watering the entire cropped surface.

Case studies

Key points from case studies exploring how two UK farms have dealt with waterlogging are set out in Table 46. These examples highlight that different waterlogging problems demand different solutions. On slowly drained heavy soils, investing in better field drainage infrastructure can dramatically improve productivity and prevent chronic waterlogging. On the other hand, when faced with sudden flood-induced waterlogging, an adaptive agronomic strategy – like changing crops and remediating soil when conditions allow – can save a season. Notably, both approaches are complementary: good infrastructure provides long-term resilience, while flexible management provides immediate benefit. In practice, farmers may need to combine both engineering fixes and crop/soil management tweaks to combat waterlogging. By doing so, they can protect their crops, maintain yields, and improve soil health even as extreme weather events become more frequent.

Table 46. Summary case studies where UK farms have sought to address waterlogging

Farm case	Waterlogging Issue	Intervention Implemented	Outcomes Achieved
Molescroft Farm *Large arable farm on heavy clay lowlands (East Yorkshire)*	Aging 30-yr-old field drains were failing on heavy clay soil. Persistent ponding (“wet patches”) in fields after rain. Weed outbreaks (e.g., blackgrass) due to damp soil; rising herbicide costs. Very short planting window in autumn; struggled to sow winter	Drainage system overhaul: Installed new subsurface plastic drains to replace old clay tiles (improving capacity & longevity). Cleared and re-dug ditches/outfalls to remove blockages (a quick ditch clean can “rejuvenate” a whole field). Added supplemental mole drains in clay subsoil to aid water flow into main drains. Staggered the drainage work over several years (post-2012) to manage costs,	Yield restoration: Grain yields rebounded by ~30-40% on drained land (e.g., wheat from ~8 → 12 t/ha on one field), unlocking ~+£175/ha/year in extra output. Extended workability: Fields dry faster, allowing on-time sowing and agrochemical applications even in wet seasons. Farming operations are timelier and more efficient. Lower weed pressure: Drier soils have fewer water-loving weeds; the farm projects cutting herbicide use by ~£30/ha as crops stay cleaner.[144]

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[143] Singh, G., & Lal, K. (2018). Review and case studies on biodrainage: An alternative drainage system to manage waterlogging and salinity. *Irrigation and Drainage*, *67*, 51-64

[144] Farmers Weekly. (2015). How to improve soil and yields with effective field drainage. [online] Available at: https://www.fwi.co.uk/arable/land-preparation/soils/how-to-improve-soil-and-yields-with-effective-field-drainage.

Farm case	Waterlogging Issue	Intervention Implemented	Outcomes Achieved
	crops on time because ground stayed wet.	eventually covering ~485 ha.	Economic gains: Improved yields and lower costs add ~£229/ha/yr benefit. Upfront costs (~£2k/ha) should be recouped in ~10 years, after which profitability on those acres is much higher.
Fownhope Farm *Mixed arable farm on river floodplain (Herefordshire)*	Severe river flooding in winter drowned ~34 ha of arable land. Winter wheat could not be sown at all (fields under water in autumn). Risk of complete crop failure on those waterlogged fields (wheat would have died). Soil left with silt, compaction, and damaged field drains after floodwaters receded.	Cropping change: Abandoned autumn sowing. Switched the 34 ha from winter wheat to a spring crop (large blue peas) that could be sown in April once land dried. Soil repair: Once floodwater fell, cleared drainage channels of silt and ran a subsoiler (Sumo) to break up compaction from flooding/potatoes. Staggered planting: Rescheduled cropping so wetter low fields went into peas (later), while maximizing wheat on higher ground that was dry enough. Used the pea crop itself to help dry the soil via transpiration and restore soil structure (a natural "biological drainage" approach).	Avoided lost land: The threatened 34 ha still produced a harvest (of peas) instead of yielding nothing. This safeguarded farm income and cropping targets despite the floods. Recovered soil health: Post-flood remedial actions improved field conditions - compaction was alleviated and drainage function restored - setting up the land for a return to normal winter cropping by the next season. Minimal fallow area: With flexible planning, almost the entire farm was cropped (only a few small patches stayed bare for recovery), showing resilient use of land. Adaptive success: By matching crop choice to field conditions, the farmer reduced potential losses. He demonstrated that *"doing something is better than doing nothing"* - planting peas was agronomically and economically smarter than either risking a wheat or leaving land idle.

The value of, impacts on and adaptation potential within the UK horticulture sector[145]

Overview

- There are around 17 million hectares of farmed land in the UK
- Horticulture occupies less than 1% of this, but accounts for around 20% of the value of UK agricultural output
- Around 50% of vegetables consumed in the UK are grown domestically, but this falls to 15% for fruits
- Although horticultural businesses are widely dispersed across the UK, there are important concentrations on low-lying, organic-rich soils such as those found in the Fens. These are particularly vulnerable to flood and drought events
- Climate change provides a number of opportunities for crop diversification across the UK

Climate Vulnerabilities and Climate opportunities

UK agriculture and horticulture are highly exposed to climate variability and extreme weather, albeit in different ways for different products. The main climate hazards include extreme heat, combined heat and drought episodes, excessive rainfall (causing waterlogging or floods), late spring frosts, and intense storms/winds. Three of the five worst harvests on record have occurred since 2020 as a result of weather extremes.[146]

Table 47. Climate change vulnerabilities within different horticultural sub-sectors

Sub-sector	Main Climate Risks	Recent Examples of Impact
Field Vegetables (carrots, brassicas, etc.)	Heat & Drought; Flooding; Storm damage	*Hot Dry 2018* – Widespread drought saw carrot yields fall ~25–30% and onions ~40% below normal due to heat and water stress. This followed winter waterlogging (delaying planting), contributing to losses estimated at £100 million. *Flooding in 2020* – Record winter rains (237% of average rainfall in February) drowned or delayed vegetable plantings, which were then established in poor seedbed conditions – potentially contributing to significant losses
Orchard Fruits (apples, pears, etc.)	Late Spring Frost; Waterlogging; Heat/drought; Storms	*Spring Frost* – Cold snaps during May 2023 reduced fruit set in apples, potentially contributing to losses of ~£150million.
Soft Fruits (berries)	Frost; Heat; Heavy Rain; Storms	*Winter Storms 2024* – Storms and flooding in Jan–Feb 2024 disrupted early strawberry crop management under polytunnels, delaying the season. *Summer Extremes 2024* – A late June heat spike

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[145] Note that further detail on this topic is provided in Appendix H.

[146] Speare-Cole, R. (2025). UK harvest on course for near record low after drought hits crops – analysis. [online] The Independent. Available at: https://www.independent.co.uk/climate-change/news/met-office-b2812587.html.

Sub-sector	Main Climate Risks	Recent Examples of Impact
		caused a glut of berries, then a cold, wet July sharply reduced yields. Variable weather led to ~4% lower strawberry yields, year-on-year.

Longer Growing Seasons & New Crop Varieties

Milder temperatures and fewer frost days will extend the growing season in many parts of the UK. Frost-free periods have increased by several weeks in some regions. This can allow earlier planting in spring and later harvesting in autumn, potentially enabling multiple crop cycles per year for fast-growing vegetables. For example, warmer springs are already allowing some growers to plant potatoes or carrots earlier (although frost risk remains a constraint). Looking ahead, climate projections suggest that by mid-century, areas of southern England will have a climate more akin to northern France historically – potentially providing conditions suited to crops that prefer slightly warmer conditions. Recent exploration of future suitability for >160 crops in the UK shows that warming increases suitability for many crops, including some not typically or widely grown here today such as sunflowers, soybeans, chickpeas and cowpeas.[147] Okra and outdoor aubergine might become more viable in the far south. For fruit, viticulture is expected to benefit particularly.[149] Moderate warming may boost yields of certain current crops, such as carrots – assuming that they are not limited by water availability.[148]

Geographical Shifts

Climate change will not affect all UK regions equally, and some currently marginal areas may become more productive. Parts of eastern Scotland and northern England, historically limited by short growing seasons, could see significantly milder conditions. A study by UKCEH highlights that the southwest of England and Scottish Borders could see the greatest increases in suitability for cropping later in the century.[147] This suggests an opportunity for those regions to expand horticultural output, for example Scottish growers might grow more field vegetables or even fruits that were once confined to Kent. Such transpositions are already starting to be visible, while there has been a significant expansion of viticulture in the south of England (which now produces ~10+ million bottles of wine a year, from around 3,500ha of vines – a tenfold increase in two decades[149]), a number have been established as far north as Yorkshire. These shifts could contribute to resilience by spreading production more evenly across the country, although land type and topography in southwest England and Wales could constrain future expansion.[147] Nonetheless, the changing climate could *rebalance* UK horticulture, with proactive farmers in current cooler regions benefiting from warming, particularly if the south fails to invest in measures to address water stress.

Adaptation strategies

Table 48 summarizes recommended measures for UK fruit & veg growers, along with how they boost climate resilience and key considerations for implementation:

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[147] Ranger, S. (2025). Climate change and farming: The surprising impact on the UK's crops. [online] Soci.org. Available at: https://www.soci.org/news/2025/1/climate-change-and-farming-the-impact-on-the-uks-crops.

[148] Paul (2025). The Weather Woes: Challenges Facing UK Crops - Four Seasons Fruiterers. [online] Four Seasons Fruiterers. Available at: https://www.fsfruit.co.uk/the-weather-woes-challenges-facing-uk-crops/

[149] English Wine -Increased Production and Exports Summary. (n.d.). Available at: https://www.theccc.org.uk/wp-content/uploads/2019/07/Outcomes-Wine-case-study.pdf.

Table 48. Adaptation measures, climate resilience benefits and implementation factors

Adaptation Measure	Climate Resilience Benefit	Implementation Factors
Efficient Irrigation & Water Storage *Build on-farm reservoirs; use drip irrigation and sensors to schedule watering events*	Buffers against drought – Ensures water supply during dry spells, maintaining yields and quality when rainfall is low.[150] Efficient drip systems deliver water directly to roots, reducing waste and helping crops cope with heat. Also provides insurance against irrigation bans by storing winter rain.	Cost: High upfront investment for reservoirs/pumps; may need grants or cooperation (shared reservoirs). Infrastructure: Requires space and suitable ground conditions; may need abstraction license to fill it in winter.[150] Operation: Drip lines need maintenance (clogging, etc.) and management skill to schedule properly (often via soil moisture sensors or weather data). Training: Farmers may need guidance on irrigation scheduling to avoid under/over-watering.
Enhanced Drainage & Flood Mitigation *Install or maintain field drains, use raised beds; maintain ditches, create runoff ponds*	Reduces waterlogging and flood damage by allowing excess water to drain rapidly during heavy rain, preventing root suffocation and crop losses.[151] This helps to maintain soil structure and allow timely field operations (planting/harvesting) even in wet seasons. Raised beds and diversions protect crops in flood-prone sites.	Cost: Moderate – installing drains or raised bed equipment has upfront costs, but often one-time. Land: Drainage improvements must align with land topology; need outlet for drained water (nearby ditches/rivers). Some soil types are not suitable for bed-forming Environmental compliance: Ensure drainage doesn't harm downstream ecosystems (may need regulatory approval). Maintenance: Ditches and drains must be kept clear annually; plan for ongoing upkeep.
Climate-Resilient Crops & Varieties *Select heat-tolerant, drought-resistant, or*	Maintains yields under new climate stresses – Varieties bred for heat or drought yield reliably in extreme conditions (e.g., broccoli varieties that resist bolting in heat).[152] Low-chill fruit varieties still flower	Testing: New varieties may require trialling to ensure they perform in local conditions and meet market specs. There may also be trade-offs between resilience,

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[150] Bradshaw, S. (2023). Future of Horticulture. [online] UK Parliment Post. Available at: https://researchbriefings.files.parliament.uk/documents/POST-PN-0707/POST-PN-0707.pdf.

[151] Collier, R. and Thomas, B. (2016). Agriculture and Forestry Climate change report card technical paper 5. Climate change impacts on horticulture. [online] UKRI.org.

[152] Collier, R. (n.d.). Climate Change and UK Horticulture: What is to come and how to build resilience? [online] Oxford Real Farming Conference.

Adaptation Measure	Climate Resilience Benefit	Implementation Factors
low-chill varieties; diversify crop mix	after mild winters, preserving fruit yield.[151] New crops (chickpeas, etc.) can exploit longer warmer seasons.[147] Diversifying crops spreads risk so one weather event won't hit all production.	productivity and marketable crop quality Knowledge: Farmers need access to information on suitable varieties (seed companies, researchers) and possibly training in new crop agronomy. Market: Ensure there is buyer acceptance for any new crop or variety (e.g., taste, appearance might differ). Might require consumer education if introducing truly novel produce. Seed availability: Resilient varieties must be obtainable; may involve participating in breeding trials or early adoption programs.
Protected Cropping (Tunnels, Greenhouses, Shade) *Use polytunnels or glasshouses; deploy shade nets or frost covers*	Shields crops from extremes where feasible, to ensure stable yields and quality.[148] Glasshouses and polytunnels can also extend growing seasons and prevent losses from pests (if enclosed). Shade netting mitigates heat stress and scalding during heatwaves, preserving crop quality. Overall, protected environments mean far fewer weather-related crop failures.	Capital Intensive: High cost for glasshouses; polytunnels cheaper but still significant investment (plus eventual plastic replacement). May need financing or grants. Energy & Ops: Glasshouses need energy (heating, cooling) – efficiency measures (solar, CHP (combined heat and power)) help but operational costs are ongoing. Polytunnels require labour to set up and vent. Planning/Community: Tunnels can face local opposition (aesthetics); need to consider planning permission and neighbour relations. Technical Skill: Managing environment (ventilation, humidity) requires knowledge – larger operations may need skilled growers or automation. Nature-poor: Enclosed systems exclude nature although offer wider system benefits such as reduced inputs (water, nutrients, pesticides) that have indirect benefits

Adaptation Measure	Climate Resilience Benefit	Implementation Factors
Soil Management for Resilience *Improve organic matter; use cover crops; reduce tillage; apply mulches*	Enhances drought and flood resilience via soil health – organic matter in soils contributes to their water holding capacity (WHC) and can reduce irrigation need and crop stress during drought.[151] Better soil structure improves drainage in heavy rain, preventing waterlogging. Healthier soils also support stronger root systems, contributing to improved crop vigour and resilience. Mulches regulate soil temperature and moisture, buffering against heat and dry spells.	Transition period: Building soil health takes time, with benefits accruing over years. Initially, cover cropping or reduced tillage may complicate planting schedules or require equipment changes. Knowledge: Farmers may need advice on selecting cover crop species and managing them, to fit into rotations. Costs/Savings: Some expense for cover crop seeds and possible yield trade-offs by not leaving land bare. But often saved costs in the long run (less fertiliser, etc.). Verification: Participating in schemes like SFI can offset costs, but requires documentation of practices for compliance.[249]
Frost Protection Techniques *Deploy frost fans, heaters, or sprinklers; choose sites less prone to frost; delay pruning/planting*	Prevents late frost damage – Frost fans or heaters in orchards can raise temperature by a few critical degrees during radiational frosts, saving blossoms from freezing.[153] Overhead sprinkler systems (common in fruit growing) coat blossoms with ice to release heat and protect them on freezing nights. Even simple measures like covering rows with fleece on cold nights can shield tender vegetables. Choosing higher elevation sites or those with air drainage for new orchards avoids frost pockets. Together, these measures greatly reduce the risk of losing an entire crop to one cold night in spring.	Expense: Wind machines and large frost control systems are expensive and need fuel/power; usually justified for high-value perennial crops (fruit orchards, vineyards). Scale/Logistics: Sprinkler frost protection needs ample water supply and pumps; feasible where water is available. For small-scale vegetable cropping, row covers are cheap but labour-intensive to deploy and remove. Knowledge of Conditions: Must have good weather forecasts and understand local microclimate to activate frost measures at right time. Long-term decisions: When planting new orchards / vineyards, factoring in frost risk is a no-cost adaptation but requires planning

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[153] T, D. (2022). Climate Change in the Orchard: Later Frosts, Earlier Harvests? – Orchard Notes. [online] Orchardnotes.com.

Adaptation Measure	Climate Resilience Benefit	Implementation Factors
		and possibly avoiding otherwise good land.

Impacts of combined heat and drought events

Overview

The traditionally stable and temperate UK climate is becoming increasingly unpredictable and extreme due to anthropogenic climate change, with serious knock-on effects making the UK agriculture sector evermore exposed to compound drought and heat events. Recent summers (primarily 2018 and 2022) brought record-breaking temperatures and rainfall deficits, leading to crop failures and livestock stress, presenting serious challenges for the sector. These compound events can cause widespread impacts on both crops and livestock. For example, eight of the ten warmest years on record in the UK have occurred since 2002.[154] Losses have occurred through reduced crop yields, degraded crop quality, and reduced livestock productivity. These losses are further compounded by increased input costs, especially for feed and water. In 2018, total income from farming fell by 17% year-on-year, equating to an almost £1 billion reduction in income. Livestock farmers faced feed shortages, resulting in early culling and reductions in fertility, while arable and horticultural producers reported yield declines of up to 20% in some cereals, 13% in potatoes, and notable quality downgrades in fruits and vegetables. In 2022, similar impacts emerged. Additional operational hazards linked to unprecedented temperatures exceeding 40°C, widespread irrigation restrictions, and elevated mortality in poultry transport were also identified.

This section examines how recent compound drought-heat episodes impacted UK farm businesses in terms of economic losses and operational disruptions, and how farmers have responded to these events.

Prior drought and heatwave events

Historical events, such as the 2011 drought, incurred substantial economic losses to UK agriculture (£400 million)[155]. Recent droughts in 2018 and 2025 have highlighted the importance of water supplies for both agricultural irrigation and for livestock, and the need to develop robust adaptations to reduce the impacts of future droughts and water scarcity on this sector.

Irrigated production is particularly vulnerable. The dry conditions in 2012 alone resulted in £72 million in losses for irrigated potato production in England[156]. As the climate warms, irrigation demand is projected to rise particularly in parts of the UK, such as East Anglia and Northwest England[157]. In areas where irrigation is well-established a changing climate will likely drive further investment in irrigation infrastructure underpinned by greater dependence on on-farm 'high flow' storage to support a transition away from

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[154] The National Farmers' Union (NFU). (2018) LEARNING LESSONS FROM THE 2018 AGRICULTURAL DROUGHT. Available at: https://www.nfuonline.com/media/mcbh24td/learning-lessons-from-the-2018-agricultural-drought.pdf

[155] University of Cambridge Programme for Sustainability Leadership, Anglian Water (2013) Water, Water Everywhere? Available at: https://www.cisl.cam.ac.uk/system/files/documents/water-water-everywhere-scroll.pdf.

[156] Akande K, Hussain S, Knox J, Hess T, Hooftman D, Stratford C, Schafer S, Acreman M and Edwards F (2013) The Impacts of Drought in England. R&D Technical Report WT0987/TR. Department for Environment, Food and Rural Affairs Water Availability Division, London

[157] Henriques, C., Holman, I.P., Audsley, E., Pearn, K (2008) 'An interactive multi-scale integrated assessment of future regional water availability for agricultural irrigation in East Anglia and North West England'. Climatic Change, 90(1-2), pp. 89-111.

rainfed cropping. However, competition for water resources is intensifying, driven by both climate change and non-climatic factors like population growth, environmental improvements and economic development. Climate change is likely to worsen this competition by creating more arid environments and increasing precipitation variability, which will force agriculture to compete with urban and industrial sectors for land, water, and economic resources[158]. The drought impacts experienced in England in 2025 are starting to become evident and the Environment Agency report that:

The impact of drought on agriculture this year has been significant. Farmers have experienced a challenging and difficult season with poor grass growth, low forage yields and, where no irrigation has been available, reduced quality and yields for field vegetables.

The harvest season finishes with minimal reservoir volumes available for carry-over to next year for irrigation and dry soils. The success and yield of crops planted this winter and next spring are dependent on the rainfall this winter and groundwater recharge. This is needed to improve soil moisture and refill reservoirs (where farmers have this available as a resilience option).

Autumn drilled crops (for example oil seed rape and winter wheat) are dependent on soil moisture for germination. The decisions made by farmers on timing of drilling will affect germination success and requirements for the control of black grass, pests and disease risk. Some areas of England have seen improving soil moisture, whilst others have not.

For livestock producers, this year has been poor for growing forage stocks. The dry conditions have led to farmers feeding existing forage stocks to their livestock in the summer months. Producers are looking to extend the grazing season as long as possible to reduce costs. Some livestock businesses are now short of forage for feeding their livestock over the winter months and will need to find alternative sources such as by-product feeds or sell their stock.[159]

Drought and Heatwave of 2018

The spring and summer of 2018 were exceptionally dry and sunny across the UK. By July–August, soil moisture deficits hit levels comparable to 1976 in parts of England.[160] Rain-fed crops wilted and pasture growth stalled. It was the joint hottest summer on record for the UK (with 1976) and among the driest for England.[154] Total income from farming (TIFF) fell by 17% in 2018 compared to 2017 (from £5.63bn down to £4.7bn).[161] The summer droughts and previous harsh winter were cited as major factors for driving reduced crop yields and increased feed costs.[161]

Cereals

- UK wheat harvest was approximately 14.1 million tonnes, down 5–6% compared to the previous five-year average.[162,163]

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[158] Motha RP (2007) Development of an agricultural weather policy. Agricultural and Forest Meteorology, 2–4:303–13

[159] Environment Agency (2025). 4. Agriculture - drought risks, impacts and actions: Drought prospects for spring 2026. [online] GOV.UK.

[160] Cranfield University. (2022) UK drought; are famers facing the crop failures of 1976 all over again? Available at: https://www.cranfield.ac.uk/press/news-2022/uk-drought-are-farmers-facing-the-crop-failures-of-1976-all-over-again

[161] Agriland. (2019) UK farm income falls by 17% in 2018. Available at: https://www.agriland.co.uk/farming-news/uk-farm-income-falls-by-17-in-2018/

[162] BCPC. (2019) Wheat yields – 2018. Available at: https://www.bcpc.org/latest-news/wheat-yields-2018-2

[163] Department for Environment Food & Rural Affairs (DEFRA). (2018) Farming Statistics – First estimates of 2018 Uk wheat and barley production.

- The West Midlands saw a sharper drop of 9% below the five-year regional average, with parts of Northern England experiencing 20% declines.[164]
- UK barley production fell by approximately 8% (nearly 0.6 million tonnes lower than 2017, with total losses of approximately £90 million based on feed barley prices of £150/t that year.[165]

Potatoes

- Potatoes saw a fall in production to 4.9 million tonnes, 13% below the five-year average of 5.6 million tonnes[166] due to a 12% decline in average yields.[167]
- It was particularly noted that yields from many unirrigated potato fields were far lower than usual, and with only ~53% of potato land in Britain normally irrigated, half the crop had no relief from the drought, with tuber growth stalling in the hot, dry June – July period.[167]
- In England, where the heat was severe, potato yields averaged just 40 t/ha – a 20% decrease from the previous year's 50 t/ha.[167]
- Impact was regionally distributed, with northern and western regions seeing slightly more rain. Yields in Scotland were 3% higher than the prior year due to the more favourable conditions.[167]

Cattle and milk

- Livestock farmers surveyed by the NFU reported forage shortages going into winter. A report noted that many farmers fed their autumn/winter forage stocks during the summer of 2018 due to insufficient pasture growth.[167]
- One Peak District farmer reported that he had lost 25% of his silage crop and 40% of his hay due to the drought, and spent £7,000 on additional straw (with another £10,000 expected) to feed his cattle,[154] contributing to an 8% increase in farm input costs in 2018 (year-over-year).[161]
- Analysis by the NFU noted 30,000 more cattle sent to slaughter in 2018 than normal. Likely due to farmers culling or selling animals early because of insufficient feed.[154]
- No quantified data are available, but it was noted that heat stress led to lower fertility in cows,[154] animal health issues such as mastitis in heat-stressed dairy cows[168] and difficulty breeding in sheep.[154]

Sheep

- Sheep are less sensitive to heat but are susceptible to drought with lack of grass leading to poor ewe condition.[169] The knock-on of a harsh late winter ("Beast from the East" storm) followed by summer drought caused the UK lamb crop to be about 1 million head lower than the previous year.[154] This highlights the knock-on effects of multiple weather events – in this case late winter storms killing newborn lambs, with the surviving flock subject to poor grazing conditions in the following summer.

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[164] Department for Environment Food & Rural Affairs (DEFRA). (2018) Farming Statistics – First estimates of 2018 Uk wheat and barley production. Available at: https://assets.publishing.service.gov.uk/media/5bb7034de5274a225d681376/structure_jun18_wheatandbarleyUK_08oct18.pdf

[165] AHDB. (2025) UK delivered prices. Available at: https://ahdb.org.uk/cereals-oilseeds/uk-delivered-prices

[166] Agriland. (2018) UK potato production hits lowest level since 2012. Available at: https://www.agriland.co.uk/farming-news/uk-potato-production-hits-lowest-level-since-2012/

[167] Salmoral, G., Ababio, B., Holman I. P. (2020) Land. *Drought Impacts, Coping Responses and Adaptation in the UK Outdoor Livestock Sector: Insights to Increase Drought Resilience.* 9(6), 202. https://doi.org/10.3390/land9060202

[168] AHDB. (2025) Reducing the risk of environmental mastitis during lactation in dairy cows. Available at: https://ahdb.org.uk/knowledge-library/reducing-the-risk-of-environmental-mastitis-during-lactation-in-dairy-cows

[169] Henry, B.K., Eckard, R.J., Beauchemin, K.A. (2018) Animal. *Review: Adaptation of ruminant livestock production systems to climate changes.* 12(2). Pp s445-s456. https://doi.org/10.1017/S1751731118001301

- In Wales, one study noted that extreme heat events can lead to the death of newborn lambs as a result of heat stress, with droughts also leading to a shortage of drinking water for livestock – bringing its own health and mortality implications.[170]

Drought and Heatwave of 2022

Vegetables, root crops & potatoes

- Unirrigated root crops including carrots and onions suffered low yields in eastern England, with undersized produce due to lack of rainfall.[171]
- Where they had access to suitable infrastructure, vegetable farmers utilised irrigation from June, with many reporting depleted and empty reservoirs by August. Reduced water availability also led to small or misshapen vegetables.[172]

Cereals

- National wheat yields in 2022 increased by 8% above the 2017 – 2021 average, due to favourable growing conditions prior to the drought. When extreme heat and drought hit in July, many cereal crops were already close to maturity[174].
- Farmers reported very early harvests, although the early harvest also meant dry grain (moisture well below normal), which reduced drying costs but raised risks of poor grain quality.[172]
- Oilseed rape and spring barley yields fell: one Welsh farm saw oilseed rape yield only 4.25 t/ha vs the anticipated 5 t/ha.[173]
- Between April and October of 2022, there were 49,678 instances where Hands-off Flow measures were in activation for spray and trickle irrigation, meaning that no water could be abstracted for direct irrigation. The effects of the water shortages during the drought were shown by reduced yields for some commodities such as potatoes and onions.[173]

Beef

- Livestock farmers across the country began feeding silage and hay to their herds months earlier than normal, with similar culling patterns to those seen in the 2018 summer.[171]
- One Devon beef farmer planned to sell half his 200 cattle by autumn 2022 because he had no grazing left and no affordable feed to sustain them through winter.[171]

Poultry

- In 2022, some poultry farms in Europe lost birds to heat; the UK largely avoided mass fatalities but only through active cooling and management. Nonetheless, the UK experienced a 9.2% reduction in chicken meat production compared to 2021, a 2.6% reduction from the 1997 – 2022 average[174]

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[170] Farmlytics. (2024) *Extreme weather and its impact on farming viability in Wales.* Available at: https://www.farmlytics.com/portfolio/extreme-weather-and-its-impact-on-farming-viability-in-wales

[171] The I Paper. (2022) UK drought shrinks potatoes, onions and other crops as farmers warn of lasting damage. Available at: https://inews.co.uk/news/uk-drought-farmers-struggle-feed-cattle-cheap-meat-heatwave-1793194

[172] FARMERS WEEKLY. (2022) Harvest 2022: Counting the yield cost of the drought. Available at: https://www.fwi.co.uk/arable/harvest/harvest-2022-counting-the-yield-cost-of-the-drought

[173] Barket, L.J. et al (2024). Weather. *An appraisal of the severity of the 2022 drought and its impacts.* 79(7). Pp 208-219. https://doi.org/10.1002/wea.4531

[174] Davie, J. et al (2023) Frontiers in Environmental Science. 2022 UK heatwave impacts on agrifood: implications for a climate-resilient food system. 11:1282284. https://doi:10.3389/fenvs.2023.1282284

- Greater damages were experienced in the east of the UK, which was exposed to the highest temperatures. Animal welfare-reported incidents of heat stress and dead-on-arrival (DOA) at slaughterhouses.[173]
- Over 18,500 chickens died in transport between August and July 2022, due to heat stress, compared to 325 deaths in the same period in 2021.[173] With the average price of a broiler chicken at £2.52[175] for 2022/23 this represents total losses of £46,620

Other general observations noted operational hazards as a result of extreme heat, flagging the importance of fire risk and harvest safety as dry conditions increase wildfire and field fire risk. A number of instances of combine harvester and field fires have been reported as a result of dry conditions, in some cases leading to complete loss of fields at the point of harvest. It is also noted that dry weather can create ideal Autumn planting conditions, although not where drought persists and renders the ground too hard for cultivation or drilling. A further point is that farmers must spend time and resources on emergency measures: transporting water, reorganising grazing (moving animals to any available grass, if any), and arranging early sales. Some farmers coordinated to share resources (e.g., water and forage trading between farms to save crops/livestock). All these activities present impacts and disruptions to typical operations with knock-on effects on farm business viability.

Practical responses

Adaptation is essential if agricultural operations and practices can continue with minimal disruption. Based on experiences from 2018 and 2022, a number of adaptation options have been developed (Table 49).

Table 49. Adaptation responses to mitigate effects of combined heat and drought events

Option	Comments
Reduce Herd or Flock Size	Many farmers chose to sell livestock early to cut losses during 2018 and 2022 to alleviates pressure on feed and water supplies.[176]
Nighttime grazing	Some farmers shifted routines moving cattle grazing to night-time or scheduling heavy work such as moving or shearing sheep for cooler hours to reduce heat stress.[177]
Buy additional feed & concentrates	Where affordable, some farmers bought feed such as hay and silage or concentrates like grain or pellets to replace grazing. This is expensive, and some needed emergency loans or support to finance it.[178]

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[175] Department for Environment Food & Rural Affairs (DEFRA). (2023) FARM BUSINESS SURVEY – Poultry Production in England. Available at: https://www.farmbusinesssurvey.co.uk/regional/reports/Poultry-Production-in-England-2022-23.pdf?utm

[176] The National Farmers' Union (NFU). (2018) LEARNING LESSONS FROM THE 2018 AGRICULTURAL DROUGHT. Available at: https://www.nfuonline.com/media/mcbh24td/learning-lessons-from-the-2018-agricultural-drought.pdf

[177] AHDB. (2018) Drought 2018 – What's happening on farm: August. Available at: https://ahdb.org.uk/news/drought-2018-what-s-happening-on-farm-august?utm

[178] Scottish Government. (2018) Early loans for farmers being made available. Available at: https://www.gov.scot/news/early-loans-for-farmers-being-made-available/?utm

Option	Comments
Use fallback resources	In 2022, the UK government granted a derogation for farmers to cut or graze land in environmental stewardship schemes that would otherwise normally have to be left untouched, allowing additional forage to be gathered from land that was otherwise off-limits.[179]
Fodder management	After 2018, many livestock farmers learned to make contingency plans for feed. This includes conserving more silage in good years as a buffer, growing drought-resilient forage crops (such as alfalfa, which has deep roots) to have a reserve, and arranging forage contracts or insurance. There's also renewed interest in feed storage and distribution infrastructure so that feed can be moved to where it's needed in an emergency.[180]
Shade and cooling for livestock	On dairy and poultry farms, emergency measures such as misting fans, sprinklers, or simply providing shade and ventilation were ramped up to reduce heat stress.[181]
Water management (priority delegation)	Crop farmers prioritised fields for irrigation and where needed, sacrificed lower-value crops to save higher-value ones.[182]
Water trading	One specific source highlighted how, through communication with a neighbour and the Environment Agency, a farmer arranged for temporary use of the neighbour's unused water abstraction allocation. The NFU highlighted this case as an innovative response; it "saved the money, over £50,000, I'd spent growing the crop" said the farmer, indicating a significant sum was rescued by quick cooperation.[154]
On-Farm water storage	The 2018 NFU report's top recommendations included making it easier to construct on-farm reservoirs. Having an irrigation reservoir can mean the difference between a total crop loss and a salvageable yield in a drought.[154] Government grant funding for water storage was also increased in 2022.[179]

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[179] Farminguk. (2022) NFU welcomes rule changes for farmer impacted by dry weather. Available at: https://www.farminguk.com/news/nfu-welcomes-rule-changes-for-farmers-impacted-by-dry-weather_60952.html

[180] Scottish Government. (2018) Early loans for farmers being made available. Available at: https://www.gov.scot/news/early-loans-for-farmers-being-made-available/?utm

[181] The Guardian. (2018) Sunscreen for cows: UK farmers struggle to cope with heatwave. Available at: https://www.theguardian.com/environment/2018/jul/13/sunscreen-for-cows-uk-farmers-struggle-to-cope-with-heatwave?utm

[182] FARMERS WEEKLY. (2019) Why potato growers need to be better prepared for drought. Available at: https://www.fwi.co.uk/arable/crop-management/irrigation/why-potato-growers-need-to-be-better-prepared-for-drought?utm_source=chatgpt.com.

Option	Comments
Community & government support	During the 2018 and 2022 droughts, the NFU and DEFRA coordinated responses that included regulatory easements, (such as relaxation on grazing restraints) accelerated subsidy payments, emergency grants for water infrastructure[179], and fast-tracked approvals for water abstraction changes.
Easing of cosmetic standards	NFU drought summit meetings in 2018 succeed with requests for supermarkets to relax cosmetic standards, preventing the waste of small or misshapen produce.[183]
Drought-tolerant crops and varieties	Farmers are gradually shifting to more drought-resilient crop choices. For example, planting earlier-maturing varieties of wheat or opting for different crops harvested at earlier periods of the year avoiding the hottest periods.[174]
Tolerant livestock breed	The 2022 poultry study suggested considering heat-tolerant chicken breeds. In the dairy sector, some farmers are introducing breeds crossbreeds that are more heat tolerant than traditional breeds.[184]
Livestock System Changes	Utilisation of better fan systems in barns or farmers opting for a silvo-pastoral approach, planting trees for shade in grazing fields.[184]

The need for a ‘Systems’ approach

In this study, it was recognised that selecting adaptation options that are measurable and address specific hazards can generate a shortlist driven my technologic measures that underestimates the value of systems change, resulting in significant disbenefits that could entrench maladaptation. In livestock, for instance, an option that proposes year-round housing to address heat stress may appear attractive on narrowly defined metrics of thermal comfort or immediate production stability, yet such a move may entail heightened disease risk, energy costs for ventilation, waste management challenges, animal welfare concerns and reduced flexibility to exploit pasture when conditions allow. It also potentially intensifies system fragility by concentrating production in fewer, larger units that are more exposed to systemic shocks. A broader framing would consider alternatives such as enhancing shade and shelter through trees, hedgerows and designed structures, improving water availability and access, adjusting grazing calendars, and integrating herbal leys that deepen rooting and maintain sward function during heat and drought, all of which contribute to resilience while maintaining landscape multifunctionality. On arable land, irrigation is materially relevant for cereals under episodic drought. The feasibility of irrigation, however, is constrained by catchment-level

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[183] Fresh produce (2018) Supermarket reveal commitments to drought-hit growers. Available at: https://www.fruitnet.com/fresh-produce-journal/supermarkets-reveal-commitments-to-drought-hit-growers/176432.article

[184] Department for Environment Food & Rural Affairs (DEFRA). (2023) FARM BUSINESS SURVEY – Poultry Production in England.

availability, abstraction licensing, capital costs of storage and conveyance, and competing demands across sectors. A purely on-farm cost-effectiveness calculation risks missing these challenges.

Crop breeding is an area where distinguishing between adaptations using genetically modified versus precision-bred crops is crucial because the regulatory pathways, development costs, consumer acceptance and potential for near-term deployment differ. It is also acknowledged that constraints on breeding relate not only to farmer uptake but the upstream investment and time required to deliver cultivars with the necessary resilience traits while also maintaining yields. For heat- and drought-tolerant wheat and barley, there is agronomic precedent from hotter, drier regions, suggesting technical feasibility. However, the suitability for these cultivars to UK production is unclear and would need further research and testing. For example, varietal adoption must align with end-user specifications, local climates and soils, market preferences and farming practices. It will take time and financial resources to refresh the varietal portfolio across the supply chain.

Potatoes again illustrate how adaptation must combine biological innovation with operational and market flexibility across the system. Drought- and heat-tolerant varieties, improved disease resistance and surveillance, and better drainage and soil management can reduce sensitivity, but supply chain flexibility is also required to ensure that a wider range of sizes and shapes are accepted. These non-biophysical levers are critical because they convert marginal weather events into manageable business risks rather than catastrophic losses. Insurance can be a complementary instrument to de-risk the adoption of novel varieties and practices by cushioning early-stage performance uncertainty, thereby accelerating learning and diffusion.

Finally, it is important to note that transformative land use change can be driven by broader climatic and market forces rather than by a single hazard such as parasite outbreaks or saline intrusion. When such shifts occur, specifying the nature of change matters for co-benefits. For example, agroforestry and hedgerows that prioritise native species can deliver biodiversity and climate resilience while providing shelter and alternative harvests. Equally, the option space includes rebalancing between spring and winter-sown crops in response to evolving storm, frost and waterlogging profiles, reconsidering the role of grass as a crop within livestock feed systems, and exploring mixed arable-livestock rotations to spread climatic and market risk. Finally, changing consumer habits to an acceptance of greater variability in produce availability, size and shape can increase utilisation and reduce waste under climate volatility. These are not simple solutions; they are systemic strategies that could help build resilience across time and hazard types.

Finally, wider pressures on land use cannot be ignored – particularly with respect to the pressures on land for development and energy. Mitigation may require rapid installation of solar PV infrastructure, which can have direct impacts on agricultural (crop or livestock) productivity. The UK’s farmed landscapes will increasingly need to deliver a much wider range of services (well beyond conventional food and fibre) with balances struck across ecosystem services, food, energy – and cultural value. Such a balance can only be delivered at a system level – informed by a sub-set of quantitative studies, as necessary.

Appendices

Appendix A - Climate Risk Analysis Method Tables

The table below lists the year ranges for each UKCP Local where the 20-year mean GWL from the corresponding driving GCM is closest to the specified temperature anomaly. These correspond to the 20 year means shown for the convective permitting model (CPM).

Table 50. Global Warming Level dates applied to each ensemble member of UKCP18 Local (convective permitting model) projections

Model	GWL	centralyear	startyear	endyear
Model01	0.9	2001	1992	2011
Model04	0.9	2001	1992	2011
Model05	0.9	2003	1994	2013
Model06	0.9	2001	1992	2011
Model07	0.9	2000	1991	2010
Model08	0.9	2002	1993	2012
Model09	0.9	1998	1989	2008
Model10	0.9	2002	1993	2012
Model11	0.9	2000	1991	2010
Model12	0.9	2003	1994	2013
Model13	0.9	1999	1990	2009
Model15	0.9	2000	1991	2010
Model23	0.9	2003	1994	2013
Model25	0.9	2001	1992	2011
Model27	0.9	2012	2003	2022
Model29	0.9	2003	1994	2013
Model01	1	2004	1995	2014
Model04	1	2003	1994	2013
Model05	1	2005	1996	2015
Model06	1	2003	1994	2013

Model	GWL	centralyear	startyear	endyear
Model07	1	2003	1994	2013
Model08	1	2004	1995	2014
Model09	1	2001	1992	2011
Model10	1	2004	1995	2014
Model11	1	2002	1993	2012
Model12	1	2007	1998	2017
Model13	1	2002	1993	2012
Model15	1	2002	1993	2012
Model23	1	2006	1997	2016
Model25	1	2004	1995	2014
Model27	1	2017	2008	2027
Model29	1	2005	1996	2015
Model01	1.1	2007	1998	2017
Model04	1.1	2005	1996	2015
Model05	1.1	2008	1999	2018
Model06	1.1	2006	1997	2016
Model07	1.1	2005	1996	2015
Model08	1.1	2006	1997	2016
Model09	1.1	2003	1994	2013
Model10	1.1	2007	1998	2017
Model11	1.1	2005	1996	2015
Model12	1.1	2010	2001	2020
Model13	1.1	2004	1995	2014
Model15	1.1	2005	1996	2015
Model23	1.1	2009	2000	2019
Model25	1.1	2006	1997	2016
Model27	1.1	2020	2011	2030
Model29	1.1	2009	2000	2019
Model01	1.5	2017	2008	2027
Model04	1.5	2014	2005	2024

Model	GWL	centralyear	startyear	endyear
Model05	1.5	2017	2008	2027
Model06	1.5	2016	2007	2026
Model07	1.5	2015	2006	2025
Model08	1.5	2016	2007	2026
Model09	1.5	2012	2003	2022
Model10	1.5	2018	2009	2028
Model11	1.5	2015	2006	2025
Model12	1.5	2021	2012	2031
Model13	1.5	2014	2005	2024
Model15	1.5	2016	2007	2026
Model23	1.5	2021	2012	2031
Model25	1.5	2020	2011	2030
Model27	1.5	2034	2025	2044
Model29	1.5	2024	2015	2034
Model01	2	2027	2018	2037
Model04	2	2024	2015	2034
Model05	2	2029	2020	2039
Model06	2	2026	2017	2036
Model07	2	2028	2019	2038
Model08	2	2029	2020	2039
Model09	2	2025	2016	2035
Model10	2	2029	2020	2039
Model11	2	2026	2017	2036
Model12	2	2032	2023	2042
Model13	2	2026	2017	2036
Model15	2	2029	2020	2039
Model23	2	2035	2026	2045
Model25	2	2033	2024	2043
Model27	2	2047	2038	2057
Model29	2	2041	2032	2051

Model	GWL	centralyear	startyear	endyear
Model01	2.5	2038	2029	2048
Model04	2.5	2034	2025	2044
Model05	2.5	2040	2031	2050
Model06	2.5	2036	2027	2046
Model07	2.5	2039	2030	2049
Model08	2.5	2040	2031	2050
Model09	2.5	2034	2025	2044
Model10	2.5	2039	2030	2049
Model11	2.5	2036	2027	2046
Model12	2.5	2042	2033	2052
Model13	2.5	2036	2027	2046
Model15	2.5	2041	2032	2051
Model23	2.5	2045	2036	2055
Model25	2.5	2043	2034	2053
Model27	2.5	2058	2049	2068
Model29	2.5	2053	2044	2063

Table 51. Baseline Yield Data for All Modelled Farmed Landscape Components

Category	Component	Nation	Baseline Area	Baseline Area Source	Baseline Yield	Baseline Yield Year	Baseline Yield Source	Additional Figures
Crops	Wheat	England	1654575 hectares	2021 AgCensus Data	7.2 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	
Crops	Wheat	Wales	22174 hectares	2018 AgCensus Data	6.6 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	
Crops	Wheat	Scotland	104528 hectares	2021 AgCensus Data	8.4 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	
Crops	Wheat	Northern Ireland	8052 hectares	2024 Daera data	7.1 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	
Crops	Barley	England	816005 hectares	2021 AgCensus Data	5.7 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	
Crops	Barley	Wales	22681 hectares	2018 AgCensus Data	5.3 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	
Crops	Barley	Scotland	292047 hectares	2021 AgCensus Data	6.6 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	
Crops	Barley	Northern Ireland	20498 hectares	2024 Daera data	6.1 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	
Crops	Oats	England	158953 hectares	2021 AgCensus Data	5.2 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	
Crops	Oats	Wales	*NA - Spatial data not available*	*NA - Not modelled*	4.8 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	
Crops	Oats	Scotland	33724 hectares	2021 AgCensus Data	6.6 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	
Crops	Oats	Northern Ireland	1795 hectares	2024 Daera data	6 tonnes/hectare/year	2024	Defra Cereal and oilseed production, 2024	

Category	Component	Nation	Baseline Area	Baseline Area Source	Baseline Yield	Baseline Yield Year	Baseline Yield Source	Additional Figures
Livestock	Dairy cattle	England	1066831 cows	2021 AgCensus Data	8219 Litres/cow/year	2023	AHDB, Average UK milk yield, 2023	
Livestock	Dairy cattle	Wales	303636 cows	2018 AgCensus Data	8219 Litres/cow/year	2023	AHDB, Average UK milk yield, 2023	
Livestock	Dairy cattle	Scotland	201929 cows	2021 AgCensus Data	8219 Litres/cow/year	2023	AHDB, Average UK milk yield, 2023	
Livestock	Dairy cattle	Northern Ireland	325325 cows	2024 Daera data	8219 Litres/cow/year	2023	AHDB, Average UK milk yield, 2023	
Livestock	Free-range laying hens	England	17941783 hens	2021 AgCensus Data	300 Eggs/hen/year	2024	Egg weight, egg sizes & types of eggs | UK Egg Info	Average egg weight (large) - 68g; 75% of laying hens free range; 300 eggs laid/hen/year
Livestock	Free-range laying hens	Wales	2590805 hens	2018 AgCensus Data	300 Eggs/hen/year	2024	Egg weight, egg sizes & types of eggs | UK Egg Info	Average egg weight (large) - 68g; 75% of laying hens free range; 300 eggs laid/hen/year
Livestock	Free-range laying hens	Scotland	3416943 hens	2021 AgCensus Data	300 Eggs/hen/year	2024	Egg weight, egg sizes & types of eggs | UK Egg Info	Average egg weight (large) - 68g; 75% of laying hens free range; 300 eggs laid/hen/year
Livestock	Free-range laying hens	Northern Ireland	6438753 hens	2024 Daera data	300 Eggs/hen/year	2024	Egg weight, egg sizes & types of eggs | UK Egg Info	Average egg weight (large) - 68g; 75% of laying hens free range; 300 eggs laid/hen/year
Livestock	Lambs	England	7312042 lambs	2021 AgCensus Data	50% of lambs infected by H. contortus parasites	2024	Silent Killers: Barber pole worm (Haemonchus contortus) | Rare Breeds Survival Trust	
Livestock	Lambs	Wales	4584608 lambs	2018 AgCensus Data	50% of lambs infected by H. contortus parasites	2024	Silent Killers: Barber pole worm (Haemonchus contortus) | Rare Breeds Survival Trust	
Livestock	Lambs	Scotland	3350058 lambs	2021 AgCensus Data	50% of lambs infected by H. contortus parasites	2024	Silent Killers: Barber pole worm (Haemonchus contortus) | Rare Breeds Survival Trust	

Category	Component	Nation	Baseline Area	Baseline Area Source	Baseline Yield	Baseline Yield Year	Baseline Yield Source	Additional Figures
Livestock	Lambs	Northern Ireland	1395672 lambs	2024 Daera data	50% of lambs infected by H. contortus parasites	2024	Silent Killers: Barber pole worm (Haemonchus contortus) | Rare Breeds Survival Trust	

Table 52. Impact Chain Descriptions for each assessed farmed landscape component

Component	Sub-component	Hazard	Proposed Threshold	Threshold Source	Proposed Impact Metric	Impact Source	Impact Metric Selection Notes/Justification
Cereals	Oats	High temperatures from April-June (anthesis)	Days where $T_{max} \geq 28°C$ from April-June (days/year)	Hakala et al., 2020	10% yield reduction per day	Assumption based on qualitative evidence from several studies. (Jacott and Boden, 2020; Hakala et al., 2020)	Hakala et al. (2020) found oat and barley yield reductions when temperatures exceeded 28 °C during the time frame of anthesis (one week before and two weeks after heading), likely from reduction in the number of flowers and seeds. Authors noted oats were more sensitive to high temperatures than barley.
Cereals	Wheat	High temperatures from May-June (anthesis)	Days where $T_{max} \geq 32$ °C from May-June (days/year)	Arnell and Freeman, 2021	10% yield reduction per day	Arnell and Freeman, 2021	Arnell and Freeman (2021) select this impact metric based on Jones et al 2020 - where wheat grain yield reduces by at least 10% for each day during anthesis (flowering and seed setting stage) that the maximum daily temperature is at or above 32°C. High temperatures reduce floret fertility and thus the number of grains which are developed, leading to yield losses.
Cereals	Barley	High temperatures from April-June (anthesis)	Days where $T_{max} \geq 28°C$ from April-June (days/year)	Hakala et al., 2020	10% yield reduction per day	Assumption based on qualitative evidence from several studies. (Jacott and Boden, 2020; Hakala et al., 2020)	Hakala et al. (2020) found oat and barley yield reductions when temperatures exceeded 28 °C during the time frame of anthesis (one week before and two weeks after heading), likely from reduction in the number of flowers and seeds. Jacott and Boden (2020) noted that barley experiences yield reductions associated with floret infertility if exposed to high temperatures during anthesis.

Component	Sub-component	Hazard	Proposed Threshold	Threshold Source	Proposed Impact Metric	Impact Source	Impact Metric Selection Notes/Justification
Livestock	Dairy (milk)	High temperatures and humidity (heat stress)	Days where Thermal Heat Index (THI) > 74 (days/year)	(Arnell and Freeman, 2021; Jones et al., 2020)	Milk yield loss of 0.55 litres/cow/day	(Jones et al., 2020)	There are several different THI thresholds for dairy cattle, varying by cow breed and animal size. According to Jones et al (2020), 72 to 79 THI results in mild heat stress, 80 to 90 results in moderate heat stress, and above 90 leads to severe heat stress. Jones et al (2020) assessed a THI threshold of 74 and an impact metric of 0.2 kg/day milk losses, but note this could range up to 0.9 kg/day.
Livestock	Lambs	Temperatures conducive to parasite outbreaks (*Haemonchus contortus*)	Days where $T_{mean} \geq 9°C$ (days/year)	(Arnell and Freeman, 2021; Jones et al., 2020)	Number of lambs exposed per year (assume 50% of lambs infected in 2024)	(Arnell and Freeman, 2021; Jones et al., 2020; RBST, n.d.)	Jones et al. (2020) used a threshold of days above 9°C whereby temperatures are more conducive to parasite outbreaks in sheep (*Haemonchus contortus*). They assume a linear relationship between change in the number of days where mean temperatures exceed 9°C and parasite infections. Lambs are especially vulnerable.
Livestock	Laying hens (eggs)	High temperatures	Days where T_{mean} 28-33°C (days/year) Days where T_{mean} 34-38°C (days/year)$^{\#}$ Days where $T_{mean} \geq 39°C$ (days/year)$^{\#}$	Freitas et al., 2017	28 to 33 = 10% reduction per day 34 to 38 = 15% reduction per day 39 and above = 20% reduction per day	Freitas et al., 2017	Freitas et al. (2017) found that egg weight had a weak negative correlation with air temperatures, where temperatures of hen cages and associated egg weights were monitored over 5 days. Previous studies cited in the paper found a correlation between high temperatures (heat stress) affecting feed intake of hens, resulting in lower feed consumption and lower egg weight (both caged and open facilities). For this analysis, we assume all assessed hens are free-range.

Appendix B - Stakeholders

Specific stakeholder activities are listed in Table 53 while the full list of stakeholder organisations is provided in Table 54.

Table 53. Stakeholder engagement activities and timeline

Date	Activity
14/10/24	Shared space established to facilitate document sharing
14/10/24	Initial invitations issued, with ToR (Terms of Reference, which included an overview of the project)
16/10/24	Specific request for SSG members to signpost key resources as part of the Rapid Evidence Assessment (REA), particularly resources that might not have received wide circulation or be readily accessible. This request was supported through circulation of a pre-populated list of >160 resources collated by the WSP team
05/11/24	The first meeting of attending SSG members, during which an overview of the project context and progress was provided, before moving into a workshop session on project scope, in particular exploring climate hazards, vulnerabilities and impact metrics - as well as synergies / differences between food and nature-positive outcomes - and priorities
20/02/25	Specific request for SSG members to signpost resources on climate thresholds and impacts, following from extensive discussions between the WSP and CCC project teams on how to disaggregate farmed landscapes into a series of components that might lend themselves to quantification in the desired way
29/04/25	The second meeting of attending SSG members, providing an update on Tasks 2.1 and 2.2. A longlist of potential adaptation options was circulated in advance, to support the discussion
13/05/25	Specific request for SSG members to signpost to resources addressing the following topics: Quantification of the value of nature within farmed landscapes (for example: soil health, pollinator services, shading, system resilience) Practitioner experience with climate adaptation - particularly where nature is a core part of the adaptation approach within farmed landscapes Understanding how farm businesses handle climate risk - and the transformation triggers that might cause a switch from different varietals to different crops or entirely different business models Technological advances that might improve system resilience (for example: reduced soil compaction through the use of swarm robotics or drones)
01/07/25	Specific request for SSG members to contribute to the development of a soil waterlogging metric, based on WSP's precipitation modelling and existing precedents from literature

Table 54. Stakeholder organisations which contributed (or were invited to contribute). As described in the main text, two sub-groups were established

Organisation	Location	Sub-group
Agri-Food and BioSciences Institute (AFBI-NI)	Northern Ireland	Attending
Department of Agriculture, Environment and Rural Affairs (DAERA)	Northern Ireland	Attending
Department for Environment Food and Rural Affairs (DEFRA)	England	Attending
Farmers Union of Wales (FUW)	England	Attending
The Institute of Biological, Environmental and Rural Sciences (IBERS)	Wales	Attending
James Hutton Institute	Scotland	Attending
Joint Nature Conservation Committee	UK	Attending
National Farmers Union (NFU)	England	Attending
Natural England	England	Attending
Natural Resources Wales	Wales	Attending
NatureScot	Scotland	Attending
Rothamsted Research	UK	Attending
Scottish Government	Scotland	Attending
Ulster Farmers Union (UFU)	Northern Ireland	Attending
Welsh Government	Wales	Attending
Wildlife Trusts	UK	Attending
ADAS	UK	Corresponding
AHDB (Agriculture and Horticulture Development Board)	UK	Corresponding
British Trust for Ornithology (BTO)	UK	Corresponding
Centre for Ecology and Hydrology (CEH)	UK	Corresponding
ClimateXChange	Scotland	Corresponding
Department for Energy Security and Net Zero (DESNZ)	UK	Corresponding
Environment Agency	England	Corresponding
Farming and Wildlife Advisory Group (FWAG)	GB	Corresponding
Food and Environment Research Agency (FERA)	UK	Corresponding
Harper Adams University	England	Corresponding
John Innes Centre	UK	Corresponding
LEAF (Linking Environment And Farming)	UK	Corresponding

Organisation	Location	Sub-group
National Trust	England and Wales	Corresponding
Nature-Friendly Farming Network (NNFN)	UK	Corresponding
NIAB (National Institute of Agricultural Botany)	UK	Corresponding
Northern Ireland Environment Agency (NIEA)	Northern Ireland	Corresponding
Norwich Institute for Sustainable Development	UK	Corresponding
Royal Agricultural University (RAU)	England	Corresponding
RSPB (Royal Society for the Protection of Birds)	UK	Corresponding
Scottish Environmental Protection Agency (SEPA)	Scotland	Corresponding
SRUC (Scotland's Rural College)	Scotland	Corresponding
Scottish Tenant Farmers Association	Scotland	Corresponding
Tenant Farmers Association	England	Corresponding
Tyndall Centre for Climate Research	UK	Corresponding

Appendix C - Adaptation longlist

Table 55. Adaptation Longlist

Component	Hazard	Adaptation Option Description	Source
Horticultural crops	Heat stress	Agroforestry / trees for shade / silvo-arable systems	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Agroforestry to provide shade for crops (i.e. silvo-arable e.g., alley cropping)	ADAS & Met Office, 2023a[185]
Dairy cattle	Heat stress	Agroforestry to provide shade for livestock (i.e. silvo-pasture) - planting may be linear or grouped	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Grow earlier maturing varieties (crops/forage)	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Move crops to more sheltered sites (e.g., North facing sites)	ADAS & Met Office, 2023a185
Cereals	Heat stress	Move production to cooler parts of the UK (e.g., North and West, rather than South and East)	ADAS & Met Office, 2023a[185]
Hens and cattle	Heat stress	Adopt diurnal (daytime) and/or summer housing	ADAS & Met Office, 2023a[185]
Hens and cattle	Heat stress	Adopt nocturnal grazing of cattle and/or sheep	ADAS & Met Office, 2023a[185]
Hens and cattle	Heat stress	Leave poultry flock outdoors at night	ADAS & Met Office, 2023a[185]
Lambs	Temperatures conducive to parasite outbreaks	Increase pest and disease surveillance	ADAS & Met Office, 2023a[185]

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[185] Department for Environment, Food & Rural Affairs (n.d.) Project 21796 – Defra Science Search. Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796

Component	Hazard	Adaptation Option Description	Source
Cereals	Heat stress	Expand use of crop shading (e.g., polytunnel covers, shade cloths)	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Increase application of trace elements like calcium	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Target production for certain periods of the year only	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Establish crops early	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Increase diversity of cultivars in terms of maturity and resistance	ADAS & Met Office, 2023a[185]
Cereals and livestock	Heat stress	Develop an adaptative management plan	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Restore degraded land to counteract productivity decreases elsewhere	ADAS & Met Office, 2023a[185]
Cereals and livestock	Heat stress	Engage with farm advisory service to guide adaptation choices	ADAS & Met Office, 2023a[185]
Cereals and livestock	Heat stress	Use weather forecasts to improve decision making	ADAS & Met Office, 2023a[185]
Cereals and livestock	Heat stress	Use seasonal climate forecasts to improve decision making	ADAS & Met Office, 2023a[185]
Cereals and livestock	Heat stress	Implement emergency action plans	ADAS & Met Office, 2023a[185]
All livestock	Heat stress	Install in-field shelters/tents (semi-permanent)	ADAS & Met Office, 2023a[185]
All livestock	Heat stress	Use different breeds of livestock that are more resilient to hotter/drier conditions	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Grow heat tolerant and drought resistant varieties (crops/forage)	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Grow range of varieties with different flowering dates to spread risk	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Use Genetically Engineered or Genetically Modified crops	ADAS & Met Office, 2023a[185]

Component	Hazard	Adaptation Option Description	Source
Dairy cattle	Heat stress	Provide mud wallows	ADAS & Met Office, 2023a[185]
Hens and cattle	Heat stress	Use Genetically Engineered or Genetically Modified livestock breeds	ADAS & Met Office, 2023a[185]
Laying hens	Heat stress	Use different breeds of poultry that are more resilient to hotter/drier conditions	ADAS & Met Office, 2023a[185]
Cereals	Heat stress	Adopt climate-resilient horticultural and arable crops, such as early-maturing varieties, heat-tolerant varieties, drought-tolerant crops etc.	ADAS & Met Office, 2023b[186]
Cereals	Heat stress	Extend production area of certain crops, as new areas become climatically suitable at higher latitudes or altitudes	ADAS & Met Office, 2023b[186]
Cereals	Heat stress	Take opportunities to double crop (multiple harvests in one year) due to extended growing season	ADAS & Met Office, 2023b[186]
Cereals and livestock	Heat stress	Account for changing climate when investing in new machinery to maximise efficiency of operations	ADAS & Met Office, 2023b[186]
All livestock	Heat stress	Shift housing turnout date (more flexibility to cope with changing local seasonal weather conditions)	ADAS & Met Office, 2023b[186]
Lambs	Temperatures conducive to parasite outbreaks	Alter lambing schedule to benefit from warming temperatures and longer growing season i.e. earlier lambing	ADAS & Met Office, 2023b[186]
Lambs	Temperatures conducive to parasite outbreaks	Increase biosecurity measures in livestock housing to guard against the spread of new diseases	ADAS & Met Office, 2023b[186]
Lambs	Temperatures conducive to parasite outbreaks	Vaccinate livestock against new and prevalent diseases	ADAS & Met Office, 2023b[186]

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[186] Department for Environment, Food & Rural Affairs (n.d.) Project 21797 – Defra Science Search. Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21797

Component	Hazard	Adaptation Option Description	Source
Wheat	Heat stress	Amend sowing dates to avoid the highest temperatures occurring at sensitive growth stages	Jones et al., 2020[187]
Lambs	Temperatures conducive to parasite outbreaks	Manage the grazing behaviour of host livestock to limit parasite spread, for example moving animals to 'safe' grazing areas	Jones et al., 2020[187]
Lambs	Temperatures conducive to parasite outbreaks	Alter the timing of reproduction, housing and grazing to reduce risk of parasites	Jones et al., 2020[187]
Cereals	Heat stress	Conduct transformative adaptation, whereby the land is taken out of cereal production and instead use this for woodland or wetland as a means of carbon storage / nature benefit	Jones et al., 2020[187]
Dairy cattle	Heat stress	Increase water intake	Jones et al., 2020[187]
Dairy cattle	Heat stress	House cows inside all year round, include fans and sprinklers	Jones et al., 2020[187]
Dairy cattle	Heat stress	Avoid unnecessary handling of cattle	AHDB, 2018. How to deal with hot weather[188]
Dairy cattle	Heat stress	Provide extra forage to stock during cooler times, to help compensate for reduced feeding activity in the heat of the day	AHDB, 2015. Managing cattle and sheep during extreme weather events[189]
Dairy cattle	Heat stress	Offer housing as shade	AHDB, n.d.[190]
Dairy cattle	Heat stress	Minimise standing time in the parlour	AHDB, n.d.

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[187] Jones, L. et al. (2020) Climate-driven threshold effects in the natural environment. Available at: https://www.ukclimaterisk.org/wp-content/uploads/2021/05/Climate-driven-threshold-effects-in-the-natural-environment-UKCEH.pdf

[188] AHDB Beef & Lamb (n.d.). How to deal with hot weather: cattle and sheep. Available at: https://projectblue.blob.core.windows.net/media/Default/Imported%20Publication%20Docs/AHDB-Beef-Lamb-cattle-and-sheep-hot-weather.pdf

[189] AHDB Beef & Lamb (n.d.) Managing cattle and sheep during extreme weather events. Available at: https://projectblue.blob.core.windows.net/media/Default/Imported%20Publication%20Docs/BRP-Managing-cattle-and-sheep-during-extreme-weather-events-1.pdf

[190] AHDB (2022) Heat stress and foot health. Available at:https://ahdb.org.uk/heat-stress-and-foot-health

Component	Hazard	Adaptation Option Description	Source
Cereals	Heat stress	Switch to alternative crops that are better suited to changing local climates, utilizing crop suitability modelling tools (e.g., chickpeas, soy, etc.)	Redhead et al., 2025[191]
Dairy cattle	Heat stress	Diet adjustments to mitigate impacts of heat stress, increasing fat and decreasing fibre intake	Henry et al., 2018[192]
Dairy cattle	Heat stress	Wet the dairy yard for an hour before cows arrive	Dairy Australia, 2023. Cool Cows[193]
Dairy cattle	Heat stress	Sprinkle cows for 30-60 minutes while standing in the dairy yard waiting for afternoon milking	Dairy Australia, 2023. Cool Cows[193]
Dairy cattle	Heat stress	Increase cows' grain and concentrate feeding rate	Dairy Australia, 2023. Cool Cows[193]
Dairy cattle	Heat stress	Develop a farm plan that incorporates significant tree plantings over time on the northern and western edges of pastures, and plant deciduous trees along laneways	Dairy Australia, 2023. Cool Cows[193]
Dairy cattle	Heat stress	Genetic selection for breeds with greater heat tolerance	Wreford & Topp, 2020[194]
Dairy cattle	Heat stress	House dairy cattle during periods of heat stress	Wreford & Topp, 2020[194]
Dairy cattle	Heat stress	Alter diet to compensate for decreased feed intake during hot weather (and amend feeding patterns)	Wreford & Topp, 2020[194]

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[191] Redhead, J.W. et al. (2025) National horizon scanning for future crops under a changing UK climate. Climate Resilience and Sustainability, 4(1), e70007. Available at: https://rmets.onlinelibrary.wiley.com/doi/10.1002/cli2.70007

[192] Henry, B.K., Eckard, R.J. & Beauchemin, K.A. (2018) Review: Adaptation of ruminant livestock production systems to climate changes. Animal, 12(s2), pp. s445–s456. Available at: https://www.cambridge.org/core/journals/animal/article/review-adaptation-of-ruminant-livestock-production-systems-to-climate-changes/CF8B075D4B8D54DDFE0E60A3CBE4A53

[193] Dairy Australia (2023). Cool Cows. Available at: https://dair-p-001.sitecorecontenthub.cloud/api/public/content/163ac1bed1d4468b9bc0d590c9e2ad5e?v=8eb23121

[194] Wreford, A. & Topp, C.F.E. (2020) Impacts of climate change on livestock and possible adaptations: A case study of the United Kingdom. Agricultural Systems, 180, 102737. Available at: https://doi.org/10.1016/j.agsy.2019.102737

Component	Hazard	Adaptation Option Description	Source
Cereals	Heat stress	Sow summer crops earlier to avoid stresses around flowering time	Rodriguez et al, 2024[195]
Dairy cattle	Heat stress	Included more concentrates into dairy cattle diet over roughage to reduce metabolic heat load	Gauly et al, 2020[196]
Dairy cattle	Heat stress	Feed additives to improve the animals' ability coping with heat stress such as niacin and castor oil	Gauly et al, 2020[196]
Dairy cattle	Heat stress	Implement cooling systems such as fans, misters, sprinklers and cooled waterbeds	Gauly et al, 2020[196]
Dairy cattle	Heat stress	Incorporate resilience to thermal load as a functional trait in breeding programs	Gauly et al, 2020[196]
Cereals	Heat stress	Crop insurance	Zhao et al, 2022[197]
Cereals and livestock	Temperatures conducive to parasite outbreaks	Enhanced monitoring of pests and diseases	Zhao et al, 2022[197]
Lambs	Heat stress	Increased surveillance programmes	Wreford et al, 2015[198]
Cereals and livestock	Heat stress	Form cooperative networks to share risks	Lopez-Hoffman et al, 2013[199]
Cereals and livestock	Heat stress	Implementation of early weather warning systems	Jenkins et al., 2023[200]
Cereals and livestock	Heat stress	Provide farmers with training and resources to understand climate impacts	Harrison et al, 2016[201]

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[195] Rodriguez, D., Serafin, L., de Voil, P., Mumford, M., Zhao, D., Aisthorpe, D., Auer, J., Broad, I., Eyre, J. and Hellyer, M., 2024. Agronomic adaptations to heat stress: Sowing summer crops earlier. Field Crops Research, 318, p.109592.

[196] Gauly, M. & Ammer, S/ (2020). Review: Challenges for dairy cow production systems arising from climate changes. Animal, 14(S1), pp.s196-s203. Available at: https://doi.org/10.1017/S1751731119003239

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[198] Wreford, A. et al. (2015). Estimating the costs and benefits of adapting agriculture to climate change. EuroChoices, 14(2), pp. 16-23. Available at: https://doi.org/10.1111/1746-692X.12086

[199] Lopez-Hoffman, L. et al. (2013) Key landscape ecology metrics for assessing climate change adaptation options: rate of change and patchiness of impacts. Ecosphere, 4(8), Article 101. Available at: https://doi.org/10.1890/ES13-00118.1

[200] Jenkins et al., (2023). ClimateXChange Adapting Scottish agriculture to a changing climate. Available at: https://www.climatexchange.org.uk/projects/adapting-scottish-agriculture-to-a-changing-climate/

[201] Harrison, M.T., Cullen, B.R. and Rawnsley, R.P., 2016. Modelling the sensitivity of agricultural systems to climate change and extreme climatic events. Agricultural Systems, 148, pp.135-148.

Component	Hazard	Adaptation Option Description	Source
		and implement effective adaptation strategies	
Lambs	Temperatures conducive to parasite outbreaks	Launch regional risk forecasting systems to provide advanced warning of Haemonchus outbreaks in sheep, giving farmers time to implement treatments	Skuce et al, 2014[202]
Laying hens	Heat stress	Provide minerals in chicken feed to support the antioxidant defence system and egg shell structure which can be weakened during periods of heat stress	AllTech, 2021[203]
Laying hens	Heat stress	Treat poultry with pre- and probiotics, as they are able to stabilize the intestinal microbiota under heat stress conditions.	Lian et al, 2020[204]
Laying hens	Heat stress	Install ventilation in chicken coups to reduce indoor temperatures, creating refuges during periods of high outdoor temperatures	The Poultry Site, 2008[205]
Laying hens	Heat stress	Lights can be turned on for an hour or two at midnight and feeders run to encourage hens to eat during a cooler time of day	Hendrix Genetics, 2021[206]
Cereals	Heat stress	Genetic Improvement Networks (GINs)	AHDB, n.d. Genetic Improvement Networks[207]
All livestock	Heat stress	Insurance against losses	Howden, 2025[208]

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[202] Skuce, P., Innocent, G. & Bartley, D. (2014) Haemonchus contortus interim report. Available at: https://www.climatexchange.org.uk/wp-content/uploads/2023/09/haemonchus_contortus_interim_report.pdf

[203] Heat stress in poultry: Causes and treatments | Alltech. (2020). Heat stress in poultry: Causes and treatments. [online] Available at: https://www.alltech.com/en-gb/blog/heat-stress-poultry-causes-and-treatments

[204] Lian, P.et al (2020). Beyond Heat Stress: Intestinal Integrity Disruption and Mechanism-Based Intervention Strategies. Nutrients, 12(3), p.734. doi:https://doi.org/10.3390/nu12030734.

[205] Thepoultrysite.com. (2026). Things To Remember To Preserve Egg Quality During Summer. [online] Available at: https://www.thepoultrysite.com/articles/things-to-remember-to-preserve-egg-quality-during-summer

[206] Hendrix Genetics (2021). Midnight feeding - Laying Hens. [online] Available at: https://layinghens.hendrix-genetics.com/en/articles/midnight-feeding/.

[207] Ahdb.org.uk. (2024). Genetic Improvement Networks | AHDB. [online] Available at: https://ahdb.org.uk/genetic-improvement-networks

[208] Peláez, A.G., Daniell, J. and Douglas, R. (2025). Market analysis| Insurance and Risk Management Tools for Agriculture in the EU. [online] fi-compass. Available at: https://www.fi-compass.eu/sites/default/files/publications/EAFRD_AGRI_Insurance_Risk_MA.pdf.

Component	Hazard	Adaptation Option Description	Source
Cereals	Heat stress	Crop diversification to improve resilience and/or crop yields	Meta-analytical evidence on diversified farming vs intensive monocultures[209]
Cereals	Heat stress	Adapting cropping patterns to meet anticipated climate scenarios	Cost-effectiveness studies on temperate nature-based farm adaptation[210]
All livestock	Heat stress	Hedgerows to provide shade for grazing livestock	Temperate/Mediterranean on-farm linear/patch features ecosystem- and climate-service studies[211]
All livestock	Heat stress	Shelterbelts / windbreaks to provide shade for grazing livestock (linear as opposed to parkland / silvo-pastoral approach)	Wreford & Topp, 2020[194]
Cereals	Heat stress	Use a combination of the following practices to improve soil water holding capacity (and quality) to provide a cooling effect: Cover cropping; Crop rotation; Adding organic matter	Petch et al., 2018[212] Liu & Pu, 2019[213]
Cereals	Heat stress	Irrigate crops to reduce canopy temperatures	Followell & Knott, 2018[214]
Cereals	Heat stress	Landscape re-wetting through installation of ponds. This is to provide a cooling effect to mitigate against cereal crop yield losses from high temperatures	Ampatzidis, P., Cintolesi, C. & Kershaw, T., 2023[215] Froglife, 2022[216]

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[209] Undermind (2026). Undermind - Meta-analytical evidence on diversified farming vs intensive monocultures. [online] Undermind.ai. Available at: https://app.undermind.ai/report/b2a99e162292007318389a170fe03db7f231c8a2aa7185c977b3addcb0878151

[210] Undermind.ai. (2026). Cost-effectiveness studies on temperate nature-based farm adaptation. [online] Available at: https://app.undermind.ai/report/5ab05eba251c3adc8fdb55d9b6bf5bd12b0daeb6c21b879b05b0bb37c6c8bff5

[211] Undermind (2026). Temperate/Mediterranean on-farm linear/patch features ecosystem- and climate-service studies. [online] Undermind.ai. Available at: https://app.undermind.ai/report/ee257bdca78f942c526bf9204e35ff6bc409bc7af0d55e37f66212968399fe49

[212] Petch, J.C. et al (2020). Sensitivity of the 2018 UK summer heatwave to local sea temperatures and soil moisture. Atmospheric Science Letters, 21(3). doi:https://doi.org/10.1002/asl.948

[213] Liu, J. and Pu, Z. (2019). Does Soil Moisture Have an Influence on Near-Surface Temperature? Journal of Geophysical Research: Atmospheres, 124(12), pp.6444–6466. doi:https://doi.org/10.1029/2018jd029750.

[214] Followell, C.A. and Knott, C. (2018). Effects of Irrigation on Wheat Canopy Temperature and Yield. [online] Kentucky Small Grain Growers Association. Available at: https://www.kysmallgrains.org/news/2018/10/2/effects-of-irrigation-on-wheat-canopy-temperature-and-yield

[215] https://doi.org/10.3390/cli11020028

[216] Stead, J. (2022). Ponds against climate change. [online] Froglife. Available at: https://www.ceh.ac.uk/sites/default/files/2022-05/SFG106_Stead_Apr22_Froglife.pdf.

Appendix D - Excluded adaptation options

The following options were removed from the longlist during an initial filter. Brief reasons for exclusion are provided.

Table 56. Adaptation Longlist

Component	Adaptation Option Description	Source	**Reasons for exclusion**
Horticultural crops	Agroforestry / trees for shade / silvo-arable systems	ADAS & Met Office, 2023a[217]	Horticultural crops not covered by impact metrics
Hens and cattle	Adopt nocturnal grazing of cattle and/or sheep	ADAS & Met Office, 2023a[185]	This is related to daytime housing / cooling as a secondary measure, captured under another option
Hens and cattle	Leave poultry flock outdoors at night	ADAS & Met Office, 2023a[185]	This is related to daytime housing / cooling as a secondary measure, captured under another option
Cereals	Restore degraded land to counteract productivity decreases elsewhere	ADAS & Met Office, 2023a[185]	Doesn't address heat specifically
Cereals and livestock	Use weather forecasts to improve decision making	ADAS & Met Office, 2023a[185]	This won't address the impacts under consideration
Cereals and livestock	Implement emergency action plans	ADAS & Met Office, 2023a[185]	This won't address the impacts under consideration
Cereals	Adopt climate-resilient horticultural and arable crops, such as early-maturing varieties, heat-tolerant varieties, drought-tolerant crops etc.	ADAS & Met Office, 2023b[218]	Covered in other options
Cereals	Take opportunities to double crop (multiple harvests in one year) due to extended growing season	ADAS & Met Office, 2023b[186]	Doesn't address heat specifically

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[217] Defra.gov.uk. (2026). Science Search. [online] Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796

[218] Defra.gov.uk. (2026). Science Search. [online] Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21797

Component	Adaptation Option Description	Source	**Reasons for exclusion**
Cereals and livestock	Account for changing climate when investing in new machinery to maximise efficiency of operations	ADAS & Met Office, 2023b[186]	Doesn't address heat specifically
All livestock	Shift housing turnout date (more flexibility to cope with changing local seasonal weather conditions)	ADAS & Met Office, 2023b[186]	Housing to address heat is covered by other options
Lambs	Alter the timing of reproduction, housing and grazing to reduce risk of parasites	Jones et al., 2020[187]	Covered in other options
Dairy cattle	Increase cows' grain and concentrate feeding rate	Dairy Australia, 2023. Cool Cows[193]	Covered in other options
Dairy cattle	Develop a farm plan that incorporates significant tree plantings over time on the northern and western edges of pastures, and plant deciduous trees along laneways	Dairy Australia, 2023. Cool Cows[193]	Covered in other options
Dairy cattle	Genetic selection for breeds with greater heat tolerance	Wreford & Topp, 2020[219]	Covered in other options
Dairy cattle	House dairy cattle during periods of heat stress	Wreford & Topp, 2020[194]	Covered in other options
Dairy cattle	Alter diet to compensate for decreased feed intake during hot weather (and amend feeding patterns)	Wreford & Topp, 2020[194]	Covered in other options
Dairy cattle	Include more concentrates into dairy cattle diet over roughage to reduce metabolic heat load	Gauly et al, 2020[220]	Covered in other options
Dairy cattle	Feed additives to improve the animals' ability coping with heat stress such as niacin and castor oil	Gauly et al, 2020[196]	Covered in other options

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[219] Wreford, A. and Topp, C.F.E. (2020). Impacts of climate change on livestock and possible adaptations: A case study of the United Kingdom. Agricultural Systems, 178. doi:https://doi.org/10.1016/j.agsy.2019.102737.

[220] Gauly, M. and Ammer, S. (2020). Review: Challenges for dairy cow production systems arising from climate changes. animal, 14(S1), pp.s196–s203. doi:https://doi.org/10.1017/s1751731119003239.

Component	Adaptation Option Description	Source	**Reasons for exclusion**
Dairy cattle	Incorporate resilience to thermal load as a functional trait in breeding programs	Gauly et al, 2020[196]	Covered in other options
Cereals and livestock	Enhanced monitoring of pests and diseases	Zhao et al, 2022[197]	Covered in other options
Lambs	Increased surveillance programmes	Wreford et al, 2015[221]	Covered in other options
Cereals and livestock	Implementation of early weather warning systems	Jenkins et al., 2023[222]	Covered in other options
Laying hens	Provide minerals in chicken feed to support the antioxidant defence system and egg shell structure which can be weakened during periods of heat stress	AllTech, 2021[223]	Doesn't address heat impacts specifically
Laying hens	Treat poultry with pre- and probiotics, as they are able to stabilize the intestinal microbiota under heat stress conditions.	Lian et al, 2020[224]	Doesn't address heat impacts specifically
Laying hens	Install ventilation in chicken coups to reduce indoor temperatures, creating refuges during periods of high outdoor temperatures	The Poultry Site, 2008[225]	Covered in other options
Cereals	Genetic Improvement Networks (GINs)	AHDB, n.d. Genetic Improvement Networks[226]	Covered in other options
Cereals	Crop diversification to improve resilience and/or crop yields	Meta-analytical evidence on diversified farming vs intensive monocultures[227]	Doesn't address heat impacts specifically

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[221] Wreford, A. et al (2015). Estimating the Costs and Benefits of Adapting Agriculture to Climate Change. EuroChoices, 14(2), pp.16–23. doi:https://doi.org/10.1111/1746-692x.12086.

[222] https://www.climatexchange.org.uk/projects/adapting-scottish-agriculture-to-a-changing-climate/

[223] Heat stress in poultry: Causes and treatments | Alltech. (2020). Heat stress in poultry: Causes and treatments. [online] Available at: https://www.alltech.com/en-gb/blog/heat-stress-poultry-causes-and-treatments.

[224] Lian, P. et al (2020). Beyond Heat Stress: Intestinal Integrity Disruption and Mechanism-Based Intervention Strategies. Nutrients, 12(3), p.734. doi:https://doi.org/10.3390/nu12030734

[225] https://www.thepoultrysite.com/articles/things-to-remember-to-preserve-egg-quality-during-summer

[226] Ahdb.org.uk. (2024). Genetic Improvement Networks | AHDB. [online] Available at: https://ahdb.org.uk/genetic-improvement-networks.

[227] Undermind. (2026). Meta-analytical evidence on diversified farming vs intensive monocultures. [online] Available at: https://app.undermind.ai/report/b2a99e162292007318389a170fe03db7f231c8a2aa7185c977b3addcb0878151.

Component	Adaptation Option Description	Source	**Reasons for exclusion**
Cereals	Adapting cropping patterns to meet anticipated climate scenarios	Cost-effectiveness studies on temperate nature-based farm adaptation[228]	Doesn't address heat impacts specifically
All livestock	Hedgerows to provide shade for grazing livestock	Temperate/Mediterranean on-farm linear/patch features ecosystem- and climate-service studies[229]	Covered in other options
All livestock	Shelterbelts / windbreaks to provide shade for grazing livestock (linear as opposed to parkland / silvo-pastoral approach)	Wreford & Topp, 2020[194]	Covered in other options

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[228] Undermind. (2026). Cost-effectiveness studies on temperate nature-based farm adaptation. [online] Available at: https://app.undermind.ai/report/5ab05eba251c3adc8fdb55d9b6bf5bd12b0daeb6c21b879b05b0bb37c6c8bff5.

[229] Undermind. (2026). Temperate/Mediterranean on-farm linear/patch features ecosystem- and climate-service studies. [online] Available at: https://app.undermind.ai/report/ee257bdca78f942c526bf9204e35ff6bc409bc7af0d55e37f66212968399fe49.

Appendix E - Deprioritised adaptation options

The following options were considered potentially relevant in adapting the components to the modelled heat risks but were excluded from detailed analysis for a number of reasons, as specified in the table. In many cases the reason for exclusion was a lack of supporting data on the ability of the adaptation measure to specifically address the modelled climate risk, or on the effectiveness of the measure. Other measures were excluded due to the lack of spatial / site-specific granularity in the Cost-Benefit Analysis model, which was developed to accommodate measures that could be universally applied to impacted crop or livestock areas.

Table 57. UK Agricultural Adaptation Measures for Heat Stress

Adaptation Measure	Pros	Cons	Supporting Sources
Grow earlier maturing varieties	Avoids peak summer heat during sensitive stages	Earlier flowering varieties may have lower yield potential; breeding and trial programmes required	AHDB Climate Adaptation[230]
Move crops to sheltered sites (e.g., North-facing)	Reduces heat stress and evapotranspiration	Ability to implement this measure will depend on geography / topography which cannot be accommodated in CBA model	ADAS Climate Resilience[231]
Shift production to cooler UK regions	North/West expected to remain cooler and wetter than South/East	Potential for different regions to support current crops requires field validation and is beyond the scope of the CBA model	UKCEH Crop Suitability Study[232]
Crop shading (polytunnels, shade cloths)	Reduces heat (and water) stress; good for high-value crops	High cost for arable crops. This measure is normally adopted for horticultural produce such as soft fruits	Horticulture Shade Study[233]

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[230] AHDB (2025). Climate change and its impact on UK agriculture | AHDB. [online] Ahdb.org.uk. Available at: https://ahdb.org.uk/climate-adaptation-report.

[231] ADAS. (2025). How UK agriculture can adjust to extreme rainfall | ADAS. [online] Available at: https://adas.co.uk/projects/investigating-how-uk-agriculture-can-adjust-to-changing-seasonality-and-extreme-rainfall/.

[232] UK Centre for Ecology & Hydrology (2025). Scientists predict what will be top of the crops in UK by 2080 due to climate change. [online] ScienceDaily. Available at: https://www.sciencedaily.com/releases/2025/01/250123193112.htm.

[233] Horticulturae. (2023). The Effects of Shade on Crops: From Greenhouse to Agrivoltaic. [online] Available at: https://www.mdpi.com/journal/horticulturae/special_issues/shade_crops

Adaptation Measure	Pros	Cons	Supporting Sources
Target production for certain periods only	Avoids hottest months (and reduces irrigation demand)	Reduced cropping cycles may impact yields; Trial programmes required	ADAS Seasonal Adaptation[234]
Establish crops early	Avoids flowering during heatwaves	Very early flowering may increase risks from late frosts; Breeding and trial programmes required	Met Office Seasonal Outlook[235]
Adaptive management planning	Builds resilience; proactive approach	Requires expertise and resources that aren't yet either available or supported by robust evidence on efficacy	NAP3 Government Plan[236]
Engage with advisory services	Access to expert guidance	Advisory capacity may be limited and may not yet be able to draw from robust evidence base	NFU Adaptation Priorities[237]
Use seasonal climate forecasts	Improves sowing (and irrigation) timing	Forecast uncertainty increases beyond 2-3 months and cultivars specifically aligned with predicted heat conditions are unlikely to be available	Met Office Climate Outlook[238]
Grow varieties with staggered flowering dates	Spreads risk across time	As above – field trial programmes would be required to develop recommended lists	ADAS Climate Resilience[239]
Provide mud wallows (livestock)	Low-cost cooling for cattle	Hygiene and disease risks to dairy cattle (mastitis etc); measure more suited to pigs	AHDB Livestock Heat Stress[240]

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[234] ADAS. (2025). How UK agriculture can adjust to extreme rainfall | ADAS. [online] Available at: https://adas.co.uk/projects/investigating-how-uk-agriculture-can-adjust-to-changing-seasonality-and-extreme-rainfall/.

[235] UK Met Office (2026). Seasonal Climate Outlooks. [online] Met Office. Available at: https://www.metoffice.gov.uk/services/government/international-development/climate-outlook

[236] Ffoulkes, C. (2023). Government agricultural action plan for climate adaption announced | ADAS. [online] ADAS. Available at: https://adas.co.uk/news/government-publishes-action-plan-to-support-climate-change-adaption-in-agriculture/.

[237] Nfuonline.com. (2023). How can we prioritise climate adaptation and resilience in UK agriculture? [online] Available at: https://www.nfuonline.com/updates-and-information/prioritising-climate-adaptation-and-resilience-in-uk-agriculture/.

[238] UK Met Office (2026). Seasonal Climate Outlooks. [online] Met Office. Available at: https://www.metoffice.gov.uk/services/government/international-development/climate-outlook

[239] ADAS. (2025). How UK agriculture can adjust to extreme rainfall | ADAS. [online] Available at: https://adas.co.uk/projects/investigating-how-uk-agriculture-can-adjust-to-changing-seasonality-and-extreme-rainfall/.

[240] Ahdb.org.uk. (2026). Avoiding and managing heat stress in livestock | AHDB. [online] Available at: https://ahdb.org.uk/avoiding-and-managing-heat-stress-in-livestock

Adaptation Measure	Pros	Cons	Supporting Sources
Extend crop production to new regions	Warmer climate may enable production of soy, chickpeas	Potential for different regions to support different crops requires field validation and is beyond the scope of the CBA model	UKCEH Crop Suitability[241]
Amend sowing dates	Avoids heat during flowering	Requires reliable forecasts and suitable varieties	ADAS Seasonal Adaptation[242]
Increase water intake (livestock)	Essential for welfare	CBA model assumes that water is not limiting for livestock (and crop) adaptation measures	DEFRA Extreme Weather Guidance[243]
Avoid handling cattle during heat	Reduces stress and mortality	Risks of milk losses modelled to be low out to 2059; Only grazed stock are in scope and appropriate handling is taken as a given	AHDB Livestock Heat Stress[244]
Switch to alternative crops (soy, chickpeas)	Exploits new climatic niches; reduces imports	Potential for different crops requires field validation and is beyond the scope of the CBA model	UKCEH Crop Suitability[245]
Cooling systems (fans, sprinklers)	Effective for intensive livestock	High energy (and water) costs	Azelis Dairy Heat Stress[246]
Cooperative resource-sharing networks	Spreads risk; promotes fairness	Governance and legal complexity; Precedents / contractual models required	Climate Resilience Partnerships[247]

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[241] Soci.org. (2025). Climate change and farming: The surprising impact on the UK's crops. [online] Available at: https://www.soci.org/news/2025/1/climate-change-and-farming-the-impact-on-the-uks-crops

[242] ADAS. (2025). How UK agriculture can adjust to extreme rainfall | ADAS. [online] Available at: https://adas.co.uk/projects/investigating-how-uk-agriculture-can-adjust-to-changing-seasonality-and-extreme-rainfall/.

[243] GOV.UK. (2013). Keeping farm animals and horses in extreme weather. [online] Available at: https://www.gov.uk/guidance/keeping-farm-animals-and-horses-in-extreme-weather.

[244] Ahdb.org.uk. (2026). Avoiding and managing heat stress in livestock | AHDB. [online] Available at: https://ahdb.org.uk/avoiding-and-managing-heat-stress-in-livestock

[245] UK Centre for Ecology & Hydrology (2025). Scientists predict what will be top of the crops in UK by 2080 due to climate change. [online] ScienceDaily. Available at: https://www.sciencedaily.com/releases/2025/01/250123193112.htm

[246] Azelis.com. (2024). Mitigating heat stress in dairy cattle. [online] Available at: https://explore.azelis.com/en_GB/uk_an/mitigating-heat-stress-in-dairy-cattle-1

[247] Environment Agency (2024). Rural Flood Resilience Partnership launched to help farmers and rural communities adapt to a changing climate. [online] GOV.UK. Available at: https://www.gov.uk/government/news/rural-flood-resilience-partnership-launched-to-help-farmers-and-rural-communities-adapt-to-a-changing-climate.

Adaptation Measure	Pros	Cons	Supporting Sources
Farmer training and resources	Builds long-term capacity	Requires sustained funding; Evidence base to support required training may not yet exist	NFU Adaptation Priorities[248]

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[248] Nfuonline.com. (2023). How can we prioritise climate adaptation and resilience in UK agriculture? [online] Available at: https://www.nfuonline.com/updates-and-information/prioritising-climate-adaptation-and-resilience-in-uk-agriculture/.

Appendix F - Adaptation measure assumptions and data sources

Adaptation option 2. Alley cropping to provide cooling via shade (silvo-arable)

Adaptation option number	2
Component in scope	Cereals
Hazard considered	Heat stress
Adaptation option description	Alley cropping to provide cooling via shade (silvo-arable)
Source of adaptation option	ADAS & Met Office (2023). *Research to assess resilience measures that support UK agriculture in adapting to drought, extreme heat, and wildfires - SCF0140.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796 (Accessed 12 December 2025)
Effect of adaptation option	Reduces hazard

Unit CAPEX	£1,250
Unit	ha
CAPEX: assumptions and sources	Based on establishment costs for a 52ha scheme as set out in: Soil Association (2019). *The Agroforestry Handbook*. Available at: https://www.scribd.com/document/422243581/The-Agroforestry-Handbook (Accessed 12 December 2025)
Unit OPEX	£75.00
Unit	ha/yr
OPEX: assumptions and sources	OPEX per cropped hectare; highest in establishment years then lower. Based on: AHDB (nd). *Agroforestry in the Sustainable Farming Incentive (SFI)*. Available at: https://ahdb.org.uk/trade-and-policy/elms/sfi/agroforestry (Accessed 12 December 2025) Forestry Commission (2023). *How trees benefit your farm business.* Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1167866/Trees_on_Farms_Feb_2023.pdf (Accessed 12 December 2025)

Lifetime of measure (years)	50
Lifetime of measure: assumptions and sources	Life varies by species/rotation: short-rotation poplar/willow ~20–30 yrs; mixed timber/fruit/nut 30–60+ yrs; long-lived oaks >80 yrs; UK example Wakelyns since 1994. Sources: The Organic Research Centre (2024). *Wakelyns Agroforestry: Resilience through diversity.* Available at: https://www.organicresearchcentre.com/wp-content/uploads/2024/05/WAF_V3_2024_final_pages_4web.pdf (Accessed 12 December 2025) Soil Association (2019). *The Agroforestry Handbook*. Available at: https://www.scribd.com/document/422243581/The-Agroforestry-Handbook (Accessed 12 December 2025)
Time for risk reduction to begin (years)	15
Time for risk reduction to begin: assumptions and sources	Based on yield effect timelines set out in: Soil Association (2019). *The Agroforestry Handbook*. Available at: https://www.scribd.com/document/422243581/The-Agroforestry-Handbook (Accessed 12 December 2025)
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	10%
Risk reduction: assumptions and sources	Assumption - silvoarable systems typically have improved moisture and temperature conditions in extreme heat years, leading to more stable cereal yields. "agroforestry systems are expected to be able to accommodate [climactic change, including droughts and heatwaves] - avoiding up to 20% yield losses that monocultures would otherwise suffer" Isević, V., Yu, Y., & van der Werf, W. (2021). Crop Yields in European Agroforestry Systems: A Meta-Analysis. *Frontiers in Sustainable Food Systems* (5). Available at: https://doi.org/10.3389/fsufs.2021.606631
Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	0%
Maximum future uptake % of farmers implementing this option	40%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2035

Uptake rates: assumptions and sources	Assumptions, based on current pilot scale activity but acknowledged potential. For example, this 2021 article: Harris, R. (2021). *Silvopasture: What it is and how it benefits livestock farming.* Available at: https://www.fwi.co.uk/business/silvopasture-what-it-is-and-how-it-benefits-livestock-farming (Accessed 12 December 2025)
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	-6.2 tCO_2e/ha/yr
Climate mitigation co-benefits: assumptions and sources	Amount varies by tree species: ONS (2024). Woodland natural capital accounts, UK:2024. Available at: https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/woodlandnaturalcapitalaccountsuk/2024 (Accessed 12 December 2025) DESNZ (2023). Traded carbon values used for modelling purposes, 2023. Available at: https://www.gov.uk/government/publications/traded-carbon-values-used-for-modelling-purposes-2023/traded-carbon-values-used-for-modelling-purposes-2023 (Accessed 12 December 2025)
Biodiversity benefits / ecosystem services provided by the option	Soil erosion control Flood regulation Air quality Habitat creation/enhancement
Biodiversity and ecosystem services: range of monetary value (£)	£149 - £241 / hectare/year
Biodiversity and ecosystem services: modelled value per unit	£66.90 / ha / year
Biodiversity / ecosystem service co-benefits: assumptions and sources	Defra (2025). Enabling a Natural Capital Approach guidance. Available at: https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance (Accessed 12 December 2025) Cranfield University (2011). *The total costs of soil degradation in England and Wales - SP1606.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 (Accessed 12 December 2025)

Adaptation option 3a. Silvopasture to provide shade for livestock - planting trees

Adaptation option number	3a
Component in scope	Dairy cattle
Hazard considered	Heat stress
Adaptation option description	Silvopasture to provide shade for livestock - planting trees
Source of adaptation option	ADAS & Met Office (2023). *Research to assess resilience measures that support UK agriculture in adapting to drought, extreme heat, and wildfires - SCF0140.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796 (Accessed 12 December 2025)
Effect of adaptation option	Reduces hazard

Unit CAPEX	£875.00
Unit	cow
CAPEX: assumptions and sources	Higher than alley cropping as the trees need to be protected from the cows. £1,750/ha (≈£875/cow assuming 2 cows/ha). Justification: lower end of UK trial costs including trees, protection, fencing and labour; per-animal cost derived from typical lowland dairy stocking rate. Based on: Harris, R. (2021). *Silvopasture: What it is and how it benefits livestock farming.* Available at: https://www.fwi.co.uk/business/silvopasture-what-it-is-and-how-it-benefits-livestock-farming (Accessed 12 December 2025) Natural England (2009). *Environmental impacts of land management (NERR030). Chapter 7. Grazing livestock in the lowlands.* Available at: https://publications.naturalengland.org.uk/publication/30026 (Accessed 12 December 2025)
Unit OPEX	£37.50
Unit	cow/yr

OPEX: assumptions and sources	Assume same as alley cropping. OPEX per cropped hectare; highest in establishment years then lower. Based on: AHDB (nd). *Agroforestry in the Sustainable Farming Incentive (SFI)*. Available at: https://ahdb.org.uk/trade-and-policy/elms/sfi/agroforestry (Accessed 12 December 2025) Forestry Commission (2023). *How trees benefit your farm business.* Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1167866/Trees_on_Farms_Feb_2023.pdf (Accessed 12 December 2025)
Lifetime of measure (years)	50
Lifetime of measure: assumptions and sources	Life varies by species/rotation: short-rotation poplar/willow ~20–30 yrs; mixed timber/fruit/nut 30–60+ yrs; long-lived oaks >80 yrs; UK example Wakelyns since 1994. Sources: The Organic Research Centre (2024). *Wakelyns Agroforestry: Resilience through diversity.* Available at: https://www.organicresearchcentre.com/wp-content/uploads/2024/05/WAF_V3_2024_final_pages_4web.pdf (Accessed 12 December 2025) Soil Association (2019). *The Agroforestry Handbook*. Available at: https://www.scribd.com/document/422243581/The-Agroforestry-Handbook (Accessed 12 December 2025)
Time for risk reduction to begin (years)	15
Time for risk reduction to begin: assumptions and sources	Based on yield effect timelines set out in: Soil Association (2019). *The Agroforestry Handbook*. Available at: https://www.scribd.com/document/422243581/The-Agroforestry-Handbook (Accessed 12 December 2025)
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	35%

Risk reduction: assumptions and sources	Assumption. Effectiveness depends on shade access time, tree density/arrangement, and heat severity (THI). Peer-review shows consistent reductions in respiration rate and surface temperature under silvopasture; UK on-farm data show very large avoidance of milk losses when shade is present during extreme heat. Sources: Systematic review: Deniz et al. (2023). A systematic review of the effects of silvopastoral system on thermal environment and dairy cows' behavioral and physiological responses. *International Journal of Biometeorology* (67): 409 – 422. Available at: https://doi.org/10.1007/s00484-023-02431-5 UK case study: James, D. (2025). *Why planting more trees could protect milk yields*. Available at: https://www.fwi.co.uk/livestock/health-welfare/why-planting-more-trees-could-protect-milk-yields (Accessed 12 December 2025) NZ modelling of tree shade reducing heat-stress occurrence: Bloomberg, M. & Bywater, A.C. (2007). *Estimating the effect of shade on heat stress in New Zealand dairy cows using two published models*. Available at: https://www.mssanz.org.au/MODSIM07/papers/7_s50/EstimatingTheEffect_s50_Bloomberg_.pdf (Accessed 12 December 2025)
Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	4%
Maximum future uptake % of farmers implementing this option	30%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2035
Uptake rates: assumptions and sources	Assumptions, based on current pilot scale activity but acknowledged potential. For example, this 2021 article: Harris, R. (2021). *Silvopasture: What it is and how it benefits livestock farming.* Available at: https://www.fwi.co.uk/business/silvopasture-what-it-is-and-how-it-benefits-livestock-farming (Accessed 12 December 2025)

Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	-3.1 tCO_2e/cow/yr
Climate mitigation co-benefits: assumptions and sources	Amount varies by tree species ONS (2024). Woodland natural capital accounts, UK:2024. Available at: https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/woodlandnaturalcapitalaccountsuk/2024 (Accessed 12 December 2025) DESNZ (2023). Traded carbon values used for modelling purposes, 2023. Available at: https://www.gov.uk/government/publications/traded-carbon-values-used-for-modelling-purposes-2023/traded-carbon-values-used-for-modelling-purposes-2023 (Accessed 12 December 2025)
Biodiversity benefits / ecosystem services provided by the option	Soil erosion control Flood regulation Air quality Habitat creation/enhancement Water quality
Biodiversity and ecosystem services: range of monetary value (£)	£118 - £241 / hectare / year
Biodiversity and ecosystem services: modelled value per unit	£33.45 / cow / year
Biodiversity / ecosystem service co-benefits: assumptions and sources	Defra (2025). Enabling a Natural Capital Approach guidance. Available at: https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance (Accessed 12 December 2025) Cranfield University (2011). *The total costs of soil degradation in England and Wales - SP1606.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 (Accessed 12 December 2025)

Adaptation option 3b. Silvopasture to provide shade for livestock - planting hedgerows

Adaptation option number	3b
Component in scope	Dairy cattle
Hazard considered	Heat stress
Adaptation option description	Silvopasture to provide shade for livestock - planting hedgerows
Source of adaptation option	ADAS & Met Office (2023). *Research to assess resilience measures that support UK agriculture in adapting to drought, extreme heat, and wildfires - SCF0140.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796 (Accessed 12 December 2025)
Effect of adaptation option	Reduces hazard

Unit CAPEX	£4,500
Unit	cow
CAPEX: assumptions and sources	Contract planted, double-width and double rabbit fenced. From: Redman, G. (2023). *John Nix Pocketbook for Farm Management*. 54th edition.
Unit OPEX	£10.00
Unit	cow/yr
OPEX: assumptions and sources	Based on £59 per hour for an 8 hour day to cut 3 miles of hedge (from Redman, G. (2023). *John Nix Pocketbook for Farm Management*. 54th edition). When rounded this equates to £500 for 5km or £0.10 per metre. This will be an underestimate as there will be maintenance costs associated with establishment in early years
Lifetime of measure (years)	50

Lifetime of measure: assumptions and sources	Assumption. Hedgerows are semi-permanent green infrastructure whose longevity depends on management (laying/coppicing cycles) and health; well-managed hedges readily persist for multiple decades to over a century. Sources: Woodland Trust (2014). *Wood Wise Woodland Conservation News. Summer 2014.* Available at: https://www.woodlandtrust.org.uk/media/1800/wood-wise-hedgerows-and-hedgerow-trees.pdf (Accessed 12 December 2025) The Tree Council (nd). *Hedgerows.* Available at: https://treecouncil.org.uk/science-and-research/hedgerows/ (Accessed 12 December 2025)
Time for risk reduction to begin (years)	5
Time for risk reduction to begin: assumptions and sources	Risk reduction begins once a dense, ~2 m tall hedge is established to cast usable shade. Typical growth of hawthorn/blackthorn ~40–60 cm/yr; SFI notes ‘fully established’ usually ~5 years after planting. Exposure, browsing and poor establishment can extend to 8–10 years. Based on: Woodland Trust (nd). Hawthorn (*Crateagus monogyna*). Available at: https://shop.woodlandtrust.org.uk/hawthorn (Accessed 12 December 2025) GOV.UK (2025). *CHRW2: Manage hedgerows.* Available at: https://www.gov.uk/find-funding-for-land-or-farms/chrw2-manage-hedgerows (Accessed 12 December 2025)
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	35%

Risk reduction: assumptions and sources	Same assumption as for silvo arable system above. Effectiveness depends on shade access time, tree density/arrangement, and heat severity (THI). Peer-review shows consistent reductions in respiration rate and surface temperature under silvopasture; UK on-farm data show very large avoidance of milk losses when shade is present during extreme heat. Sources: Systematic review: Deniz et al. (2023). A systematic review of the effects of silvopastoral system on thermal environment and dairy cows' behavioral and physiological responses. *International Journal of Biometeorology* (67): 409 – 422. Available at: https://doi.org/10.1007/s00484-023-02431-5 UK case study: James, D. (2025). *Why planting more trees could protect milk yields*. Available at: https://www.fwi.co.uk/livestock/health-welfare/why-planting-more-trees-could-protect-milk-yields (Accessed 12 December 2025) NZ modelling of tree shade reducing heat-stress occurrence: Bloomberg, M. & Bywater, A.C. (2007). *Estimating the effect of shade on heat stress in New Zealand dairy cows using two published models*. Available at: https://www.mssanz.org.au/MODSIM07/papers/7_s50/EstimatingTheEffect_s50_Bloomberg_.pdf (Accessed 12 December 2025)
Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	60%
Maximum future uptake % of farmers implementing this option	75%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2045
Uptake rates: assumptions and sources	Assumes that hedgerows are already common, and that more could be planted. For example, this 2022 report notes that 62% of livestock farmers think hedgerows are important: CPRE (2022). *Farming and hedgerows: stretching the boundaries*. Available at: https://www.cpre.org.uk/wp-content/uploads/2022/12/CPRE-farming-and-hedgrows-report.pdf (Accessed 12 December 2025)

Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	-0.18tCO2e/cow/yr
Climate mitigation co-benefits: assumptions and sources	Assumes 1.5 m hedge width with 200m hedge/ha. GWCT (nd). *Hedgerow Carbon Code.* Available at: https://www.allertontrust.org.uk/projects/hedgerow-carbon-code/ (Accessed 12 December 2025) Chapman, P. (2023). *What is the annual carbon sequestration of planting hedgerows?* Available at: https://hedgelink.org.uk/wp-content/uploads/2023/10/Sequestering-carbon-by-planting-hedgerows-powerpoint.pdf (Accessed 12 December 2025)
Biodiversity benefits / ecosystem services provided by the option	Soil erosion control Flood regulation Air quality Boundary habitat creation Water quality
Biodiversity and ecosystem services: range of monetary value (£)	£149 - £241 / hectare/year
Biodiversity and ecosystem services: modelled value per unit	£20.90 / cow / year
Biodiversity / ecosystem service co-benefits: assumptions and sources	Defra (2025). Enabling a Natural Capital Approach guidance. Available at: https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance (Accessed 12 December 2025) Cranfield University (2011). *The total costs of soil degradation in England and Wales - SP1606.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 (Accessed 12 December 2025)

Adaptation option 3c. Silvopasture to provide shade for livestock - planting trees

Adaptation option number	3c
Component in scope	Hens
Hazard considered	Heat stress
Adaptation option description	Silvopasture to provide shade for livestock - planting trees
Source of adaptation option	ADAS & Met Office (2023). *Research to assess resilience measures that support UK agriculture in adapting to drought, extreme heat, and wildfires - SCF0140.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796 (Accessed 12 December 2025)
Effect of adaptation option	Reduces hazard

Unit CAPEX	£0.70
Unit	hen
CAPEX: assumptions and sources	Higher than alley cropping as the trees need to be protected. £1,750/ha (≈£0.75/hen assuming 2500 hens/ha). Justification: lower end of UK trial costs including trees, protection, fencing and labour; per-animal cost derived from EU max hen stocking rate. Based on: Harris, R. (2021). *Silvopasture: What it is and how it benefits livestock farming.* Available at: https://www.fwi.co.uk/business/silvopasture-what-it-is-and-how-it-benefits-livestock-farming (Accessed 12 December 2025) Natural England (2009). *Environmental impacts of land management (NERR030). Chapter 7. Grazing livestock in the lowlands.* Available at: https://publications.naturalengland.org.uk/publication/30026 (Accessed 12 December 2025)
Unit OPEX	£0.03
Unit	hen/yr

OPEX: assumptions and sources	Assume same as alley cropping. OPEX per cropped hectare; highest in establishment years then lower. Based on: AHDB (nd). *Agroforestry in the Sustainable Farming Incentive (SFI)*. Available at: https://ahdb.org.uk/trade-and-policy/elms/sfi/agroforestry (Accessed 12 December 2025) Forestry Commission (2023). *How trees benefit your farm business.* Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1167866/Trees_on_Farms_Feb_2023.pdf (Accessed 12 December 2025)
Lifetime of measure (years)	50
Lifetime of measure: assumptions and sources	Life varies by species/rotation: short-rotation poplar/willow ~20–30 yrs; mixed timber/fruit/nut 30–60+ yrs; long-lived oaks >80 yrs; UK example Wakelyns since 1994. Sources: The Organic Research Centre (2024). *Wakelyns Agroforestry: Resilience through diversity.* Available at: https://www.organicresearchcentre.com/wp-content/uploads/2024/05/WAF_V3_2024_final_pages_4web.pdf (Accessed 12 December 2025) Soil Association (2019). *The Agroforestry Handbook*. Available at: https://www.scribd.com/document/422243581/The-Agroforestry-Handbook (Accessed 12 December 2025)
Time for risk reduction to begin (years)	10
Time for risk reduction to begin: assumptions and sources	Based on yield effect timelines set out in: Soil Association (2019). *The Agroforestry Handbook*. Available at: https://www.scribd.com/document/422243581/The-Agroforestry-Handbook (Accessed 12 December 2025)
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	35%
Risk reduction: assumptions and sources	Similar assumptions and sources as for dairy cattle, including: Farming connect (2023). *Silvopoultry: Three birds, one stone.* Available at: https://businesswales.gov.wales/farmingconnect/news-and-events/technical-articles/silvopoultry-three-birds-one-stone (Accessed 12 December 2025) Forest Service of the US Department of Agriculture (2025). *Silvopasture: An Agroforestry Practice.* Available at: https://www.fs.usda.gov/research/publications/an/silvopasture-an-agroforestry-practice-an8-final-508.pdf (Accessed 12 December 2025)

Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	0%
Maximum future uptake % of farmers implementing this option	30%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2040
Uptake rates: assumptions and sources	As above for dairy cattle
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	-0.00248 tCO_2e/hen/yr
Climate mitigation co-benefits: assumptions and sources	Amount varies by tree species ONS (2024). Woodland natural capital accounts, UK:2024. Available at: https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/woodlandnaturalcapitalaccountsuk/2024 (Accessed 12 December 2025) DESNZ (2023). Traded carbon values used for modelling purposes, 2023. Available at: https://www.gov.uk/government/publications/traded-carbon-values-used-for-modelling-purposes-2023/traded-carbon-values-used-for-modelling-purposes-2023 (Accessed 12 December 2025)
Biodiversity benefits / ecosystem services provided by the option	Soil erosion control Flood regulation Air quality Habitat creation/enhancement Water quality
Biodiversity and ecosystem services: range of monetary value (£)	£118 - £241 / hectare /year
Biodiversity and ecosystem services: modelled value per unit	£0.03 / hen / year

Biodiversity / ecosystem service co-benefits: assumptions and sources	Defra (2025). Enabling a Natural Capital Approach guidance. Available at: https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance (Accessed 12 December 2025) Cranfield University (2011). *The total costs of soil degradation in England and Wales - SP1606.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 (Accessed 12 December 2025)

Adaptation option 3d. Silvopasture to provide shade for livestock – planting hedgerows

Adaptation option number	3d
Component in scope	Hens
Hazard considered	Heat stress
Adaptation option description	Silvopasture to provide shade for livestock – planting hedgerows
Source of adaptation option	ADAS & Met Office (2023). *Research to assess resilience measures that support UK agriculture in adapting to drought, extreme heat, and wildfires - SCF0140.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796 (Accessed 12 December 2025)
Effect of adaptation option	Reduces hazard

Unit CAPEX	£3.60
Unit	hen
CAPEX: assumptions and sources	Contract planted, double-width and double rabbit fenced. From Nix handbook 2024
Unit OPEX	£0.01
Unit	hen/yr
OPEX: assumptions and sources	Based on £59 per hour for an 8 hour day to cut 3 miles of hedge (from Redman, G. (2023). *John Nix Pocketbook for Farm Management*. 54th edition). When rounded this equates to £500 for 5km or £0.10 per metre. This will be an underestimate as there will be maintenance costs associated with establishment in early years
Lifetime of measure (years)	50

Lifetime of measure: assumptions and sources	Assumption. Hedgerows are semi-permanent green infrastructure whose longevity depends on management (laying/coppicing cycles) and health; well-managed hedges readily persist for multiple decades to over a century. Sources: Woodland Trust (2014). *Wood Wise Woodland Conservation News. Summer 2014.* Available at: https://www.woodlandtrust.org.uk/media/1800/wood-wise-hedgerows-and-hedgerow-trees.pdf (Accessed 12 December 2025) The Tree Council (nd). *Hedgerows.* Available at: https://treecouncil.org.uk/science-and-research/hedgerows/ (Accessed 12 December 2025)
Time for risk reduction to begin (years)	5
Time for risk reduction to begin: assumptions and sources	Risk reduction begins once a dense, ~2 m tall hedge is established to cast usable shade. Typical growth of hawthorn/blackthorn ~40–60 cm/yr; SFI notes ‘fully established’ usually ~5 years after planting. Exposure, browsing and poor establishment can extend to 8–10 years. Based on: Woodland Trust (nd). Hawthorn (*Crataegus monogyna*). Available at: https://shop.woodlandtrust.org.uk/hawthorn (Accessed 12 December 2025) GOV.UK (2025). *CHRW2: Manage hedgerows.* Available at: https://www.gov.uk/find-funding-for-land-or-farms/chrw2-manage-hedgerows (Accessed 12 December 2025)
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	35%
Risk reduction: assumptions and sources	Similar assumptions and sources as for dairy cattle, including: Farming connect (2023). *Silvopoultry: Three birds, one stone.* Available at: https://businesswales.gov.wales/farmingconnect/news-and-events/technical-articles/silvopoultry-three-birds-one-stone (Accessed 12 December 2025) Forest Service of the US Department of Agriculture (2025). *Silvopasture: An Agroforestry Practice.* Available at: https://www.fs.usda.gov/research/publications/an/silvopasture-an-agroforestry-practice-an8-final-508.pdf (Accessed 12 December 2025)

Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	60%
Maximum future uptake % of farmers implementing this option	75%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2045
Uptake rates: assumptions and sources	As above for dairy cattle
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	-0.000144tCO2e/hen/yr
Climate mitigation co-benefits: assumptions and sources	Assumes 1.5 m hedge width with 200m hedge/ha. GWCT (nd). *Hedgerow Carbon Code.* Available at: https://www.allertontrust.org.uk/projects/hedgerow-carbon-code/ (Accessed 12 December 2025) Chapman, P. (2023). *What is the annual carbon sequestration of planting hedgerows?* Available at: https://hedgelink.org.uk/wp-content/uploads/2023/10/Sequestering-carbon-by-planting-hedgerows-powerpoint.pdf (Accessed 12 December 2025)
Biodiversity benefits / ecosystem services provided by the option	Soil erosion control Flood regulation Air quality Boundary habitat creation Water quality
Biodiversity and ecosystem services: range of monetary value (£)	£149 - £241 / hectare/year
Biodiversity and ecosystem services: modelled value per unit	£0.02 / hen / year

Biodiversity / ecosystem service co-benefits: assumptions and sources	Defra (2025). Enabling a Natural Capital Approach guidance. Available at: https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance (Accessed 12 December 2025) Cranfield University (2011). *The total costs of soil degradation in England and Wales - SP1606.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 (Accessed 12 December 2025)

Adaptation option 7. Housing cattle inside during hot periods

Adaptation option number	7
Component in scope	Cattle
Hazard considered	Heat stress
Adaptation option description	House cows inside during hot periods, using winter housing facilities which have been suitably upgraded to deliver required shade and cooling
Source of adaptation option	ADAS & Met Office (2023). *Research to assess resilience measures that support UK agriculture in adapting to drought, extreme heat, and wildfires - SCF0140.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796 (Accessed 12 December 2025)
Effect of adaptation option	Reduces hazard

Unit CAPEX	£200
Unit	cow
CAPEX: assumptions and sources	UK articles and suppliers indicate ~£1,300/fan with energy-efficient models; ROI from milk and health benefits. Based on: British Dairying (nd). *Tackling heat stress with fans.* Available at: https://www.britishdairying.co.uk/2023/08/17/tackling-heat-stress-with-fans/ (Accessed 12 December 2025) Balsom, A. (2022). *Guide to choosing a ventilation system for your dairy unit.* Available at: https://www.fwi.co.uk/livestock/housing/guide-to-choosing-a-ventilation-system-for-your-dairy-unit (Accessed 12 December 2025)
Unit OPEX	£30.00
Unit	cow/yr

OPEX: assumptions and sources	UK articles and suppliers indicate ~£1,300/fan with energy-efficient models; ROI from milk and health benefits. Based on: British Dairying (nd). *Tackling heat stress with fans.* Available at: https://www.britishdairying.co.uk/2023/08/17/tackling-heat-stress-with-fans/ (Accessed 12 December 2025) Balsom, A. (2022). *Guide to choosing a ventilation system for your dairy unit.* Available at: https://www.fwi.co.uk/livestock/housing/guide-to-choosing-a-ventilation-system-for-your-dairy-unit (Accessed 12 December 2025)
Lifetime of measure (years)	10
Lifetime of measure: assumptions and sources	Assume fans 10–15 yr; controls/ducts 15–20 yr; maintenance dependent. Based on: ELTA (nd). *Fans.* Available at: https://eltauk.com/products/fans/ (Accessed 12 December 2025); EG Agri (nd). *Elta Turbulator HTS Recirculation Fan.* Available at: https://egagri.co.uk/product/elta-turbulator-recirculation-fan/ (Accessed 12 December 2025)
Time for risk reduction to begin (years)	0
Time for risk reduction to begin: assumptions and sources	Immediate installation (during winter / cooler period) and operation
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	10%
Risk reduction: assumptions and sources	Based on optimistic view of effectiveness from this 2003 US study: Brouk, M.J., Smith, J.F. & Harner, J.P. III (2003). *Effectiveness of Cow Cooling Strategies Under Different Environmental Conditions.* Available at: https://www.asi.k-state.edu/doc/dairy/effectiveness-of-cow-cooling-strategies-under-diff-environmental-conditions.pdf (Accessed 12 December 2025)
Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	5%
Maximum future uptake % of farmers implementing this option	50%
Year that adaptations start (modelling assumption)	2025

Year that max uptake is achieved (modelling assumption)	2040
Uptake rates: assumptions and sources	Assumptions based on likely low current provision of actively cooled housing, but that such measures might be straightforward to implement (James, D. (2023). *Cool cows are priority as dairy industry faces hotter summers.* Available at: https://www.walesfarmer.co.uk/news/23511920.cool-cows-priority-dairy-industry-faces-hotter-summers/ (Accessed 12 December 2025))
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	Extra electricity (fans + sprinklers): +1.3 t CO_2e/year Embodied carbon (annualized): +0.05–0.1 t CO_2e/year Total added emissions: ~+1.4 t CO_2e/year Assumptions for a 100-cow barn. Total added emissions per cow ≈ +0.014 t CO_2e/cow/year DESNZ (2024). *Greenhouse gas reporting: conversion factors for 2024.* Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2024 (Accessed 12 December 2025) IPTEnergised (2024). *New 2024 UK grid emissions factors.* Available at: https://www.itpenergised.com/new-2024-uk-grid-emissions-factors/ (Accessed 12 December 2025)
Climate mitigation co-benefits: assumptions and sources	NA
Biodiversity benefits / ecosystem services provided by the option	NA
Biodiversity and ecosystem services: range of monetary value (£)	NA
Biodiversity and ecosystem services: modelled value per unit	NA
Biodiversity / ecosystem service co-benefits: assumptions and sources	NA

Adaptation option 7b. Housing hens inside during hot periods

Adaptation option number	7b
Component in scope	Hens
Hazard considered	Heat stress
Adaptation option description	House hens inside during hot weather. Upgrade night time housing to include fans + high-pressure fogging, and paint roof with reflective paint
Source of adaptation option	ADAS & Met Office (2023). *Research to assess resilience measures that support UK agriculture in adapting to drought, extreme heat, and wildfires - SCF0140.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796 (Accessed 12 December 2025)
Effect of adaptation option	Reduces hazard

Unit CAPEX	£2.47
Unit	hen
CAPEX: assumptions and sources	Adds fogging equipment & install ~£12k–£25k/house to fans (above); costs vary by nozzle count, pump size and controls. Based on: EG Agri (nd). *Evaporative Cooling System.* Available at: https://egagri.co.uk/product/evaporative-cooling-system/ (Accessed 12 December 2025); VALCO (nd). *PolAIR High Pressure Fogging.* Available at: https://www.val-co.com/polair-high-pressure-fogging/ (Accessed 12 December 2025) In addition: reflective roof coating to minimise solar gain- assume £8 per m2, with a 2000m2 area = £16000 GB Cleaning Services (2024). *How Much Does Roof Coating Cost? (UK Guide)*. Available at: https://www.gbcleaningservicesnorfolk.co.uk/how-much-does-roof-coating-cost-uk-guide (Accessed 12 December 2025)
Unit OPEX	£0.06
Unit	hen/yr

OPEX: assumptions and sources	Fans as above plus fogging pump 2 kW for same hours; electricity 18.5 p/kWh; water cost excluded (minor vs drinking water). Based on: DESNX (2025). *Quarterly Energy Prices.* Available at: https://assets.publishing.service.gov.uk/media/685a9f35db207fc18744d608/quarterly-energy-prices-june-2025.pdf (Accessed 12 December 2025) The University of Georgia (2009). *Poultry Housing Tips. How Much Water Does a Broiler House Use?* Available at: https://www.poultryventilation.com/wp-content/uploads/vol21n5.pdf (Accessed 12 December 2025)
Lifetime of measure (years)	10
Lifetime of measure: assumptions and sources	Fans 10–15 yr; fogging pumps/nozzles 7–10 yr with maintenance; controls/ducts 15–20 yr. Based on: ELTA (nd). *Fans.* Available at: https://eltauk.com/products/fans/ (Accessed 12 December 2025); EG Agri (nd). *Elta Turbulator HTS Recirculation Fan.* Available at: https://egagri.co.uk/product/elta-turbulator-recirculation-fan/ (Accessed 12 December 2025)
Time for risk reduction to begin (years)	0
Time for risk reduction to begin: assumptions and sources	Immediate installation (during winter / cooler period) and operation
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	60%
Risk reduction: assumptions and sources	Meta-analysis shows egg mass/HDEP drop 9–22.6% under heat; evaporative cooling (pads/fogging) lowers indoor T by ~6–8.5 °C, moving conditions towards thermo-neutral; increased air velocity improves output. Sources: Grasteau et al. (2015). Robustness to chronic heat stress in laying hens: a meta-analysis. *Poultry Science* **94(4): 586-600.** Available at: https://hal.science/hal-01194091v1 Purswell et al. (2013). Effects of Air Velocity on Laying Hen Production from 24 to 27 Weeks under Simulated Evaporatively Cooled Conditions. *Transactions of the ASABE* **56(6): 1503-1508.** Available at: https://doi.org/10.13031/trans.58.10982 EG Agri (nd). *Evaporative Cooling System.* Available at: https://egagri.co.uk/product/evaporative-cooling-system/ (Accessed 12 December 2025);

Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	5%
Maximum future uptake % of farmers implementing this option	50%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2040
Uptake rates: assumptions and sources	As above for dairy cattle and assumed to be more effective than fans but have a lower current uptake rate. Sources: EG Agri (nd). *The Most Suitable Ventilation For Chicken Houses*. Available at: https://egagri.co.uk/blog/the-most-suitable-ventilation-for-chicken-houses/ (Accessed 12 December 2025) Defra (2024). *Introducing Laying Hen Housing for Health and Welfare Grants*. Available at: https://defrafarming.blog.gov.uk/2024/05/15/introducing-laying-hen-housing-for-health-and-welfare-grants/ (Accessed 12 December 2025)
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	+0.00012 tCO_2e/hen/year
Climate mitigation co-benefits: assumptions and sources	Assumes a 16,000-hen flock (≈6.4 ha outdoor range) and an extra 5,000 kWh/year for cooling upgrades. Reflective paint has negligible embodied emissions and may slightly reduce fan runtime, but no sequestration occurs. Ryan, C. (2020). *Analysis: Cracking down on the carbon footprint of eggs to reach net zero*. Available at: https://www.poultrynews.co.uk/production/egg-production/analysis-cracking-down-on-the-carbon-footprint-of-eggs-to-reach-net-zero.html (Accessed 12 December 2025) Defra (2024). *Code of practice for the welfare of laying hens and pullets*. Available at: https://www.gov.uk/government/publications/poultry-on-farm-welfare/poultry-welfare-recommendations (Accessed 12 December 2025)
Biodiversity benefits / ecosystem services provided by the option	NA

Biodiversity and ecosystem services: range of monetary value (£)	NA
Biodiversity and ecosystem services: modelled value per unit	NA
Biodiversity / ecosystem service co-benefits: assumptions and sources	NA

Adaptation option 29a. Install in-field shelters/tents (semi-permanent) to provide shade

Adaptation option number	29a
Component in scope	Dairy cattle
Hazard considered	Heat stress
Adaptation option description	Install in-field shelters/tents (semi-permanent) to provide shade
Source of adaptation option	ADAS & Met Office (2023). *Research to assess resilience measures that support UK agriculture in adapting to drought, extreme heat, and wildfires - SCF0140.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796 (Accessed 12 December 2025)
Effect of adaptation option	Reduces hazard

Unit CAPEX	£770
Unit	cow
CAPEX: assumptions and sources	Assume 11m2 floor space per cow (Red Tractor Assurance (2018). *Appendix HF.f. Housing space allowances*. Available at: https://redtractorassurance.org.uk/wp-content/uploads/2018/05/HF.f-BEEF_LAMB_Housing-Space-allowance.pdf (Accessed 12 December 2025)) and £70/m2 for large shelter tent (£7000 for 10x10m) Hardlife Utility (nd). *Livestock field shelters.* Available at: https://hardlifeutility.com/collections/livestock-shelters?srsltid=AfmBOorulVtvkQe3QvjSFuAWDvm3Q4t6xd7QhkEoi3pG-_5-pN9Njhhg (Accessed 12 December 2025)
Unit OPEX	£30.00
Unit	cow/yr

OPEX: assumptions and sources	Costs include 30% capital cost every 10 years to replace tarp covering and 1% annual cost of capex for other maintenance. OPEX mainly inspection/anchor re-tensioning, occasional relocations and periodic cover replacement. No utilities needed. Tarp warranties 3–5 years; frames galvanised steel with 10-year guarantee on some lines. Based on: House of Tents (2022). *Guarantee Policy of TOOLPORT GmbH.* Available at: https://www.houseoftents.co.uk/guarantee-policy-of-toolport-gmbh/ (Accessed 12 December 2025); northern polytunnels (nd). *Field Shelter*. Available at: https://northernpolytunnels.co.uk/product/field-shelter/ (Accessed 12 December 2025)
Lifetime of measure (years)	10
Lifetime of measure: assumptions and sources	Covers typically 3–5 year warranties; structures 10-year guarantees and longer real-world lifetimes; plastisol cladding up to ~25 years. Based on: House of Tents (2022). *Guarantee Policy of TOOLPORT GmbH.* Available at: https://www.houseoftents.co.uk/guarantee-policy-of-toolport-gmbh/ (Accessed 12 December 2025); northern polytunnels (nd). *Field Shelter*. Available at: https://northernpolytunnels.co.uk/product/field-shelter/ (Accessed 12 December 2025)
Time for risk reduction to begin (years)	0
Time for risk reduction to begin: assumptions and sources	Immediate installation (during winter / cooler period)
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	10%
Risk reduction: assumptions and sources	Shade from buildings ~ 1/3rd as effective at delivering cattle weight gain compared with tree shade: Higgins, S.F., Agouridis, C.T. & Wightman, S.J. (2024). *Shading Options for Grazing Cattle.* Available at: https://publications.ca.uky.edu/sites/publications.ca.uky.edu/files/aen99.pdf (Accessed 12 December 2025)
Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	25%
Maximum future uptake % of farmers implementing this option	50%

Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2035
Uptake rates: assumptions and sources	Assumptions based on this recently published study: McFadzean, H. (2024) *Enhancing The Resilience Of UK Dairy Sector: How Do We* *Practically Adapt To Increasingly Volatile Weather Conditions?* Available at: https://www.nuffieldscholar.org/reports/gb/2025/enhancing-resilience-uk-dairy-sector-how-do-we-practically-adapt-increasingly (Accessed 12 December 2025)
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	+0.0725 tCO2e per cow
Climate mitigation co-benefits: assumptions and sources	House of Tents (nd). *TOOLPORT 10x12m Container Top Shelter*. Available at: https://www.houseoftents.co.uk/container-shelter/49669.html (Accessed 12 December 2025) circular ecology (nd). *Embodied Carbon – The ISE Database.* Available at: https://circularecology.com/embodied-carbon-footprint-database.html (Accessed 12 December 2025) Rubio-Domingo, G. & Halevi, A. (2022). *Making Plastics Emissions Transparent*. Available at: https://ccsi.columbia.edu/sites/ccsi.columbia.edu/files/content/COMET-making-plastics-emissions-transparent.pdf (Accessed 12 December 2025) CarbonCloud (nd). *PVC Container, fossil based.* Available at: https://apps.carboncloud.com/climatehub/product-reports/id/84862703638 (Accessed 12 December 2025)
Biodiversity benefits / ecosystem services provided by the option	NA
Biodiversity and ecosystem services: range of monetary value (£)	NA
Biodiversity and ecosystem services: modelled value per unit	NA
Biodiversity / ecosystem service co-benefits: assumptions and sources	NA

Adaptation option 29b. Install in-field shelters/tents (semi-permanent) for free range hens to provide shade

Adaptation option number	29b
Component in scope	Hens
Hazard considered	Heat stress
Adaptation option description	Install in-field shelters/tents (semi-permanent) for free range hens to provide shade
Source of adaptation option	ADAS & Met Office (2023). *Research to assess resilience measures that support UK agriculture in adapting to drought, extreme heat, and wildfires - SCF0140.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21796 (Accessed 12 December 2025)
Effect of adaptation option	Reduces hazard

Unit CAPEX	£1.00
Unit	hen
CAPEX: assumptions and sources	Assumptions: use shade net at ~£2–£3/m² plus posts, fixings and installation; scale by flock size and shaded area (3–5 m² shade per 10 birds). Sources: LBS (nd). *Fabricated Netting – 50% Shade Value (Per Sq. Meter).* Available at: https://www.lbsbuyersguide.co.uk/fabricated-netting-50-shade-value-per-sq-meter (Accessed 12 December 2025) RSPCA (2025). *RSPCA welfare standards: Laying Hens.* Available from: https://www.rspca.org.uk/documents/d/rspca/rspca-welfare-standards-for-laying-hens (Accessed 12 December 2025)
Unit OPEX	£0.10
Unit	hen/yr
OPEX: assumptions and sources	Netting typically replaced every 5–10 years depending on UV exposure; minimal energy OPEX. Sources: Shade cloth UK pricing: LBS (nd). *Fabricated Netting – 50% Shade Value (Per Sq. Meter).* Available at: https://www.lbsbuyersguide.co.uk/fabricated-netting-50-shade-value-per-sq-meter (Accessed 12 December 2025)
Lifetime of measure (years)	8

Lifetime of measure: assumptions and sources	UV-stabilised cloth warranty 3–8 years; frames galvanised steel last longer. Based on: LBS (nd). *Fabricated Netting – 50% Shade Value (Per Sq. Meter).* Available at: https://www.lbsbuyersguide.co.uk/fabricated-netting-50-shade-value-per-sq-meter (Accessed 12 December 2025)
Time for risk reduction to begin (years)	0
Time for risk reduction to begin: assumptions and sources	Immediate installation (during winter / cooler period)
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	15%
Risk reduction: assumptions and sources	Estimate, based on: Kim, H-R et al. (2024). Effects of Heat Stress on the Laying Performance, Egg Quality, and Physiological Response of Laying Hens. *Animals* **14(7): 1076.** https://doi.org/10.3390/ani14071076 Campbell, D.L.M., Bari, M.S. & Rault, J-L. (2021). Free-range egg production: its implications for hen welfare. *Animal Production Science* **61(10): 848-855.** https://doi.org/10.1071/AN19576 Assumes metric is % reduction in heat-stress-induced egg weight loss; heat stress reduces egg production and mass; shade reduces radiant load. Evidence of heat stress impacts: Laying hens heat stress impacts:
Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	25%
Maximum future uptake % of farmers implementing this option	50%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2035
Uptake rates: assumptions and sources	Uses the same assumptions as for dairy cattle
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	Embodied carbon low for netting (High-Density Polyethylene is +0.00275 tCO2e/kg) and frames; per bird impact very small; assume zero emissions

Climate mitigation co-benefits: assumptions and sources	Generic plastics/steel factors (overview papers): Rubio-Domingo, G. & Halevi, A. (2022). *Making Plastics Emissions Transparent*. Available at: https://ccsi.columbia.edu/sites/ccsi.columbia.edu/files/content/COMET-making-plastics-emissions-transparent.pdf (Accessed 12 December 2025
Biodiversity benefits / ecosystem services provided by the option	NA
Biodiversity and ecosystem services: range of monetary value (£)	NA
Biodiversity and ecosystem services: modelled value per unit	NA
Biodiversity / ecosystem service co-benefits: assumptions and sources	NA

Adaptation option 70. Increase biosecurity measures on farms to guard against the import and/or spread of *Haemonchus contortus*

Adaptation option number	70
Component in scope	Lambs
Hazard considered	Temperatures conducive to parasite outbreaks
Adaptation option description	Increase biosecurity measures on farms to guard against the import and/or spread of *Haemonchus contortus*
Source of adaptation option	ADAS & Met Office (2023). *Research to assess resilience measures that support UK agriculture in adapting to changing seasonality and extreme rainfall - SCF0141.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21797 (Accessed 12 December 2025)
Effect of adaptation option	Decreases vulnerability

Unit CAPEX	£5.00
Unit	lamb
CAPEX: assumptions and sources	Assumptions using general biosecurity costing frameworks; measures reduce introduction of parasites and anthelmintic resistance. Based on: BIOSECURE (2023). *Enhancing biosecurity in livestock production.* Available at: https://biosecure.eu/ (Accessed 12 December 2025); SCOPS (nd). *Helping sheep farmers to maximise productivity by sustainably controlling parasites.* Available at: https://www.scops.org.uk/ (Accessed 12 December 2025) Although these estimates are for sheep we have assumed 1:1 sheep:lamb cost equivalents for the measures"
Unit OPEX	£1.00
Unit	lamb/yr
OPEX: assumptions and sources	OPEX mostly FEC tests and occasional treatments; targeted selective treatment approach recommended. Sources: SCOPS (nd). *Helping sheep farmers to maximise productivity by sustainably controlling parasites.* Available at: https://www.scops.org.uk/ (Accessed 12 December 2025) As with Capex, assumes 1:1 sheep:lamb cost equivalent

Lifetime of measure (years)	1
Lifetime of measure: assumptions and sources	Assumes that the measure is implemented continuously
Time for risk reduction to begin (years)	0
Time for risk reduction to begin: assumptions and sources	Assume immediate efficacy
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	70%
Risk reduction: assumptions and sources	Quarantine alone is partially effective: Swedish study showed FEC-positive rams dropped from 40% to 8% after ivermectin and isolation, but some infections persisted and reappeared later, highlighting limitations of single-drug reliance and larval survival. Adding diagnostics improves detection: ddPCR and FEC testing during quarantine reduce false negatives and lower introduction risk, though not perfect due to dormant larvae and resistance. Source: Höglund et al. (2024). Ramming the parasites: Evaluation of quarantine procedures against *Haemonchus contortus* at sheep markets in Sweden. *Veterinary Parasitology: Regional Studies and Reports* **56.** https://doi.org/10.1016/j.vprsr.2024.101125 Closed flock + strict sourcing can nearly eliminate risk: Buying only from accredited flocks, pre-movement testing, and effective anthelmintic treatment (with resistance check) can reduce introduction risk to very low levels. Source: SCOPS (nd). *Helping sheep farmers to maximise productivity by sustainably controlling parasites.* Available at: https://www.scops.org.uk/ (Accessed 12 December 2025)
Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	70%
Maximum future uptake % of farmers implementing this option	90%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2035

Uptake rates: assumptions and sources	Estimates - Farmers using general biosecurity measures (e.g. quarantine, rotational grazing, selective treatment) that may indirectly help control Haemonchus. SCOPS programme is widely promoted, but uptake of its full suite of recommendations (e.g. species-specific diagnostics, strategic grazing, FAMACHA scoring) is not universal. Surveys and workshops suggest that many farmers still rely on blanket treatments and are unfamiliar with targeted parasite control, especially for Haemonchus. SCOPS (nd). *Helping sheep farmers to maximise productivity by sustainably controlling parasites.* Available at: https://www.scops.org.uk/ (Accessed 12 December 2025); Howell et al. (2025). Identifying barriers to the sustainable control of gastro-intestinal nematodes in sheep: a social science perspective. *Animal* **19.** https://doi.org/10.1016/j.animal.2025.101506
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	No direct sequestration; potential emissions avoided by fewer treatments/inputs (not quantified).
Climate mitigation co-benefits: assumptions and sources	NA
Biodiversity benefits / ecosystem services provided by the option	NA
Biodiversity and ecosystem services: range of monetary value (£)	NA
Biodiversity and ecosystem services: modelled value per unit	NA
Biodiversity / ecosystem service co-benefits: assumptions and sources	NA

Adaptation option 71. Vaccinate lambs against *Haemonchus contortus*

Adaptation option number	71
Component in scope	Lambs
Hazard considered	Temperatures conducive to parasite outbreaks
Adaptation option description	Vaccinate lambs against *Haemonchus contortus*
Source of adaptation option	ADAS & Met Office (2023). *Research to assess resilience measures that support UK agriculture in adapting to changing seasonality and extreme rainfall - SCF0141.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=21797 (Accessed 12 December 2025)
Effect of adaptation option	Decreases vulnerability

Unit CAPEX	£10.00
Unit	lamb
CAPEX: assumptions and sources	Based on Australian data and import logistics: Barbervax (nd). *Barbervax. A vaccine for Barber's Pole worm.* Available at: https://barbervax.com/ (Accessed 12 December 2025); South East Farmer (2024). *Nature's vampire: Barber's Pole worm.* Available at: https://www.southeastfarmer.net/livestock/natures-vampire/ (Accessed 12 December 2025)
Unit OPEX	£1.80
Unit	lamb/yr
OPEX: assumptions and sources	Boosters required every six weeks during pest season. Assume 18 weeks = 3 doses, each dose at £0.60, based on Australian data: N&W Livestock (nd). *Barbervax | Barbers Pole Worm Vaccine.* Available at: https://nwlivestock.com.au/product/barbervax/ (Accessed 12 December 2025)
Lifetime of measure (years)	1
Lifetime of measure: assumptions and sources	Assumes immunity for a year
Time for risk reduction to begin (years)	0

Time for risk reduction to begin: assumptions and sources	Three priming doses are needed, spaced at four weekly intervals: Barbervax (nd). *How to use*. Available at: https://barbervax.com/how-to-use/ (Accessed 12 December 2025) Immediate efficacy assumed for modelling purposes
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	80%
Risk reduction: assumptions and sources	Assumption from study abstract - In hair sheep lambs given Barbervax, 79-87% of worm burdens and egg counts were reduced, respectively Teixeira et al. (2019). Strategic vaccination of hair sheep against *Haemonchus contortus.* Parasitology Research **118: 2383-2388.** Available at: https://link.springer.com/article/10.1007/s00436-019-06367-x
Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	1%
Maximum future uptake % of farmers implementing this option	40%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2050
Uptake rates: assumptions and sources	Assumptions based on AHDB (2023) - overall sheep vaccine use (not Barbervax specific) AHDB (2023). *Vaccine uptake report for cattle and sheep.* Available from: https://ahdb.org.uk/knowledge-library/vaccine-uptake-report-for-cattle-and-sheep (Accessed 12 December 2025). Barbervax is only available via veterinary prescription – must be imported from Australia.
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	No direct carbon effect; potential avoided emissions from fewer treatments/stock losses (not quantified).
Climate mitigation co-benefits: assumptions and sources	NA

Biodiversity benefits / ecosystem services provided by the option	NA
Biodiversity and ecosystem services: range of monetary value (£)	NA
Biodiversity and ecosystem services: modelled value per unit	NA
Biodiversity / ecosystem service co-benefits: assumptions and sources	NA

Adaptation option 74. Deploy rotational grazing with appropriate layoff intervals to ensure demise of *Haemonchus contortus*

Adaptation option number	74
Component in scope	Lambs
Hazard considered	Temperatures conducive to parasite outbreaks
Adaptation option description	Deploy rotational grazing with appropriate layoff intervals to ensure demise of *Haemonchus contortus*
Source of adaptation option	Jones et al. (2020). *Climate driven threshold effects in the natural environment.* Available from: https://www.ukclimaterisk.org/wp-content/uploads/2021/05/Climate-driven-threshold-effects-in-the-natural-environment-UKCEH.pdf (Accessed 12 December 2025)
Effect of adaptation option	Decreases vulnerability

Unit CAPEX	£0.00
Unit	lamb
CAPEX: assumptions and sources	"This is conventional practice although it must be noted that the rotational approach is different for Haemonchus control in as much as the resting period (between grazings) doubles. This would reduce the number of lambs that could be reared by half Acharya, M. & Brown, D. (2025). *Grazing Management for Parasite Control in Small Ruminants.* Available from: https://extension.missouri.edu/publications/g2613 (Accessed 12 December 2025); Hart, S. (2014). *Parasite Control with Multispecies and Rotational Grazing.* Available from: https://kerrcenter.com/wp-content/uploads/2014/04/hart_multispp_presentation.pdf (Accessed 12 December 2025)
Unit OPEX	£0.00
Unit	lamb/yr

OPEX: assumptions and sources	This is conventional practice although it must be noted that the rotational approach is different for Haemonchus control in as much as the resting period (between grazings) doubles. This would reduce the number of lambs that could be reared by half Acharya, M. & Brown, D. (2025). *Grazing Management for Parasite Control in Small Ruminants.* Available from: https://extension.missouri.edu/publications/g2613 (Accessed 12 December 2025); Hart, S. (2014). *Parasite Control with Multispecies and Rotational Grazing.* Available from: https://kerrcenter.com/wp-content/uploads/2014/04/hart_multispp_presentation.pdf (Accessed 12 December 2025)
Lifetime of measure (years)	1
Lifetime of measure: assumptions and sources	Assumes that the measure is implemented continuously
Time for risk reduction to begin (years)	0
Time for risk reduction to begin: assumptions and sources	Assumes that 'clean' pasture is immediately available
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	60%
Risk reduction: assumptions and sources	Assumed to be slightly less effective than vaccination
Consequential losses, resulting from the implementation of the measure	50% (field area lost to measure)
Baseline uptake % of farmers currently implementing this option	0%
Maximum future uptake % of farmers implementing this option	10%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2050

Uptake rates: assumptions and sources	Rotational grazing is increasingly recognised for its benefits, but adoption is uneven, with many farmers citing barriers such as infrastructure costs, labour, and uncertainty about benefits. However, 4-week rest periods are most commonly used in UK rotational grazing, which may not be long enough to reduce exposure to H. contortus - so assumes no current uptake of this measure and modest future uptake given potential impact on stocking rates Jordon, M.W., Winter, D.M. & Petrofsky, G. (2023). Advantages, disadvantages, and reasons for nonadoption of rotational grazing, herbal leys, trees on farms and ley-arable rotations on English livestock farms. *Agroecology and Sustainable Food Systems* **47(3): 330-354.** https://doi.org/10.1080/21683565.2022.2146253
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	-0.04 tCO_2e/ha/year
Climate mitigation co-benefits: assumptions and sources	Modest sequestration based on increase in soil organic matter. Fielding, D. (2022). *Unravelling the terminology and impacts of rotational grazing – what evidence is there for environmental benefits?* Available from: https://www.hutton.ac.uk/sites/default/files/files/publications/ClimPosReview_Unravelling_terminology_and_impacts_of_rotational_grazing_Fielding_April2022.pdf (Accessed 12 December 2025); Wardell et al. (2025). *The impacts on carbon and nature associated with transitioning to regenerative dairy farming practices*. Available from: https://www.wwf.org.uk/sites/default/files/2025-03/farm-carbon-toolkit-2025.pdf (Accessed 12 December 2025)
Biodiversity benefits / ecosystem services provided by the option	NA
Biodiversity and ecosystem services: range of monetary value (£)	NA
Biodiversity and ecosystem services: modelled value per unit	NA
Biodiversity / ecosystem service co-benefits: assumptions and sources	NA

Adaptation option 121. Improve soil water holding capacity

Adaptation option number	121
Component in scope	Cereals
Hazard considered	Heat stress
Adaptation option description	The relationship between soil moisture and air temperature means that (in theory) measures to improve soil water holding capacity such as added organic matter may reduce air temperatures above those soils. This measure combines: Cover cropping; Min-till; Crop rotation; Controlled Traffic Farming; Organic matter additions
Source of adaptation option	Petch et al. (2020). Sensitivity of the UK summer heatwave to local seas temperatures and soil moisture. *Atmospheric Science Letters* **21(3).** https://doi.org/10.1002/asl.948 Liu, J. & Pu, Z. (2019). Does Soil Moisture Have an Influence on Near-Surface Temperature? *JGR Atmospheres* **124(12).** https://doi.org/10.1029/2018JD029750
Effect of adaptation option	Reduces hazard and decreases vulnerability

Unit CAPEX	£110
Unit	ha

CAPEX: assumptions and sources	Based on the following sources: NAAC (2024). *Contracting Prices Survey 2024.* Available at: https://www.naac.co.uk/wp-content/uploads/2021/01/NAAC-Contracting-Prices-Survey-2024-Final-.pdf (Accessed 12 December 2025) AHDB (2020). *Cover crop costs calculated by AHDB research.* Available at: https://ahdb.org.uk/news/cover-crop-costs-calculated-by-ahdb-research (Accessed 12 December 2025) Jarvis, P.E. & Woolford, A.R. (2017). *Economic and ecological benefits of reduced tillage in the UK*. Available from: https://agricology.co.uk/sites/default/files/Economic%20and%20ecological%20benefits%20of%20reduced%20tillage%20in%20the%20Uk%20-%20Final.pdf (Accessed 12 December 2025) Soil Association (2018). *To plough or not to plough.* Available from: https://www.soilassociation.org/media/17472/to-plough-or-not-to-plough-policy-briefing.pdf (Accessed 12 December 2025) Cooper et al. (2020). Conservation tillage and soil health: Lessons from a 5-year UK farm trial (2013–2018) *Soil and Tillage Research* **202.** https://doi.org/10.1016/j.still.2020.104648 AHDB (nd). *Livestock manures for the arable rotation.* Available from: https://ahdb.org.uk/knowledge-library/livestock-manures-for-the-arable-rotation (Accessed 12 December 2025)
Unit OPEX	£56
Unit	ha/yr
OPEX: assumptions and sources	Based on the following sources: NAAC (2024). *Contracting Prices Survey 2024.* Available at: https://www.naac.co.uk/wp-content/uploads/2021/01/NAAC-Contracting-Prices-Survey-2024-Final-.pdf (Accessed 12 December 2025) AHDB (2020). *Cover crop costs calculated by AHDB research.* Available at: https://ahdb.org.uk/news/cover-crop-costs-calculated-by-ahdb-research (Accessed 12 December 2025) KUHN (nd). *Fuel saving from minimum tillage.* Available at: https://www.kuhn.co.uk/agricultural-methods/minimum-tillage/fuel-saving-minimum-tillage (Accessed 12 December 2025) Jarvis, P.E. & Woolford, A.R. (2017). *Economic and ecological benefits of reduced tillage in the UK*. Available from: https://agricology.co.uk/sites/default/files/Economic%20and%20ecological%20benefits%20of%20reduced%20tillage%20in%20the%20Uk%20-%20Final.pdf (Accessed 12 December 2025) Cooper et al. (2020). Conservation tillage and soil health: Lessons from a 5-year UK farm trial (2013–2018) *Soil and Tillage Research* **202.** https://doi.org/10.1016/j.still.2020.104648

Lifetime of measure (years)	1
Lifetime of measure: assumptions and sources	Assumption, based on annual cropping cycles
Time for risk reduction to begin (years)	5

Time for risk reduction to begin: assumptions and sources	Based on the following sources: Araya et al. (2022). Long-term impact of cover crop and reduced disturbance tillage on soil pore size distribution and soil water storage. *SOIL* **8:177-198.** https://doi.org/10.5194/soil-8-177-2022 Garba, I.I., Bell, L.W. & Williams, A. (2022). Cover crop legacy impacts on soil water and nitrogen dynamics, and on subsequent crop yields in drylands: a meta-analysis. *Agronomy for Sustainable Development* **42(34).** https://doi.org/10.1007/s13593-022-00760-0 Jarvis, P.E. & Woolford, A.R. (2017). *Economic and ecological benefits of reduced tillage in the UK*. Available from: https://agricology.co.uk/sites/default/files/Economic%20and%20ecological%20benefits%20of%20reduced%20tillage%20in%20the%20Uk%20-%20Final.pdf (Accessed 12 December 2025) Soil Association (2018). *To plough or not to plough.* Available from: https://www.soilassociation.org/media/17472/to-plough-or-not-to-plough-policy-briefing.pdf (Accessed 12 December 2025) Cooper et al. (2020). Conservation tillage and soil health: Lessons from a 5-year UK farm trial (2013–2018) *Soil and Tillage Research* **202.** https://doi.org/10.1016/j.still.2020.104648 AHDB (nd). *Livestock manures for the arable rotation.* Available at: https://ahdb.org.uk/knowledge-library/livestock-manures-for-the-arable-rotation (Accessed 12 December 2025) AHDB (nd). *'Controlled traffic' farming: Literature review and appraisal of potential use in the UK.* Available from: https://ahdb.org.uk/controlled-traffic-farming-literature-review-and-appraisal-of-potential-use-in-the-u-k (Accessed 12 December 2025) GOV.UK (2025). *Run-off management.* Available from: https://www.gov.uk/government/publications/natural-flood-management-evidence/run-off-management (Accessed 12 December 2025) AHDB (2020). *Cover crop costs calculated by AHDB research.* Available at: https://ahdb.org.uk/news/cover-crop-costs-calculated-by-ahdb-research (Accessed 12 December 2025) Basche, A.D. & DeLonge, M.S. (2019). Comparing infiltration rates in soils managed with conventional and alternative farming methods: A meta-analysis. *PLoS One* **14(9).** https://doi.org/10.1371/journal.pone.0215702 Rothamsted Research (2023). *New long-term experiments at Rothamsted will shed lights on potential impacts of regenerative agriculture.* Available at: https://www.rothamsted.ac.uk/news/new-long-term-experiments-rothamsted-will-shed-light-potential-impacts-regenerative (Accessed 12 December 2025)

Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	10%
Risk reduction: assumptions and sources	Assumes recovery of a fraction of heat/drought penalty via improved WHC and root access; magnitude scales with biomass and site aridity. Sources: Araya et al. (2022). Long-term impact of cover crop and reduced disturbance tillage on soil pore size distribution and soil water storage. *SOIL* **8:177-198.** https://doi.org/10.5194/soil-8-177-2022 Garba, I.I., Bell, L.W. & Williams, A. (2022). Cover crop legacy impacts on soil water and nitrogen dynamics, and on subsequent crop yields in drylands: a meta-analysis. *Agronomy for Sustainable Development* **42(34).** https://doi.org/10.1007/s13593-022-00760-0 AHDB (2020). *Cover crop costs calculated by AHDB research.* Available at: https://ahdb.org.uk/news/cover-crop-costs-calculated-by-ahdb-research (Accessed 12 December 2025)
Consequential losses, resulting from the implementation of the measure	0%
Baseline uptake % of farmers currently implementing this option	30%
Maximum future uptake % of farmers implementing this option	70%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2035

Uptake rates: assumptions and sources	Assumptions based on: Storr, T., Simmons, R.W. & Hannam, J.A. (2017). The Use of Cover Crops in the UK: A Survey. *Aspects of Biology Series: Aspects 136.* *https://dspace.lib.cranfield.ac.uk/server/api/core/bitstreams/b40b9819-83e5-48bf-8a03-7538c50950ed/content* AHDB (2020). *Cover crop costs calculated by AHDB research.* Available at: https://ahdb.org.uk/news/cover-crop-costs-calculated-by-ahdb-research (Accessed 12 December 2025) Jarvis, P.E. & Woolford, A.R. (2017). *Economic and ecological benefits of reduced tillage in the UK*. Available from: https://agricology.co.uk/sites/default/files/Economic%20and%20ecological%20benefits%20of%20reduced%20tillage%20in%20the%20Uk%20-%20Final.pdf (Accessed 12 December 2025) Soil Association (2018). *To plough or not to plough.* Available from: https://www.soilassociation.org/media/17472/to-plough-or-not-to-plough-policy-briefing.pdf (Accessed 12 December 2025) Cooper et al. (2020). Conservation tillage and soil health: Lessons from a 5-year UK farm trial (2013–2018) *Soil and Tillage Research* **202.** https://doi.org/10.1016/j.still.2020.104648 Defra Fertiliser Use Survey suggests that 40–60% of UK arable farms apply some form of organic material annually (including livestock manure, compost, or crop residues), with higher rates in mixed farming systems. Adoption is higher among farms using reduced tillage or cover cropping, which often coincide with organic matter additions. Defra (2025). *Fertiliser usage on farm, England 2022/23 – Statistics Notice.* Available from: https://www.gov.uk/government/statistics/fertiliser-usage-on-farm-england/fertiliser-usage-on-farm-england-202223-statistics-notice (Accessed 12 December 2025) CTF reported as used by ~8% of applicable farms Defra (2020). *Farm Practices Autumn 2019.* Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/870305/fps-general-statsnotice-05mar20.pdf (Accessed 12 December 2025)
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	-4 tCO_2e/ha/year

Climate mitigation co-benefits: assumptions and sources	Assuming additive effects (with caution for overlaps), combined practices could sequester roughly -4 tCO_2e/ha/year over 10–20 years, declining as soils approach saturation AHDB (nd). *Reduce emissions with cover and catch crops.* Available from: https://ahdb.org.uk/knowledge-library/reduce-emissions-with-cover-and-catch-crops (Accessed 12 December 2025) Soil Association (2018). *To plough or not to plough.* Available from: https://www.soilassociation.org/media/17472/to-plough-or-not-to-plough-policy-briefing.pdf (Accessed 12 December 2025) Emmett et al. (2023). *The opportunities and limitations of carbon capture in soil and peatlands.* Available from: https://erammp.wales/sites/default/files/2024-02/Report101_ERAMMPShortReport_Carboninsoil_Eng_v1.0.1%20%281%29.pdf (Accessed 12 December 2025) Villat, J. & Nicholas, K.A. (2024). Quantifying soil caron sequestration from regenerative agricultural practices in crops and vineyards. *Frontiers in Sustainable Food Systems* **7.** https://doi.org/10.3389/fsufs.2023.1234108
Biodiversity benefits / ecosystem services provided by the option	Soil erosion control Flood regulation Water quality
Biodiversity and ecosystem services: range of monetary value (£)	£149-£800/hectare/year
Biodiversity and ecosystem services: modelled value per unit	£2,195 / ha / yr
Biodiversity / ecosystem service co-benefits: assumptions and sources	Defra (2025). Enabling a Natural Capital Approach guidance. Available at: https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance (Accessed 12 December 2025) ONS (2022). *UK natural capital accounts: 2022*. Available from: https://www.ons.gov.uk/economy/environmentalaccounts/bulletins/uknaturalcapitalaccounts/2022 (Accessed 12 December 2025) Cranfield University (2011). *The total costs of soil degradation in England and Wales - SP1606.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 (Accessed 12 December 2025)

Adaptation option 123a. Re-wetting landscapes

Adaptation option number	123A
Component in scope	Cereals
Hazard considered	Heat stress
Adaptation option description	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits
Source of adaptation option	Petch et al. (2020). Sensitivity of the UK summer heatwave to local seas temperatures and soil moisture. *Atmospheric Science Letters* **21(3).** https://doi.org/10.1002/asl.948 Liu, J. & Pu, Z. (2019). Does Soil Moisture Have an Influence on Near-Surface Temperature? *JGR Atmospheres* **124(12).** https://doi.org/10.1029/2018JD029750
Effect of adaptation option	Decreases vulnerability

Unit CAPEX	£12,500
Unit	ha
CAPEX: assumptions and sources	Assumes ponds of 5000m2 surface area with 200m cooling radius. This equates to a landscape which is 12.5% pond (each of 5000m2) - or 1250m2 per hectare. 5000m2 and 2m deep reservoir costs £50000, converted to £12500 per hectare Ashbridge Partners (nd). *Want to build your own reservoir? It's time to dig deep.* Available from: https://www.ashbridgepartners.co.uk/2022/10/02/want-to-build-your-own-reservoir-its-time-to-dig-deep/ (Accessed 12 December 2025) The Water Channel (nd). *Ponds as an asset for agriculture: how to keep them full.* Available from: https://thewaterchannel.tv/thewaterblog/water-ponds-as-an-asset-for-agriculture-how-to-keep-them-full/ (Accessed 12 December 2025) Cheng et al. (2022). Impacts of Water Bodies on Microclimates and Outdoor Thermal Comfort: Implications for Sustainable Rural Revitalization. *Frontiers in Environmental Science* **10.** https://doi.org/10.3389/fenvs.2022.940482
Unit OPEX	£140
Unit	ha/yr

OPEX: assumptions and sources	Based on wetland management costs of $185/ha converted to GBP from this paper: Peh et al. (2014). Benefits and costs of ecological restoration: Rapid assessment of changing ecosystem service values at a U.K. wetland. *Ecology and Evolution* **4(20): 3875-3886.** https://doi.org/10.1002/ece3.1248
Lifetime of measure (years)	50
Lifetime of measure: assumptions and sources	Assumption, based on build quality
Time for risk reduction to begin (years)	5
Time for risk reduction to begin: assumptions and sources	Based on time to secure any necessary permissions and build - as an estimate
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	15%
Risk reduction: assumptions and sources	Estimate. 'Evidence of cooling in regions with a large number of wetlands - 'A cooling effect of 1–3°C in summer temperature is evident where wetlands are abundant. In particular, the wetland simulation shows reduction in the number of hot days for >10 days over the summer of 2006, when a long-lasting heatwave occurred.' Zhang et al. (2022). Cooling Effects Revealed by Modeling of Wetlands and Land-Atmosphere Interactions. *Water Resources Research* **58.** https://doi.org/10.1029/2021WR030573 Cheng et al. (2022). Impacts of Water Bodies on Microclimates and Outdoor Thermal Comfort: Implications for Sustainable Rural Revitalization. *Frontiers in Environmental Science* **10.** https://doi.org/10.3389/fenvs.2022.940482
Consequential losses, resulting from the implementation of the measure	12.5% (of cereal area lost to measure: this is an assumption based on the size of ponds required to deliver meaningful cooling)
Baseline uptake % of farmers currently implementing this option	0%
Maximum future uptake % of farmers implementing this option	5%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2045

Uptake rates: assumptions and sources	Assumptions, with low future potential driven by impacts on land take to implement the measure
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	+3tCO_2e/ha/year
Climate mitigation co-benefits: assumptions and sources	Unmanaged ponds in temperate agricultural landscapes are likely to emit more GHGs than they sequester - as they are a source of methane emissions. Emissions range from −8 to +17 tCO2e/ha/yr; mean ~+3 emitted Jeffries et al. (2023). Organic carbon in British lowland ponds: estimating sediment stocks, possible practical benefits and significant unknowns. *Hydrobiologia* **850: 3225-3239.** https://doi.org/10.1007/s10750-022-04972-z
Biodiversity benefits / ecosystem services provided by the option	Flood regulation Water quality (nutrient and sediment retention, pesticide removal) Habitat creation
Biodiversity and ecosystem services: range of monetary value (£)	£1000-£6000/ha/yr (nutrients); £100-£1000/ha/yr (sediment)
Biodiversity and ecosystem services: modelled value per unit	£501.75 / ha / yr
Biodiversity / ecosystem service co-benefits: assumptions and sources	Defra (2025). Enabling a Natural Capital Approach guidance. Available at: https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance (Accessed 12 December 2025) Mitsch, W.J. & Gosselink, J.G. (2015). *Wetlands*. 5th Edition, Wiley. https://www.wiley.com/en-gb/Wetlands%2C+5th+Edition-p-9781119019787 Heathwaite, A.L. (2010). Multiple stressors on water availability at global to catchment scales: understanding human impact on nutrient cycles to protect water quality and water availability in the long term. *Freshwater Biology* **55: 241-257**. https://doi.org/10.1111/j.1365-2427.2009.02368.x Everard, M., Harrington, R. & McInnes, R.J. (2012). Facilitating implementation of landscape-scale water management: The integrated constructed wetland concept. *Ecosystem Services* **2: 27-37.** https://doi.org/10.1016/j.ecoser.2012.08.001

Adaptation option 123b. Re-wet landscapes

Adaptation option number	123B
Component in scope	Dairy cattle
Hazard considered	Heat stress
Adaptation option description	Re-wet landscapes through installation of ponds, to deliver a cooling effect - and provide a wide range of nature benefits
Source of adaptation option	Petch et al. (2020). Sensitivity of the UK summer heatwave to local seas temperatures and soil moisture. *Atmospheric Science Letters* **21(3).** https://doi.org/10.1002/asl.948 Liu, J. & Pu, Z. (2019). Does Soil Moisture Have an Influence on Near-Surface Temperature? *JGR Atmospheres* **124(12).** https://doi.org/10.1029/2018JD029750
Effect of adaptation option	Decreases vulnerability

Unit CAPEX	£6,250
Unit	cow
CAPEX: assumptions and sources	Assumes ponds of 5000m2 surface area with 200m cooling radius. This equates to a landscape which is 12.5% pond (each of 5000m2) - or 1250m2 per hectare. 5000m2 and 2m deep reservoir costs £50000, converted to £12500 per hectare Ashbridge Partners (nd). *Want to build your own reservoir? It's time to dig deep.* Available from: https://www.ashbridgepartners.co.uk/2022/10/02/want-to-build-your-own-reservoir-its-time-to-dig-deep/ (Accessed 12 December 2025) The Water Channel (nd). *Ponds as an asset for agriculture: how to keep them full.* Available from: https://thewaterchannel.tv/thewaterblog/water-ponds-as-an-asset-for-agriculture-how-to-keep-them-full/ (Accessed 12 December 2025) Cheng et al. (2022). Impacts of Water Bodies on Microclimates and Outdoor Thermal Comfort: Implications for Sustainable Rural Revitalization. *Frontiers in Environmental Science* **10.** https://doi.org/10.3389/fenvs.2022.940482
Unit OPEX	£70
Unit	cow/yr

OPEX: assumptions and sources	Based on wetland management costs of $185/ha converted to GBP from this paper: Peh et al. (2014). Benefits and costs of ecological restoration: Rapid assessment of changing ecosystem service values at a U.K. wetland. *Ecology and Evolution* **4(20): 3875-3886.** https://doi.org/10.1002/ece3.1248 Converted on the basis of 2 cows per ha
Lifetime of measure (years)	50
Lifetime of measure: assumptions and sources	Assumption, based on build quality
Time for risk reduction to begin (years)	5
Time for risk reduction to begin: assumptions and sources	Based on time to secure any necessary permissions and build – as an estimate
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	15%
Risk reduction: assumptions and sources	Estimate. 'Evidence of cooling in regions with a large number of wetlands - 'A cooling effect of 1–3°C in summer temperature is evident where wetlands are abundant. In particular, the wetland simulation shows reduction in the number of hot days for >10 days over the summer of 2006, when a long-lasting heatwave occurred.' Zhang et al. (2022). Cooling Effects Revealed by Modeling of Wetlands and Land-Atmosphere Interactions. *Water Resources Research* **58.** https://doi.org/10.1029/2021WR030573 Cheng et al. (2022). Impacts of Water Bodies on Microclimates and Outdoor Thermal Comfort: Implications for Sustainable Rural Revitalization. *Frontiers in Environmental Science* **10.** https://doi.org/10.3389/fenvs.2022.940482
Consequential losses, resulting from the implementation of the measure	12.5% (of grazing area lost to measure: this is an assumption based on the size of ponds required to deliver meaningful cooling)
Baseline uptake % of farmers currently implementing this option	0%
Maximum future uptake % of farmers implementing this option	5%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2045

Uptake rates: assumptions and sources	Assumptions, with low future potential driven by impacts on land take to implement the measure
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	+1.5tCO_2e/ha/year
Climate mitigation co-benefits: assumptions and sources	Unmanaged ponds in temperate agricultural landscapes are likely to emit more GHGs than they sequester - as they are a source of methane emissions. Emissions range from −8 to +17 tCO2e/ha/yr; mean ~+3 emitted Jeffries et al. (2023). Organic carbon in British lowland ponds: estimating sediment stocks, possible practical benefits and significant unknowns. *Hydrobiologia* **850: 3225-3239.** https://doi.org/10.1007/s10750-022-04972-z
Biodiversity benefits / ecosystem services provided by the option	Flood regulation Water quality (nutrient and sediment retention, pesticide removal) Habitat creation
Biodiversity and ecosystem services: range of monetary value (£)	£1000-£6000/ha/yr (nutrients); £100-£1000/ha/yr (sediment)
Biodiversity and ecosystem services: modelled value per unit	£250.88 / cow / yr
Biodiversity / ecosystem service co-benefits: assumptions and sources	Defra (2025). Enabling a Natural Capital Approach guidance. Available at: https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance (Accessed 12 December 2025) Mitsch, W.J. & Gosselink, J.G. (2015). *Wetlands*. 5th Edition, Wiley. https://www.wiley.com/en-gb/Wetlands%2C+5th+Edition-p-9781119019787 Heathwaite, A.L. (2010). Multiple stressors on water availability at global to catchment scales: understanding human impact on nutrient cycles to protect water quality and water availability in the long term. *Freshwater Biology* **55: 241-257**. https://doi.org/10.1111/j.1365-2427.2009.02368.x Everard, M., Harrington, R. & McInnes, R.J. (2012). Facilitating implementation of landscape-scale water management: The integrated constructed wetland concept. *Ecosystem Services* **2: 27-37.** https://doi.org/10.1016/j.ecoser.2012.08.001

Adaptation option 76a. Conduct transformative adaptation, whereby a proportion of the cropped area is taken out of cereal production and used for woodland

Adaptation option number	76A
Component in scope	Cereals
Hazard considered	Heat stress
Adaptation option description	Conduct transformative adaptation, whereby a proportion of the cropped area is taken out of cereal production and used for woodland instead [Note that this measure was initially envisaged for application to pasture]
Source of adaptation option	Jones et al. (2020). *Climate driven threshold effects in the natural environment.* Available from: https://www.ukclimaterisk.org/wp-content/uploads/2021/05/Climate-driven-threshold-effects-in-the-natural-environment-UKCEH.pdf (Accessed 12 December 2025)
Effect of adaptation option	Avoids risk

Unit CAPEX	£10,000
Unit	ha
CAPEX: assumptions and sources	Based on Nix Handbook, 2024 (Redman, G. (2023). *John Nix Pocketbook for Farm Management*. 54th edition)
Unit OPEX	£5,000
Unit	ha/yr
OPEX: assumptions and sources	Based on Nix Handbook, 2024 (although note that costs are higher initially, to account for beating-up / weeding etc). Redman, G. (2023). *John Nix Pocketbook for Farm Management*. 54th edition
Lifetime of measure (years)	100

Lifetime of measure: assumptions and sources	Assumptions: measure persists as woodland beyond any single timber rotation; broadleaf rotations commonly ~80–120+ years, conifer ~35–45 years, and many native woodlands retained indefinitely. UKFS underpins sustainable management over long horizons. Based on: Forestry Commission (2025). *The UK Forestry Standard.* Available from: https://www.gov.uk/government/publications/the-uk-forestry-standard (Accessed 12 December 2025) Moore, J., Lyon, A., Lehneke (2012). Effects of rotation length on the grade recovery and wood properties of Sitka spruce structural timber grown in Great Britain. *Annals of Forest Science* **69: 353-362.** https://doi.org/10.1007/s13595-011-0168-x
Time for risk reduction to begin (years)	0
Time for risk reduction to begin: assumptions and sources	Could consider risk reduction as immediate, as land is converted for another use
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	n/a - this is transformational
Risk reduction: assumptions and sources	-
Consequential losses, resulting from the implementation of the measure	100% (of transformed land lost to measure)
Baseline uptake % of farmers currently implementing this option	2%
Maximum future uptake % of farmers implementing this option	30%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2050
Uptake rates: assumptions and sources	Assumptions to illustrate potential of this approach
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	-4.9 tCO_2e/ha/year

Climate mitigation co-benefits: assumptions and sources	Varies based on species and soil type: for mineral soils, ranges from -1.3 - 6.7tCO_2e/ha/yr to ~2050 Vanguelova, E. (nd). *Woodland creation and soil carbon and nutrient dynamics.* Available from: https://www.forestresearch.gov.uk/research/soil-sustainability/woodland-creation-and-soil-carbon-and-nutrient-dynamics/ (Accessed 12 December 2025) Joly et al. (2025). Temperate grassland conversion to conifer forest destabilises mineral soil carbon stocks. *Journal of Environmental Management* **374.** https://doi.org/10.1016/j.jenvman.2025.124149
Biodiversity benefits / ecosystem services provided by the option	Soil erosion control Flood regulation Air quality Habitat creation Water quality
Biodiversity and ecosystem services: range of monetary value (£)	£133-241/hectare/year
Biodiversity and ecosystem services: modelled value per unit	£446 / ha / yr
Biodiversity / ecosystem service co-benefits: assumptions and sources	Defra (2025). Enabling a Natural Capital Approach guidance. Available at: https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance (Accessed 12 December 2025) Cranfield University (2011). *The total costs of soil degradation in England and Wales - SP1606.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 (Accessed 12 December 2025)

Adaptation option 76b. Conduct transformative adaptation, whereby a proportion of the cropped area is taken out of cereal production and used for wetland

Adaptation option number	76B
Component in scope	Cereals
Hazard considered	Heat stress
Adaptation option description	Conduct transformative adaptation, whereby a proportion of the cropped area is taken out of cereal production and used for wetland instead
Source of adaptation option	[Note that this measure was initially envisaged for application to pasture]
Effect of adaptation option	Jones et al. (2020). *Climate driven threshold effects in the natural environment.* Available from: https://www.ukclimaterisk.org/wp-content/uploads/2021/05/Climate-driven-threshold-effects-in-the-natural-environment-UKCEH.pdf (Accessed 12 December 2025)

Unit CAPEX	£15,000
Unit	ha
CAPEX: assumptions and sources	Based on: Environment Agency (2015). Cost estimation for habitat creation – summary of evidence. Available from: https://assets.publishing.service.gov.uk/media/6034ef5ee90e0766033f2ea7/Cost_estimation_for_habitat_creation.pdf (Accessed 12 December 2025)
Unit OPEX	£140
Unit	ha/yr
OPEX: assumptions and sources	Based on wetland management costs of $185/ha converted to GBP from this paper: Peh et al. (2014). Benefits and costs of ecological restoration: Rapid assessment of changing ecosystem service values at a U.K. wetland. *Ecology and Evolution* **4(20): 3875-3886.** https://doi.org/10.1002/ece3.1248
Lifetime of measure (years)	50
Lifetime of measure: assumptions and sources	Assumption

Time for risk reduction to begin (years)	0
Time for risk reduction to begin: assumptions and sources	Could consider risk reduction as immediate, as land is converted for another use
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	n/a - this is transformational
Risk reduction: assumptions and sources	-
Consequential losses, resulting from the implementation of the measure	100% (of transformed land lost to measure)
Baseline uptake % of farmers currently implementing this option	2%
Maximum future uptake % of farmers implementing this option	30%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2050
Uptake rates: assumptions and sources	Assumptions to illustrate potential of this approach
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	-4.5 tCO_2e/ha/year
Climate mitigation co-benefits: assumptions and sources	Estimate for new wetlands on mineral soils is -4.5 tCO_2e/ha/year sequestration after establishment, but with high uncertainty due to CH_4 dynamics Penny Anderson Associates (2020). *Habitats and carbon, storage and sequestration*. Available from: https://cieem.net/wp-content/uploads/2020/08/Habitats-and-Carbon-Storage-and-Sequestration-Penny-Anderson.pdf (Accessed 12 December 2025) NatureScot (nd). *Guidance – Evidence on carbon and nature.* Available from: https://www.nature.scot/doc/guidance-evidence-carbon-and-nature (Accessed 12 December 2025)
Biodiversity benefits / ecosystem services provided by the option	Flood regulation Water quality (nutrient and sediment retention, pesticide removal) Habitat creation

Biodiversity and ecosystem services: range of monetary value (£)	£1000-£6000/ha/yr (nutrients); £100-£1000/ha/yr (sediment)
Biodiversity and ecosystem services: modelled value per unit	£3,535 / ha /yr
Biodiversity / ecosystem service co-benefits: assumptions and sources	Defra (2025). Enabling a Natural Capital Approach guidance. Available at: https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance (Accessed 12 December 2025) Mitsch, W.J. & Gosselink, J.G. (2015). *Wetlands*. 5th Edition, Wiley. https://www.wiley.com/en-gb/Wetlands%2C+5th+Edition-p-9781119019787 Heathwaite, A.L. (2010). Multiple stressors on water availability at global to catchment scales: understanding human impact on nutrient cycles to protect water quality and water availability in the long term. *Freshwater Biology* **55: 241-257**. https://doi.org/10.1111/j.1365-2427.2009.02368.x Everard, M., Harrington, R. & McInnes, R.J. (2012). Facilitating implementation of landscape-scale water management: The integrated constructed wetland concept. *Ecosystem Services* **2: 27-37.** https://doi.org/10.1016/j.ecoser.2012.08.001

Adaptation option 76c. Conduct transformative adaptation, whereby a proportion of the cropped area is taken out of cereal production and used for wildflowers

Adaptation option number	76C
Component in scope	Cereals
Hazard considered	Heat stress
Adaptation option description	Conduct transformative adaptation, whereby a proportion of the cropped area is taken out of cereal production and used for wildflowers instead
Source of adaptation option	[Note that this measure was initially envisaged for application to pasture]
Effect of adaptation option	Jones et al. (2020). *Climate driven threshold effects in the natural environment.* Available from: https://www.ukclimaterisk.org/wp-content/uploads/2021/05/Climate-driven-threshold-effects-in-the-natural-environment-UKCEH.pdf (Accessed 12 December 2025)

Unit CAPEX	£3,000
Unit	ha
CAPEX: assumptions and sources	Based on: Cotswold Life (2024). *How much does it cost to create a wildflower meadow?* Available from: https://www.greatbritishlife.co.uk/magazines/cotswold/24267426.much-cost-create-wildflower-meadow/ (Accessed 12 December 2025) Plantlife (nd). *How Much does a Meadow Cost?* Available from: https://www.plantlife.org.uk/learning-resource/how-much-does-a-meadow-cost/ (Accessed 12 December 2025)
Unit OPEX	£90.00
Unit	ha/yr
OPEX: assumptions and sources	Based on forage harvest costs from Nix Handbook 2024
Lifetime of measure (years)	25
Lifetime of measure: assumptions and sources	Assumption

Time for risk reduction to begin (years)	0
Time for risk reduction to begin: assumptions and sources	Could consider risk reduction as immediate, as land is converted for another use
Risk reduction (% risk reduction per unit of deployment or quantitative metric of effectiveness)	n/a - this is transformational
Risk reduction: assumptions and sources	-
Consequential losses, resulting from the implementation of the measure	100% (of transformed land lost to measure)
Baseline uptake % of farmers currently implementing this option	2%
Maximum future uptake % of farmers implementing this option	30%
Year that adaptations start (modelling assumption)	2025
Year that max uptake is achieved (modelling assumption)	2050
Uptake rates: assumptions and sources	Assumptions to illustrate potential of this approach
Climate mitigation co-benefits (Calculated carbon sequestered (-) or emitted (+) by the option (tCO2e))	-3 tCO_2e/ha/year
Climate mitigation co-benefits: assumptions and sources	Net sequestration begins as roots develop. After 11-30 years, may increase to -5-8 tCO2e/ha/year sequestered. Garget, J. (nd). *A break from the lawn.* Available from: https://www.cam.ac.uk/stories/kings-wildflower-meadow-a-break-from-the-lawn (Accessed 12 December 2025) Meadowmania (2025). *Wildflower Meadows & Carbon Offsetting: How Native Flowers Help Fight Climate Change.* Available from: https://meadowmania.co.uk/blogs/news/wildflower-meadows-amp-carbon-offsetting-how-native-flowers-help-fight-climate-change (Accessed 12 December 2025)
Biodiversity benefits / ecosystem services provided by the option	Soil erosion control Habitat creation

Biodiversity and ecosystem services: range of monetary value (£)	£149 - £241 / hectare/year
Biodiversity and ecosystem services: modelled value per unit	£195 / ha / yr
Biodiversity / ecosystem service co-benefits: assumptions and sources	Defra (2025). Enabling a Natural Capital Approach guidance. Available at: https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance (Accessed 12 December 2025) Cranfield University (2011). *The total costs of soil degradation in England and Wales - SP1606.* Available at: https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 (Accessed 12 December 2025)

Appendix G - Ecosystem services mapping

Adaptation measure	Habitat created/enhanced (ENCA/ONS class)	Service type	Ecosystem service / co benefit (high level)	Qualitative	Biophysical proxy	Biophysical units (notes)	Valuation route (how to monetise)	Monetary value (£)	Notes/ Assumptions / caveats	References
Alley cropping	Woodland / Agroforestry	Regulating	Carbon sequestration	Sequestration and storage of carbon dioxide by growing vegetation, soils and sediments (reducing GHG emissions in the atmosphere)	6.2 tCO$_2$e/ha/yr	tCO$_2$e/ha/yr	BEIS/DesNZ £/tCO$_2$e	£600–900/ha/yr	Varies by species	ONS Woodland NC Accounts 2023; BEIS / DESNZ carbon values 2023
		Regulating	Soil erosion control	An estimated 1 million hectares of soils in England and Wales are at risk of erosion from wind or water. Soil erosion puts pressure on water bodies through increased sediment runoff, nitrate and phosphorous pollution. Offsite impacts of soil erosion include loss of carbon from soils to the atmosphere, dredging costs, costs to remove eroded material from drinking water, rivers, and lakes. Reducing soil erosion helps maintain soil stability, preventing the loss of fertile topsoil and reducing sedimentation in rivers and lakes. By limiting erosion, these services protect agricultural productivity, preserve water quality, and reduce the risk of flooding and landslides.	0.21 tonnes / hectare	Average annual national erosion rate over the total land area	Average cost of soil erosion based on flood risk, production loss and water quality loss, 2024 prices	£149 - £241 / hectare		ENCA Soil. Monetary values from https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 within ENCAs list
		Regulating	Water quality	-	-	-	-	-	-	-
		Regulating	Flood regulation	Some habitats can offer a flood risk management service. For example, relative to bare soil or managed grassland, woodland reduces fluvial flooding risk to downstream populations by reducing rainfall flows entering rivers. It does this through canopy interception, higher infiltration and water storage in soils, impeding water flows and reducing siltation.	520m3/ha per event	flood storage	Avoided flood damages	£133/ha/yr vs grassland		https://cdn.forestresearch.gov.uk/2020/07/FR_valuing_flood_regulation_service-63b460b80cf4f.pdf?utm_source=chatgpt.com)

Adaptation measure	Habitat created/enhanced (ENCA/ONS class)	Service type	Ecosystem service / co benefit (high level)	Qualitative	Biophysical proxy	Biophysical units (notes)	Valuation route (how to monetise)	Monetary value (£)	Notes/ Assumptions / caveats	References
		Regulating	Air quality	Removal of harmful air pollutants from the atmosphere through (a) direct deposition onto leaves and bark and (b) internal absorption of pollutants through stomatal uptake. The benefit is reduced health costs from lower levels of pollution exposure than would otherwise be the case.	1.37m tonnes removed	tonnes pollutant	Defra AQ damage costs	£2.6bn/yr (UK)	All pollutants. Mainly $PM_{2.5}$	ONS Air Quality Accounts 2024; Defra Damage Costs 2023 https://www.ons.gov.uk/economy/environmentalaccounts/datasets/uknaturalcapitalaccounts2024detailedsummary
Planting trees/copses	Woodland , linear tree features for silvopasture	Regulating	Carbon sequestration	Sequestration and storage of carbon dioxide by growing vegetation, soils and sediments (reducing GHG emissions in the atmosphere)	6.2 tCO_2e/ha/yr	tCO_2e/ha/yr	BEIS/DesNZ £/tCO_2e	£600–900/ha/yr	ONS Woodland Accounts	ONS Woodland NC Accounts 2023; BEIS/DesNZ carbon values 2023
		Regulating	Air quality	Removal of harmful air pollutants from the atmosphere through (a) direct deposition onto leaves and bark and (b) internal absorption of pollutants through stomatal uptake. The benefit is reduced health costs from lower levels of pollution exposure than would otherwise be the case.	1.37m tonnes removed	tonnes pollutant	Defra AQ damage costs	£2.6bn/yr (UK)	Mostly urban trees	ONS Air Quality Accounts 2024; Defra Damage Costs 2023 https://www.ons.gov.uk/economy/environmentalaccounts/datasets/uknaturalcapitalaccounts2024detailedsummary
		Regulating	Water quality	Water purification is a vital ecosystem service in which greenscapes, bluescapes, and soils naturally filter pollutants, sediments, and excess nutrients from water. This process improves water quality, safeguards human health, and reduces the need for costly artificial treatment. By maintaining clean water, ecosystems also support biodiversity and provide safe, healthy environments for both people and wildlife.						

Adaptation measure	Habitat created/enhanced (ENCA/ONS class)	Service type	Ecosystem service / co benefit (high level)	Qualitative	Biophysical proxy	Biophysical units (notes)	Valuation route (how to monetise)	Monetary value (£)	Notes/ Assumptions / caveats	References
		Regulating	Flood regulation	Some habitats can offer a flood risk management service. For example, relative to bare soil or managed grassland, woodland reduces fluvial flooding risk to downstream populations by reducing rainfall flows entering rivers. It does this through canopy interception, higher infiltration and water storage in soils, impeding water flows and reducing siltation.	520m3/ha per event	flood storage	Avoided flood damages	£133/ha/yr vs grassland		https://cdn.forestresearch.gov.uk/2020/07/FR_valuing_flood_regulation_service-63b460b80cf4f.pdf?utm_source=chatgpt.com)
		Regulating	Soil erosion control	An estimated 1 million hectares of soils in England and Wales are at risk of erosion from wind or water. Soil erosion puts pressure on water bodies through increased sediment runoff, nitrate and phosphorous pollution. Offsite impacts of soil erosion include loss of carbon from soils to the atmosphere, dredging costs, costs to remove eroded material from drinking water, rivers, and lakes. Reducing soil erosion helps maintain soil stability, preventing the loss of fertile topsoil and reducing sedimentation in rivers and lakes. By limiting erosion, these services protect agricultural productivity, preserve water quality, and reduce the risk of flooding and landslides.	0.21 tonnes / hectare	Average annual national erosion rate over the total land area	Average cost of soil erosion based on flood risk, production loss and water quality loss, 2024 prices	£149 - £241 / hectare		ENCA Soil. Monetary values from https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 within ENCAs list
Plant hedgerows	Hedgerows - linear woody features /	Regulating	Carbon sequestration	Sequestration and storage of carbon dioxide by growing vegetation, soils and sediments (reducing GHG emissions in the atmosphere)	144.5 tC/ha (stock)	tC/ha	Annualised £/tCO_2e	£200–400/ha/yr	Assumes low management	ONS Woodland NC Accounts 2023; BEIS/DesNZ carbon values 2023

Adaptation measure	Habitat created/enhanced (ENCA/ONS class)	Service type	Ecosystem service / co benefit (high level)	Qualitative	Biophysical proxy	Biophysical units (notes)	Valuation route (how to monetise)	Monetary value (£)	Notes/ Assumptions / caveats	References
	boundary habitats	Regulating	Soil erosion control	An estimated 1 million hectares of soils in England and Wales are at risk of erosion from wind or water. Soil erosion puts pressure on water bodies through increased sediment runoff, nitrate and phosphorous pollution. Offsite impacts of soil erosion include loss of carbon from soils to the atmosphere, dredging costs, costs to remove eroded material from drinking water, rivers, and lakes. Reducing soil erosion helps maintain soil stability, preventing the loss of fertile topsoil and reducing sedimentation in rivers and lakes. By limiting erosion, these services protect agricultural productivity, preserve water quality, and reduce the risk of flooding and landslides.	0.21 tonnes / hectare	Average annual national erosion rate over the total land area	Average cost of soil erosion based on flood risk, production loss and water quality loss, 2024 prices	£149 - £241 / hectare		ENCA Soil. Monetary values from https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 within ENCAs list
		Regulating	Flood regulation	Some habitats can offer a flood risk management service. For example, relative to bare soil or managed grassland, woodland reduces fluvial flooding risk to downstream populations by reducing rainfall flows entering rivers. It does this through canopy interception, higher infiltration and water storage in soils, impeding water flows and reducing siltation.	50m hedgerow intercepts runoff equivalent to 150-375m3 storage per ha			£70-175/ha/yr		https://www.farminguk.com/news/farming-connect-potential-of-tree-and-hedgerow-planting-to-reduce-frequency-and-impact-of-flood-events_44697.html?utm_source=chatgpt.com
		Regulating	Water quality (field run off interception)	Water purification is a vital ecosystem service in which greenscapes, bluescapes, and soils naturally filter pollutants, sediments, and excess nutrients from water. This process improves water quality, safeguards human health, and reduces the need for costly artificial treatment. By maintaining clean water, ecosystems also support biodiversity and provide safe, healthy environments for both people and wildlife.	10-30kg of N/ha/yr	typical ranges in the UK / temperate	annualised and indicative	£200-£600/ha/yr (nutrients)		ENCA water quality - Baude et al, 2019 ; YDRT NFM Guide 2021

Adaptation measure	Habitat created/enhanced (ENCA/ONS class)	Service type	Ecosystem service / co benefit (high level)	Qualitative	Biophysical proxy	Biophysical units (notes)	Valuation route (how to monetise)	Monetary value (£)	Notes/ Assumptions / caveats	References
		Regulating	Air quality	Removal of harmful air pollutants from the atmosphere through (a) direct deposition onto leaves and bark and (b) internal absorption of pollutants through stomatal uptake. The benefit is reduced health costs from lower levels of pollution exposure than would otherwise be the case.	1.37m tonnes removed	tonnes	Defra AQ costs	£2.6bn/yr (UK)	Mostly $PM_{2.5}$	ONS Air Quality Accounts 2024; Defra Damage Costs 2023 https://www.ons.gov.uk/economy/environmentalaccounts/datasets/uknaturalcapitalaccounts2024detailedsummary
Convert grazed pasture to woodland	Woodland / Agroforestry	Regulating	Carbon sequestration	Sequestration and storage of carbon dioxide by growing vegetation, soils and sediments (reducing GHG emissions in the atmosphere)	6.2 tCO_2e/ha/yr	tCO_2e/ha/yr	BEIS/DesNZ £/tCO_2e	£600–900/ha/yr	ONS Woodland Accounts	ONS Woodland NC Accounts 2023; BEIS/DesNZ carbon values 2023
		Regulating	Air quality	Removal of harmful air pollutants from the atmosphere through (a) direct deposition onto leaves and bark and (b) internal absorption of pollutants through stomatal uptake. The benefit is reduced health costs from lower levels of pollution exposure than would otherwise be the case.	1.37m tonnes removed	tonnes pollutant	Defra AQ damage costs	£2.6bn/yr (UK)	Mostly urban trees	ONS Air Quality Accounts 2024; Defra Damage Costs 2023 https://www.ons.gov.uk/economy/environmentalaccounts/datasets/uknaturalcapitalaccounts2024detailedsummary
		Regulating	Water quality	Water purification is a vital ecosystem service in which greenscapes, bluescapes, and soils naturally filter pollutants, sediments, and excess nutrients from water. This process improves water quality, safeguards human health, and reduces the need for costly artificial treatment. By maintaining clean water, ecosystems also support biodiversity and provide safe, healthy environments for both people and wildlife.						
		Regulating	Flood regulation	Some habitats can offer a flood risk management service. For example, relative to bare soil or managed grassland, woodland reduces fluvial flooding risk to downstream populations by reducing rainfall flows entering rivers. It does this through canopy	520m3/ha per event	flood storage	Avoided flood damages	£133/ha/yr vs grassland		https://cdn.forestresearch.gov.uk/2020/07/FR_valuing_flood_regulation_service-63b460b80cf4f.pdf?

Adaptation measure	Habitat created/enhanced (ENCA/ONS class)	Service type	Ecosystem service / co benefit (high level)	Qualitative	Biophysical proxy	Biophysical units (notes)	Valuation route (how to monetise)	Monetary value (£)	Notes/ Assumptions / caveats	References
				interception, higher infiltration and water storage in soils, impeding water flows and reducing siltation.						utm_source=chatgpt.com)
		Regulating	Soil erosion control	An estimated 1 million hectares of soils in England and Wales are at risk of erosion from wind or water. Soil erosion puts pressure on water bodies through increased sediment runoff, nitrate and phosphorous pollution. Offsite impacts of soil erosion include loss of carbon from soils to the atmosphere, dredging costs, costs to remove eroded material from drinking water, rivers, and lakes. Reducing soil erosion helps maintain soil stability, preventing the loss of fertile topsoil and reducing sedimentation in rivers and lakes. By limiting erosion, these services protect agricultural productivity, preserve water quality, and reduce the risk of flooding and landslides.	0.21 tonnes / hectare	Average annual national erosion rate over the total land area	Average cost of soil erosion based on flood risk, production loss and water quality loss, 2024 prices	£149 - £241 / hectare		ENCA Soil. Monetary values from https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 within ENCAs list
Convert grazed pasture to wetland	Wetland	Regulating	Flood regulation	Some habitats can offer a flood risk management service. For example, relative to bare soil or managed grassland, woodland reduces fluvial flooding risk to downstream populations by reducing rainfall flows entering rivers. It does this through canopy interception, higher infiltration and water storage in soils, impeding water flows and reducing siltation.			Site specific case studies from. Site-specific fen protection value	£35040/ha/yr	ONS/ENCA don't include flood regulation for wetland. Therefore, the case study for monetary values is indicative only and not referenced from mainstream accounting frameworks	https://wcl.org.uk/docs/WCL_EAC_Flood_Resilience_Inquiry_Response_Jan_2025.pdf
		Regulating	Water quality (nutrient and sediment retention, pesticide removal)	Water purification is a vital ecosystem service in which greenscapes, bluescapes, and soils naturally filter pollutants, sediments, and excess nutrients from water. This process improves water quality, safeguards human health, and reduces the need for costly artificial treatment. By maintaining clean water, ecosystems also support biodiversity and provide safe, healthy environments for both people and wildlife.	50-300kg N/ha/yr ; 1010kg P/ha/yr ; ~2 tonnes sediment/ha/yr	typical ranges in the UK / temperate	annualised and indicative	£1000-£6000/ha/yr (nutrients) ; £100-£1000/ha/yr (sediment)		ENCA water quality - Mitsch & Gosselink 2015 ; Heathwaite 2010 ; Everard 2012

Adaptation measure	Habitat created/enhanced (ENCA/ONS class)	Service type	Ecosystem service / co benefit (high level)	Qualitative	Biophysical proxy	Biophysical units (notes)	Valuation route (how to monetise)	Monetary value (£)	Notes/ Assumptions / caveats	References
Regenerative soil management practices (Cover cropping, Minimum tillage, Organic matter additions, Controlled traffic farming (CTF), Crop rotation)	Cropland / arable with cover crops Cropland management change - reduced tillage Cropland management change / perennial components Soil	Regulating	Soil erosion control	An estimated 1 million hectares of soils in England and Wales are at risk of erosion from wind or water. Soil erosion puts pressure on water bodies through increased sediment runoff, nitrate and phosphorous pollution. Offsite impacts of soil erosion include loss of carbon from soils to the atmosphere, dredging costs, costs to remove eroded material from drinking water, rivers, and lakes. Reducing soil erosion helps maintain soil stability, preventing the loss of fertile topsoil and reducing sedimentation in rivers and lakes. By limiting erosion, these services protect agricultural productivity, preserve water quality, and reduce the risk of flooding and landslides.	0.21 tonnes / hectare	Average annual national erosion rate over the total land area	Average cost of soil erosion based on flood risk, production loss and water quality loss, 2024 prices	£149 - £241 / hectare		ENCA Soil. Monetary values from https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 within ENCAs list
		Regulating	Soil carbon accrual		0.5–1.0 tCO_2e/ha/yr	tCO_2e/ha/yr	BEIS/DesNZ £/tCO_2e	£50–150/ha/yr		ONS Land Use NC Accounts; BEIS values
		Regulating	Water quality (nutrient retention)	Water purification is a vital ecosystem service in which greenscapes, bluescapes, and soils naturally filter pollutants, sediments, and excess nutrients from water. This process improves water quality, safeguards human health, and reduces the need for costly artificial treatment. By maintaining clean water, ecosystems also support biodiversity and provide safe, healthy environments for both people and wildlife.	30-120kg N/ha/yr reduced leaching ; 1-5kg P/ha/yr	typical ranges in the UK / temperate	annualised and indicative	£600-2400/ha/yr of N at £20/kg		ENCA water quality - Drinkwater & Snapp 2007 ; MacLead et al, 2012 ; Oxera/Ofwat 2004
		Regulating	Flood regulation	Some habitats can offer a flood risk management service. For example, relative to bare soil or managed grassland, woodland reduces fluvial flooding risk to downstream populations by reducing rainfall flows entering rivers. It does this through canopy interception, higher infiltration and water storage in soils, impeding water flows and reducing siltation.			Avoided damages	£200–800/ha/yr	Depends on catchment	ENCA Flood Regulation (EA/ONS NC Accounts 2022)

Adaptation measure	Habitat created/enhanced (ENCA/ONS class)	Service type	Ecosystem service / co benefit (high level)	Qualitative	Biophysical proxy	Biophysical units (notes)	Valuation route (how to monetise)	Monetary value (£)	Notes/ Assumptions / caveats	References
Landscape re-wetting through installation of ponds	Ponds	Regulating	Flood regulation	Some habitats can offer a flood risk management service. For example, relative to bare soil or managed grassland, woodland reduces fluvial flooding risk to downstream populations by reducing rainfall flows entering rivers. It does this through canopy interception, higher infiltration and water storage in soils, impeding water flows and reducing siltation.	Flood storage capacity: typically 100-1000m3 per small pond	Dependant on design of pond	Avoided damages	£47-470/yr per 100-1000m3 pond	Depends on catchment	https://assets.publishing.service.gov.uk/media/6034edf1e90e076609e4c522/Cost_estimation_for_flood_storage.pdf?utm_source=chatgpt.com
		Regulating	Water quality (nutrient and sediment retention, pesticide removal)	Water purification is a vital ecosystem service in which greenscapes, bluescapes, and soils naturally filter pollutants, sediments, and excess nutrients from water. This process improves water quality, safeguards human health, and reduces the need for costly artificial treatment. By maintaining clean water, ecosystems also support biodiversity and provide safe, healthy environments for both people and wildlife.	50-300kg N/ha/yr ; 1010kg P/ha/yr ; ~2 tonnes sediment/ha/yr	typical ranges in the UK / temperate	annualised and indicative	£1000-£6000/ha/yr (nutrients) ; £100-£1000/ha/yr (sediment)		ENCA water quality - Mitsch & Gosselink 2015 ; Heathwaite 2010 ; Everard 2012
		Regulating	Carbon sequestration	Sequestration and storage of carbon dioxide by growing vegetation, soils and sediments (reducing GHG emissions in the atmosphere)	0.5–2.0 tCO$_2$e/ha/yr	tCO$_2$e/ha/yr	BEIS/DesNZ £/tCO$_2$e	£50–300/ha/yr		ONS Wetlands NC Accounts; BEIS values

Adaptation measure	Habitat created/enhanced (ENCA/ONS class)	Service type	Ecosystem service / co benefit (high level)	Qualitative	Biophysical proxy	Biophysical units (notes)	Valuation route (how to monetise)	Monetary value (£)	Notes/ Assumptions / caveats	References
Establish narrow strips of wildflowers cross-slope to encourage infiltration of surface runoff		Regulating	Soil erosion control	An estimated 1 million hectares of soils in England and Wales are at risk of erosion from wind or water. Soil erosion puts pressure on water bodies through increased sediment runoff, nitrate and phosphorous pollution. Offsite impacts of soil erosion include loss of carbon from soils to the atmosphere, dredging costs, costs to remove eroded material from drinking water, rivers, and lakes. Reducing soil erosion helps maintain soil stability, preventing the loss of fertile topsoil and reducing sedimentation in rivers and lakes. By limiting erosion, these services protect agricultural productivity, preserve water quality, and reduce the risk of flooding and landslides.	0.21 tonnes / hectare	Average annual national erosion rate over the total land area	Average cost of soil erosion based on flood risk, production loss and water quality loss, 2024 prices	£149 - £241 / hectare		ENCA Soil. Monetary values from https://sciencesearch.defra.gov.uk/ProjectDetails?ProjectId=16992 within ENCAs list
		Regulating	Carbon sequestration	Sequestration and storage of carbon dioxide by growing vegetation, soils and sediments (reducing GHG emissions in the atmosphere)	1.0–1.5 tCO_2e/ha/yr	tCO_2e/ha/yr	BEIS/DesNZ £/tCO_2e	£100–200/ha/yr		ONS Semi-natural Grasslands NC Accounts; BEIS values

Appendix H - UK horticulture

Overview

Agriculture and horticulture differ markedly in scale and focus in the UK. Agricultural activities (including arable crops such as cereals and oilseeds, as well as potatoes, sugar beet, grazing land and livestock) occupy around 70% of the UK's land area, or ~17 million hectares. In contrast, commercial horticultural activities (specifically the cultivation of edible fruits and vegetables) occupy ~150,000 hectares.[249] Despite this modest area, horticulture accounts for around 20% of UK agricultural output value.[249] Major horticultural crops include field vegetables (~97,000 ha in 2024) and orchards & soft fruits (~20,000+ ha).[250] The UK is largely self-reliant or only moderately dependent on imports of cereals, dairy products and meat, and while local farms supply over half of vegetables (53%), they supply only 15% of fruit consumed in the UK.[250] UK agriculture and horticulture are highly exposed to climate variability and extreme weather, albeit in different ways for different products. The main climate hazards include extreme heat, combined heat and drought episodes, excessive rainfall (causing waterlogging or floods), late spring frosts, and intense storms/winds.

The UK's field horticultural production is highly region-specific, with the east and southeast of England being particularly critical. With proactive interventions, it is possible that the UK can maintain and (potentially) expand horticultural output under a changing climate – but each grower will need to consider a different mix of adaptations depending on their crops, location and resources. No single adaptation measure can mitigate against all potential future changes, but a combination of efficient water use, healthy soils, crop variety and crop diversity can provide general resilience. Transitioning to protected cropping provides the ultimate means to avoid climate risks but is not appropriate for the majority of horticultural crops and has significant implications for cost, ecosystem services and nature.

The UK government and industry bodies are actively supporting interventions: through funding (grants for water infrastructure, R&D on new varieties), knowledge transfer (farm clusters sharing best practices on soil health), and adjusting standards (e.g., retailer tolerance for climate-induced imperfections).

Regional Breakdown

The areas of horticultural crops by Devolved Administration in 2024 were[251]:

- England: 113,000ha
- Scotland: 26,000ha
- Wales: 1,600ha
- Northern Ireland: 2,300ha

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[249] Bradshaw, S. and Wentworth, J. (2023). Future of Horticulture. [online] UK Parliament Post. Available at: https://researchbriefings.files.parliament.uk/documents/POST-PN-0707/POST-PN-0707.pdf.

[250] DEFRA (2025). Horticulture statistics 2024. [online] GOV.UK. Available at: https://www.gov.uk/government/statistics/latest-horticulture-statistics/horticulture-statistics-2024.

[251] DEFRA (2022). Agricultural land use in the United Kingdom. [online] GOV.UK. Available at: https://www.gov.uk/government/statistics/agricultural-land-use-in-the-united-kingdom

Table 58. Geographical distributions of key horticultural crops

Region	Key Crops & Notes
Eastern England	Carrots, onions, potatoes, brassicas, salads. Largest vegetable growing area. Vulnerable to drought and flooding.
Southeast England	Apples, pears, cherries, plums, strawberries. Kent produces ~90% of England's cherries.
West Midlands & Southwest England	Cider apples (Herefordshire), brassicas, salads.
North of England	Field vegetables (and protected cropping) along Humber corridor
Scotland	Soft fruits (raspberries, strawberries), carrots, swedes, peas. Concentrated in Angus and Fife. The region is also important for seed potatoes
Wales	Early potatoes, cauliflowers (Pembrokeshire), apples (Vale of Clwyd)
Northern Ireland	Apples (County Armagh), field vegetables (particularly potatoes)

Key climate change vulnerabilities by sector

Drought & Water Scarcity

Many high-value vegetables (such as field brassicas, potatoes, carrots, onions) suffer yield losses if soil moisture is too low – especially during transplanting and early growth.[252] In the 2018 heatwave and drought, the UK's onion harvest dropped by ~50% and potato yields fell ~33%; overall vegetable output dropped ~20% due to the combined extreme weather that year.[253] Dry conditions not only reduce yields but also lead to smaller produce and quality issues (e.g., heat can increase bacterial rot in lettuce or cause bitter flavours). Profitability suffers as growers have less product to sell, may incur costs for emergency irrigation or water purchase, and can face contractual penalties for supply shortfalls. Moreover, growers sometimes face limits on irrigation abstractions during drought[252], compounding the risk. In summary, drought threatens both yield quantity and quality, directly hitting revenues.

Heat Stress & Extreme Temperature

Many fruit and vegetable crops are cool season species that experience reduced pollination, poor fruit set, or sunscald in extreme heat. For example, temperate fruits like strawberries and apples can suffer sunburn or softening in temperatures above ~30°C. Salad greens and broccoli may "bolt" (go to seed) or develop disorders (such as broccoli "buttoning") in hot weather.[254] Quality downgrades (like sunscald on apples or peppers) mean lower market prices or rejection by retailers. High night-time temperatures can also impede some crops' development, as many need cool nights for sugar accumulation or uniform

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[252] Collier, R. and Thomas, B. (2016). Agriculture and Forestry Climate change report card technical paper 5. Climate change impacts on horticulture. [online] Available at: https://www.ukri.org/wp-content/uploads/2021/12/131221-NERC-LWEC-AgricultureForestrySource5-Horticulture.pdf.

[253] Farmers Weekly. (2022). *Bad weather takes toll on Europe's processed veg crops - Eurofresh Distribution*. [online] Available at: https://eurofresh-distribution.com/news/bad-weather-takes-toll-on-europes-processed-veg-crops/https://www.eurofresh-distribution.com/news/uk-vegetable-production-decimated-by-2018-weather/

[254] Collier, R., Rolfe, J. and Organics, R. (n.d.). Climate Change and UK Horticulture: What is to come and how to build resilience? [online] Available at: https://orfc.org.uk/wp-content/uploads/2022/08/ORFC-Agricology-OGA-Climate-Resilience-0701-compressed.pdf

flowering. Overall, increasing hot periods pose a risk of lower yield and quality for many UK fruit and vegetable crops, which haven't necessarily been bred for heat or drought tolerance.

Excess Rainfall, Flooding & Waterlogging

Many vegetable crops are sensitive to sitting in water – onions and potatoes will rot, while leafy crops are prone to foliar diseases under persistently wet conditions.[255] Waterlogging also compacts soil and prevents machinery from entering fields, disrupting planting and harvest schedules.[252] In the autumn / winter of 2019/20, record rainfall left fields unworkable: some carrot and potato growers couldn't plant on time or harvest the previous crop, causing supply gaps.[254] Flood-related impacts are linked to the immediate loss of revenue from sales of produce – and damage to soils which may require remediation.

Late Spring Frosts & Climatic Variability

Even as average temperatures rise, the UK faces damaging cold periods. Warmer winters cause fruit trees and some early vegetables to develop or flower earlier in spring – making them more vulnerable if an unseasonal frost occurs in April or May.[256] This risk has been realised in recent years: a cold spell in April 2021 brought frost and snow after a mild March. This destroyed the majority of plum, pear, and early apple flowers in some areas, resulting in a much-reduced fruit harvest.[254] Late frosts can also damage potato sprouts or kill off early plantings of tender vegetables.

Changing Pest & Disease Pressures

Many insect pests can breed more quickly in warmer weather and survive winters more easily. For example, modelling suggests carrot root fly and brassica pests can complete more generations per year with just a small increase in temperature.[251] Growers are already noting new pests: the invasive Spotted Wing Drosophila (SWD), a fruit fly that attacks soft fruit, established in the UK in the 2010s and is worsened by warm summers. In a long, hot summer like 2023, SWD populations caused serious damage in some berry farms and vineyards.[257] Conversely, milder, wetter conditions also promote fungal diseases[254], with lettuce downy mildew and late blight of potato outbreaks occurring earlier in the season or more frequently, requiring additional chemical control to avoid crop losses.[254] Climate change effectively raises the baseline pest pressure, eroding margins through increased pesticide use, lost yield, or both. An overview of some climate change vulnerabilities in different sub-sectors is provided in Table 59.

Table 59. Climate change vulnerabilities within different horticultural sub-sectors

Sub-sector	Main Climate Risks	Recent Examples of Impact
Field vegetables (carrots, brassicas, etc.)	Heat & Drought Flooding Storm damage	*Hot Dry 2018* – Widespread drought saw carrot yields fall ~25–30% and onions ~40% below normal due to heat and water stress. This followed winter waterlogging (delaying planting), contributing to losses estimated at £100 million

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[255] Four Seasons Fruiterers. (2025). The Weather Woes: Challenges Facing UK Crops - Four Seasons Fruiterers. [online] Available at: https://www.fsfruit.co.uk/the-weather-woes-challenges-facing-uk-crops/.

[256] T, D. (2022). Climate Change in the Orchard: Later Frosts, Earlier Harvests? – Orchard Notes. [online] Orchardnotes.com. Available at: https://orchardnotes.com/2022/04/23/climate-change-in-the-orchard-later-frosts-earlier-harvests/.

[257] Hadland, L. (2025). Spotted Wing Drosophila – The big picture. [online] Vineyard Magazine. Available at: https://www.vineyardmagazine.co.uk/grape-growing/spotted-wing-drosophila-the-big-picture/

Sub-sector	Main Climate Risks	Recent Examples of Impact
		Flooding in 2020 – Record winter rains (237% of average rainfall in February) drowned or delayed vegetable plantings, which were then established in poor seedbed conditions – potentially contributing to significant losses
Orchard Fruits (apples, pears, etc.)	Late Spring Frost Waterlogging Heat/drought Storms	*Spring Frost* – Cold snaps during May 2023 reduced fruit set in apples, potentially contributing to losses of ~£150million
Soft Fruits (berries)	Frost Heat Heavy Rain Storms	*Winter Storms 2024* – Storms and flooding in Jan–Feb 2024 disrupted early strawberry crop management under polytunnels, delaying the season *Summer Extremes 2024* – A late June heat spike caused a glut of berries, then a cold, wet July sharply reduced yields. Variable weather led to ~4% lower strawberry yields, year-on-year

Regional vulnerability to future climate change

- East/Southeast England: Faces intensifying drought and heat risks. Fens are vulnerable to both drought and flooding. Adaptation options include irrigation and use of heat-tolerant crops.
- Wales & Western UK: Dominant risks are flooding and storm damage. Adaptation options include drainage and storm-proofing (of structures).
- Scotland: Eastern lowlands may benefit from longer growing seasons but face emerging drought and pest risks. Western Scotland is vulnerable to waterlogging.
- Northern Ireland: Mild and wet climate facing increases in storms and flooding. Orchard sector in County Armagh may benefit from fewer frosts but excess rainfall may become challenging.

Opportunities in a Changing Climate

Longer growing seasons & new crop varieties

Milder temperatures and fewer frost days will extend the growing season in many parts of the UK. Frost-free periods have increased by several weeks in some regions. This can allow earlier planting in spring and later harvesting in autumn, potentially enabling multiple crop cycles per year for fast-growing vegetables. For example, warmer springs are already allowing some growers to plant potatoes or carrots earlier (although frost risk remains a constraint). Climate projections suggest that by mid-century, areas of southern England will have a climate more akin to northern France historically – potentially providing conditions suited to crops that prefer slightly warmer conditions. Recent exploration of future suitability for >160 crops in the UK shows that warming increases suitability for many crops, including some not typically or widely grown here today such as sunflowers, soybeans, chickpeas and cowpeas.[258]

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[258] Ranger, S. (2025). Climate change and farming: The surprising impact on the UK's crops. [online] Soci.org. Available at: https://www.soci.org/news/2025/1/climate-change-and-farming-the-impact-on-the-uks-crops.

Experimental plantings of warm-season crops such as chickpeas and rice have already taken place.[146] Similarly, okra and outdoor aubergine might become more viable in the far south. For fruit, viticulture is expected to benefit particularly.[148] Moderate warming may boost yields of certain current crops, such as cereals and carrots – assuming that they are not water limited.[254]

Geographical Shifts

Climate change will not affect all UK regions equally, and some currently marginal areas may become more productive. Parts of eastern Scotland and northern England, historically limited by short growing seasons, could see significantly milder conditions. A study by UKCEH highlights that the southwest of England and Scottish Borders could see the greatest increases in suitability for cropping later in the century.[146] This suggests an opportunity for those regions to expand horticultural output – e.g., Scottish growers might grow more field vegetables or even fruits that were once confined to southern England. Such transpositions are already starting to be visible – while there has been a significant expansion of viticulture in the south of England (which now produces ~10+ million bottles of wine a year, from around 3,500ha of vines – a tenfold increase in two decades[259]), a number have been established as far north as Yorkshire. These shifts could contribute to resilience by spreading production more evenly across the country, although land type and topography in southwest England and Wales could constrain future expansion.[146] Nonetheless, the changing climate could *rebalance* UK horticulture, with proactive farmers in current cooler regions benefiting from warming, particularly if the south fails to invest in measures to address water stress.

Adaptation Strategies for Resilience

Water Storage Capacity

Availability and consistency of water are key to success in irrigated horticultural systems, which are expected to expand as growing seasons become warmer and drier. Growers are investing in on-farm reservoirs and rainwater harvesting to capture winter rain for use in summer. Government policy recognizes this need: Defra’s Plan for Water aims for a 66% increase in water storage on farms by 2050, with grant support available for building reservoirs.[252] Alongside storage, improving irrigation efficiency helps make the most of limited water. Techniques like drip irrigation and precision scheduling (using soil moisture sensors) minimise waste. Drought-resistant management approaches such as using mulch to retain soil moisture also contribute to optimum water management.

Drainage

Growers are also adapting to cope with intense rainfall. Improved field drainage systems help excess water clear faster to prevent or reduce waterlogging. Where soils and crops are suitable, some vegetable producers are using bed-forming techniques to create raised beds that lift crop roots above the saturated zone. The success of this approach has already been demonstrated in Lincolnshire, where raised beds protected potato and carrot crops during the wet autumn of 2019. Protecting soil structure is part of this adaptation too, with growers increasingly raising organic matter levels in soil through addition of compost or establishment of cover crops, improving infiltration rates (and water retention during drier periods) and

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[259] English Wine -Increased Production and Exports Summary. (n.d.). Available at: https://www.theccc.org.uk/wp-content/uploads/2019/07/Outcomes-Wine-case-study.pdf.

reducing physical damage to soils.[252] Overall, these measures ensure that fields remain accessible and productive in spite of heavier rainfall. Better drained soils also mean that crops can “keep their feet dry” and are more likely to avoid root diseases or harvest disruptions. However, improvements in field drainage need to be considered in the context of flood risk – whilst free-draining soils are desirable for crop growth, it can be desirable to retain drained water within catchments to reduce downstream risks. This may mean combining field drainage with areas set aside for ponds, wetlands, wet woodland or braided channels to slow the flow.[260]

Crop selection and breeding

In principle, the simplest adaptation response is to switch to varieties that are tolerant to future forecast conditions. Apple and pear growers are trialling low-chill varieties that still flower reliably after mild winters – mitigating the risk of insufficient winter cold leading to poor fruit set.[254] Newer apple cultivars (and rootstocks) from breeding programs in warmer countries are also being tested for their resilience to heat, drought and reduced winter chilling. Vegetable varieties are also bred for resistance to weather-related events, with broccoli varieties less prone to heat-induced “buttoning”, and lettuce bred for bolt-resistance. Where feasible, growers might switch to different crops if a traditional one becomes too risky – e.g., some salad growers in the southeast are considering switching a portion of land to root crops or onions which are more tolerant to heat than leafy greens. The UK may also see the introduction of new crops such as sweet potatoes or chickpeas, which thrive in heat and are relatively drought-hardy. It should be noted that there can be a cost to moving away from a familiar variety in favour of a new one if it yields less under “normal” conditions – the trade-offs need to be fully understood by growers and the wider supply chain before interventions as made. Over time, however, breeding for resilience (drought, heat, disease resistance) is likely to represent a major source of adaptation in the form of ‘climate ready’ varieties.

Microclimate control

Frost mitigation technologies such as wind machines, overhead sprinklers and smudge pots[261] are already in common use in areas such as the western USA – where stone fruits and apples are widely grown. Whether UK growers choose to adopt these will come down to commercial considerations / risk management. For vegetables, shade netting can be used in summer to protect tender crops from heat stress and scalding: some lettuce growers in the Midlands now drape shade cloth over fields during heatwaves to maintain quality. Taller windbreak hedges can also create a more stable environment for crops and reduce risks of storm damage.

In glasshouse production (tomatoes, peppers, cucumbers), climates can be optimised to manage external temperatures and minimise crop stress.[254] Modern glasshouses use evaporative cooling and thermal screens to mitigate heat peaks. The advantages of protected cropping are obvious: by controlling temperature, humidity, and water, high quality yields can be delivered consistently despite external extremes. Protected cropping does some with downsides – both in terms of costs, but also in terms of poor or low nature benefits when compared with sustainable field production. For lower-margin crops, it may not be commercially feasible to grow under cover; thus many adaptations require a mixed

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[260] Williamson, P. (2015). Channel Management Handbook - Report – SC110002. [online] Environment Agency,. Available at: https://assets.publishing.service.gov.uk/media/603500cad3bf7f265b74bbb2/Channel_management__handbook.pdf.

[261] Smudge Pot Direct. (2025). What Is a Smudge Pot? | Smudge Pot Direct. [online] Available at: https://smudgepotdirect.com/pages/outdoor-portable-heaters.

approach, whereby the most vulnerable/highest value crops are protected, with other remaining in fields. Overall, the trend in UK horticulture is toward more protected cropping, as climate unpredictability adds to the risks of field cropping.

Soil health and agroecological practices

Growers are increasingly adopting soil management practices to improve organic matter levels, structure and resilience. These techniques are captured in the main report as a basket of adaptation measures focussed on soils: cover cropping, organic matter additions, controlled traffic farming and minimum tillage. Improved soil conditions can also contribute to improved crop health and resilience under stress. These benefits are acknowledged through funding available under the Sustainable Farming Incentive, which pays farmers for establishing cover crops and improving soils.[252] Transitioning to these practices may require new equipment (such as new drills) and training, and financial support may be necessary to accommodate short-term yield dips as the system re-balances. An overview of adaptation options, their resilience benefits and related factors is provided in Table 60.

Table 60. Adaptation measures, climate resilience benefits and implementation factors

Adaptation measure	Climate resilience benefit	Implementation factors
Efficient irrigation & water storage *Build on-farm reservoirs; use drip irrigation and sensors to schedule watering events*	Buffers against drought – ensures water supply during dry spells, maintaining yields and quality when rainfall is low.[252] Efficient drip systems deliver water directly to roots, reducing waste and helping crops cope with heat. Also provides insurance against irrigation restrictions by storing winter rain.	Cost: High upfront investment for reservoirs/pumps; may need grants or cooperation (shared reservoirs). Infrastructure: Requires space and suitable ground conditions; may need abstraction license to fill it in winter.[252] Operation: Drip lines need maintenance and management skill to schedule properly (often via soil moisture sensors or weather data). Training: Growers may need guidance on irrigation scheduling to avoid under / over-watering.
Enhanced drainage & flood mitigation *Install or maintain field drains, use raised beds; maintain ditches, create runoff ponds*	Reduces waterlogging and flood damage by allowing excess water to drain rapidly during heavy rain, preventing root suffocation and crop losses.[252] This helps to maintain soil structure and allow timely field operations (planting/harvesting) even in wet seasons. Raised beds and diversions protect crops in flood-prone sites.	Cost: Moderate – installing drains or investing in raised bed equipment. Land: Drainage improvements must align with land topography and drained water will require an outlet. Some soil types are not suitable for bed-forming Environmental compliance: Ensure drainage doesn't harm downstream ecosystems (may need regulatory approval).

Adaptation measure	Climate resilience benefit	Implementation factors
		Maintenance: Ditches and drains must be kept clear annually; plan for ongoing upkeep.
Climate-resilient crops & varieties *Select heat-tolerant, drought-resistant, or low-chill varieties; diversify crop mix*	Maintains yields under new climate stresses – varieties bred for heat or drought yield reliably in extreme conditions (e.g., broccolis that resist bolting in heat).[254] Low-chill fruit varieties still flower after mild winters, preserving fruit yield.[252] New crops (chickpeas, etc.) can exploit longer warmer seasons.[147] Diversifying crops spreads risk so one weather event won't hit all production.	Testing: New varieties may require trialling to ensure they perform in local conditions and meet market specs. There may also be trade-offs between resilience, productivity and marketable crop quality Knowledge: Farmers need access to information on suitable varieties (seed companies, researchers) and possibly training in new crop agronomy. Market: Ensure there is buyer acceptance for any new crop or variety (e.g., taste, appearance might differ). Might require consumer education if introducing truly novel produce. Seed availability: Resilient varieties must be obtainable; may involve participating in breeding trials or early adoption programs.
Protected cropping (tunnels, greenhouses, shade) *Use polytunnels or glasshouses; deploy shade nets or frost covers*	Shields crops from extremes where feasible, to ensure stable yields and quality.[255] Glasshouses and polytunnels can also extend growing seasons and prevent losses from pests (if enclosed). Shade netting mitigates heat stress and scalding during heatwaves, preserving crop quality. Overall, protected environments mean far fewer weather-related crop failures.	Capital Intensive: High cost for glasshouses; polytunnels cheaper but still significant investment (plus eventual plastic replacement). May need financing or grants. Energy & Ops: Glasshouses need energy (heating, cooling) – efficiency measures (solar, CHP (combined heat and power)) help but operational costs are ongoing[252] Polytunnels require labour to set up and vent. Planning/Community: Tunnels can face local opposition (aesthetics); need to consider planning permission and neighbour relations. Technical Skill: Managing environment (ventilation, humidity) requires knowledge – larger operations may need skilled growers or automation. Nature-poor: Enclosed systems exclude nature although offer wider system benefits such as reduced inputs (water, nutrients,

Adaptation measure	Climate resilience benefit	Implementation factors
		pesticides) that have indirect benefits.
Soil management for resilience *Improve organic matter; use cover crops; reduce tillage; apply mulches*	Enhances drought and flood resilience via soil health – organic matter in soils contributes to their water holding capacity (WHC) and can reduce irrigation need and crop stress during drought.[254] Better soil structure improves drainage in heavy rain, preventing waterlogging. Healthier soils also support stronger root systems, contributing to improved crop vigour and resilience. Mulches regulate soil temperature and moisture, buffering against heat and dry spells.	Transition period: Building soil health takes time, with benefits accruing over years. Initially, cover cropping or reduced tillage may complicate planting schedules or require equipment changes. Knowledge: Farmers may need advice on selecting cover crop species and managing them, to fit into rotations. Costs/Savings: Some expense for cover crop seeds and possible yield trade-offs by not leaving land bare. But often saved costs in the long run (less fertiliser, etc.). Verification: Participating in schemes like SFI can offset costs but requires documentation of practices for compliance.[252]
Frost protection techniques *Deploy frost fans, heaters, or sprinklers; choose sites less prone to frost; delay pruning/planting*	Prevents late frost damage – frost fans or heaters in orchards can raise temperatures by a few critical degrees during radiational frosts, preventing blossom from freezing.[256] Overhead sprinkler systems coat blossom with ice to release heat and protect it on freezing nights. Covering rows with fleece on cold nights can shield tender vegetables. Choosing higher elevation sites or those with air drainage for new orchards avoids frost pockets. Together, these measures greatly reduce the risk of losing an entire crop to one cold night in spring.	Expense: Wind machines and large frost control systems are expensive and need fuel/power; usually justified for high-value perennial crops (fruit orchards, vineyards). Scale/Logistics: Sprinkler frost protection needs ample water supply and pumps; feasible where water is available. For small-scale vegetable cropping, row covers are cheap but labour-intensive to deploy and remove. Knowledge of conditions: Must have good weather forecasts and understand local microclimate to activate frost measures at right time. Long-term decisions: When planting new orchards / vineyards, factoring in frost risk is a no-cost adaptation but requires planning and possibly avoiding otherwise good land.

Conclusions

The UK's field horticultural production is highly region-specific, with the East and Southeast of England being particularly critical. With proactive measures, the UK can maintain and (potentially) expand horticultural output while safeguarding food security and rural livelihoods. Each grower will need to consider a different mix of adaptations depending on their crops, location and resources. No single adaptation measure can mitigate against all potential future changes, but a combination of efficient water use, healthy soils, crop variety and crop diversity can provide general resilience. Transitioning to protected cropping provides the ultimate means to avoid climate risks but is not appropriate for the majority of horticultural crops and has significant implications for cost and nature.

The UK government and industry bodies are actively supporting these adaptations: through funding (grants for water infrastructure, R&D on new varieties), knowledge transfer (farm clusters sharing best practices on soil health), and updates to standards (e.g., retailer tolerance for climate-induced imperfections).

Appendix I - Waterlogging

Introduction

Waterlogging is the accumulation of water in the soil beyond its water holding capacity, leading to adverse effects on soil conditions and hence soil function and plant growth. Agriculture in the UK is highly sensitive to waterlogging, whether through its direct impacts on crop production and livestock health, or its indirect impacts on soil quality and resilience. Excess water can lead to reduced oxygen supply, root rot, and nutrient deficiencies whilst also hindering livestock movement, reducing forage quality and increasing disease risk ultimately resulting in lower harvests and economic losses for farmers (Striker, 2012)[262]. Livestock activity can damage wet soils through poaching, but avoiding this by housing livestock during wet periods can have implications for fodder costs.

This paper examines the impacts of waterlogging on UK crop and livestock farming, reviews historical occurrences and explores how waterlogging may evolve in the future.

The Causes of Waterlogging in UK Agriculture

Waterlogging is complex, dynamic, and difficult to predict, resulting from interactions within the soil-plant-atmosphere continuum (Liu et al, 2020)[263] Waterlogging occurs as a result of numerous factors linked to climate, including geography, soil type, lateral ground water flows, and rising or perched water tables. As a result, identifying the direct cause of waterlogging is often not straightforward, due to poor reproducibility in field trials, high soil variability (clay content, layering structure, mineral content, etc.), and the unique nature of each waterlogging event.

Waterlogging can be classified as[264]:

- **Perennial Waterlogging:** Persistent soil saturation throughout the year, often occurring in low-lying areas with poor drainage and high groundwater levels.
- **Subsoil Waterlogging:** This occurs when the groundwater table rises to levels that saturate the root zone. It is often caused by over-irrigation, poor drainage, or a high water table.
- **Seasonal Waterlogging:** Occurs during certain seasons, usually in rainy periods, due to heavy rainfall and insufficient drainage.
- **Riverine Flood Waterlogging:** This occurs when rivers overflow their banks during heavy rainfall or floods, inundating adjacent areas.
- **Marine Flood Waterlogging:** Results from seawater inundating coastal land during tidal surges, tsunamis, or cyclones.

The most common forms of waterlogging in the UK are seasonal waterlogging and subsoil waterlogging, which frequently impact agricultural areas due to heavy rainfall, high groundwater levels, inadequate drainage, and poor irrigation and farming practices. This is often dependent on the soil type and management regime. For example, soils with high clay content or those that have become densely

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[262] https://doi.org/10.1007/s11284-012-0978-9
[263] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020EF001801 .
[264] Encyclopedia of Applied Plant Sciences. (2016). Netherlands: Elsevier Science.

compacted from repeated machinery traffic often exhibit inadequate drainage, thereby increasing the likelihood of waterlogging events[265,266,267]. Riverine waterlogging is also a significant factor, especially in floodplain areas that experience flooding during heavy rainfall events.[264]

The Effect of Waterlogging on Agriculture Practices

When fields experience waterlogging, soil pores become saturated with water, displacing air and reducing gas diffusion. These conditions can impact both crops and livestock, and this section outlines the effects of waterlogging on agricultural production.

Impacts on Crops

Waterlogging has become a notable issue for many major crops in recent decades, affecting plant growth, development, and overall productivity. In these conditions, oxygen availability in plant root systems decreases, resulting in hypoxic or anoxic environments. Plants respond through various physiological, morphological, and biochemical changes[268]. According to Manghwar et al. (2024)[268] waterlogging prompts stomatal closure, which limits photosynthesis. Prolonged waterlogging can result in toxic metabolite buildup and higher levels of reactive oxygen species, leading to cellular changes and advanced senescence. In addition, these conditions inhibit root and shoot growth, reduce grain yield, disrupt mitochondrial respiration, impede gas exchange, and alter key plant hormone levels. Waterlogged conditions primarily affect plants at the root level - and root damage can lead to considerable reductions in shoot growth. Studies[269,270] have shown that exposing wheat plants to waterlogging can reduce shoot mass by 43% to 67% compared with well-drained soil.

In a global scale study, Tian et al (2021)[125] found that waterlogging decreased crop yield by an average of 32.9%, affecting grain weight, biomass, plant height, and leaf area index. They also reported that the overall impact of waterlogging on crop yield depends on the crop type. For wheat, this reduction was 25.53% with an overall average value of 36.81% under field conditions. Any reduction in crop yield is also dependent on the waterlogging duration; the greatest reductions in crop yield occurred at $15 < D \leq 28$ (53.19 and 55.96%) under field and bench study conditions, respectively. Ding et al. (2020) found that wheat yields reduced by 9-15% when waterlogging was imposed at seedling, jointing and tillering stages and a decrease in leaf area by 10% and 29% at anthesis and at the milk-ripe stage[271]. The duration of waterlogging events significantly influences the extent of damage, with longer periods of waterlogging leading to greater negative impacts on plants[272,273.] Cannell et al. (1980)[274], found that winter wheat in Britain is most vulnerable to waterlogging after germination and before emergence. Their experiments found that sixteen days of waterlogging killed all seedlings, while six days reduced plant populations by 12% in clay soils and 38% in sandy loam soils. Subsequent compensation growth made up for some of these early losses, with final populations at about 82% of the control.

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[265] https://doi.org/10.3389/fpls.2021.634898
[266] https://doi.org/10.1093/aobpla/plv080
[267] https://doi.org/10.3389/fpls.2018.01863
[268] https://doi.org/10.1016/j.envexpbot.2024.105824
[269] https://nph.onlinelibrary.wiley.com/doi/pdfdirect/10.1046/j.0028-646X.2001.00318.x
[270] https://onlinelibrary.wiley.com/doi/pdf/10.1111/pce.12676
[271] https://doi.org/10.1016/j.fcr.2019.107695
[272] https://doi.org/10.1080/09064710701794024
[273] https://doi.org/10.1071/FP11165
[274] https://doi.org/10.1002/jsfa.2740310203

Impacts on Livestock

Waterlogging poses serious challenges not only to arable crops but also to livestock health and productivity. When fields and pastures are inundated for prolonged periods, the direct and indirect consequences for farm animals extend beyond discomfort. Wet conditions can increase the risk of infections and parasite outbreaks. For example, prolonged exposure to water and deep mud predisposes livestock to foot rot[275] and bovine mastitis[276]. Research suggests that 90% of all lameness in sheep in the UK is caused by foot rot.[276] A study on lameness in dairy cattle indicated that lameness could reduce milk yield by approximately 357 kg per 305-day lactation, with negative impacts persisting for up to nine months[277]. Additionally, lameness increases the risk of infertility by contributing to delayed reproductive cycles, a higher incidence of cystic ovarian disease, decreased expression of oestrus, and an increased likelihood of conception failure.

As a direct result of prolonged waterlogging, lambs in the UK have faced significant challenges and increased mortality[278]. Persistent rainfall can lead to saturated fields, forcing both ewes and their lambs to lie in cold, standing water. Newborn lambs are particularly vulnerable, struggling to survive wet and cold conditions, while even those born indoors have shown reduced resilience. Ewes, overwhelmed by the continuous exposure to waterlogged environments, have been observed abandoning weaker lambs to prioritise the survival of stronger offspring[279,280].

Standing water can also provide optimum conditions for other organisms which impact on livestock. In the United Kingdom, for instance, standing water provides an optimal environment for snails that complete the life cycle of Liver Fluke; this organism can cause sudden mortality in sheep and chronic wasting in cattle[281]. Furthermore, it is hypothesised that flood events facilitate growth in populations of biting midges (Culicoides), known vectors of Schmallenberg virus (SBV), which is endemic across many regions of Great Britain. Internationally, post-flood conditions have been associated with increased tick infestations causing tick-borne fever, surges in nuisance fly populations leading to livestock distress and acting as mechanical vectors of disease, and heightened cases of blowfly strike resulting in significant welfare concerns for sheep.[276]

When waters have receded, there are increased risks to livestock returning to potentially contaminated pastures. The main contaminants associated with flood water are human and animal faecal waste (raw or processed), chemical contaminants including agrochemicals (e.g., pesticides), heavy metals and hydrocarbons[282]. Microbial contaminants associated with human and animal faecal material, including agents that could cause diseases of livestock and a number of zoonotic organisms e.g., *Cryptosporidium* and *Salmonella* spp. Tapeworm is known to cause cysticercosis in cattle, leading to reduced meat quality and potentially rendering carcasses unsuitable for use. Faecal contamination events following flooding may also introduce or spread antimicrobial resistant bacteria.

Feed quality is also affected by flooding. Growth of mould on crops reduces the nutritional value and palatability of standing and stored feeds. Fungal moulds can also produce toxins such as ergot alkaloids

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[275] https://ahdb.org.uk/knowledge-library/advice-for-livestock-farmers-affected-by-flooding
[276] https://doi.org/10.1016/j.prevetmed.2016.05.009
[277] https://doi.org/10.1136/inp.c6672?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle
[278] https://plantbasednews.org/animals/how-extreme-weather-in-the-uk-is-hurting-farmed-animals/
[279] https://doi.org/10.1079/bjn2002743
[280] https://pdst.ie/sites/default/files/lamb%20survival.pdf
[281] https://www.larkmead.co.uk/farm/flooding-the-long-term-impacts-on-livestock-health
[282] https://www.gov.uk/government/publications/guidance-document-to-enable-the-assessment-of-risk-to-livestock-post-flooding/guidance-document-to-enable-the-assessment-of-risk-to-livestock-post-flooding

that can cause death and liver disease[273] Waterlogged fields and farmland may restrict access to livestock, preventing them from reaching secure areas for feeding – while stored feed may be spoiled. Exposing hay bales to standing water can diminish their nutritional value and increase risks of microbial or fungal contamination.

Risk Analysis: Historical and Future Threats

The literature identifies two notable historical instances of waterlogging in the UK: the 2013/2014 winter flood event and the extended wet period of 2023/2024. These occurrences exemplify both acute and chronic waterlogging impacts within the UK.

October 2022 to March 2024 Event

The United Kingdom recorded its wettest 18-month period from October 2022 to March 2024. Notably, the autumn of 2023 and the following winter (2023 - 2024) saw rainfall totals that were twice the monthly averages for 1991-2020, leading to considerable flooding across the region. According to the EA's summary report of the Water Situation for February 2024[283]:

- All river catchments in England received above average rainfall, resulting in wetter than expected soils, particularly in the North East, East, and South East regions.
- Mean river flows increased at two-thirds of indicator sites, and all indicator sites saw a rise in groundwater levels.
- Rainfall for February was exceptionally high for the time of year in 75% of catchments, notably high in 8%, and above normal in 12%.
- All river monitoring sites recorded monthly mean flows that were at least normal, with 35% of sites classed as notably high and 36% as exceptionally high. Six sites broke records for their highest February flow, including the Rivers Yare, Gipping, Nene, Avon at Evesham, Upper Brue, and Exe.
- From September 2022 to February 2024, England experienced its wettest recorded 18-month period for these months, with 40% of catchments also reporting their wettest 18-month period on record.

During the autumn of 2023, heavy rainfall adversely impacted domestic production of broccoli and other vegetables, including carrots, parsnips, cauliflower, and potatoes[284]. It also hindered farmers across many regions of the UK from planting key crops such as potatoes, wheat, and vegetables during the spring season of 2024 and negatively affected the quality of those already sown. Crop reports[285] from 2024 indicate that wheat production decreased by 15%, the largest reduction observed since 2020. Similarly, winter barley production experienced a decline of 22%, also the most substantial drop since 2020.

In 2024, UK farmers incurred losses exceeding £1 billion in arable crop income, primarily due to persistently wet winter conditions[286]. Official statistics show that crop output fell by £0.6 billion in 2023[287], with challenging weather during planting and declining prices for cereals and oilseeds exacerbating the

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[283] https://www.gov.uk/government/publications/water-situation-national-monthly-reports-for-england-2024/water-situation-february-2024-summary

[284] https://lordslibrary.parliament.uk/climate-change-supporting-farmers-and-growers/#fn-4

[285] https://www.gov.uk/government/statistics/cereal-and-oilseed-rape-production/cereal-and-oilseed-production-in-the-united-kingdom-2024

[286] https://www.fwi.co.uk/news/weather/farmers-lost-1bn-to-extreme-weather-in-2024-defra-says

[287] https://www.gov.uk/government/statistics/total-income-from-farming-in-the-uk/total-income-from-farming-in-the-uk-in-2024

situation. Despite these setbacks, the total contribution of agriculture to the UK economy reached £14.6 billion in 2024, an increase of £1.6 billion over 2023. This growth was mainly attributed to higher overall livestock output, accompanied by rising prices for eggs, beef, and milk.129

2013 - 2014 Winter Flood Event

The winter 2013/2014 flooding was caused by the succession of deep Atlantic depressions and North Sea storm surges[288]. Widespread coastal flooding and prolonged rainfall was attributed to an unusual configuration within the jet stream. The winter was distinctive for the occurrence of multiple types of flooding. Pluvial, fluvial, groundwater and coastal flooding all affected the UK, sometimes simultaneously, although the relative importance of these varied geographically and over the course of the winter[289].

The western UK saw coastal flooding intensified by storm surge, swell waves, storm waves, and high spring tides, with river flooding exacerbated by tidal blocking[290]. In the South East, rainfall at 250% of the long-term average overwhelmed already saturated catchments, causing the River Thames and its tributaries to flood large areas[291]. Economic damages from the floods reached £1,300 million in England and Wales, with agriculture facing £19 million in losses, primarily affecting arable crops (£6.9m), grassland (£1.7m), and livestock (£4.1m).[129] Whilst Flood defences protected 250,000 hectares of farmland, compared to 45,000 hectares that flooded (40,259 ha of cattle grazing, 51,267 ha of sheep and lamb grazing and 11,911 ha of pig paddock), saving an estimated £106.25 million in agricultural damages[292].

According to a 2014 ADAS report, a total of 44,405 ha of crop land was affected, with 40,259 ha of cattle grazing, 51,267 ha of sheep and lamb grazing and 11,911 ha of pig paddock. For fields waterlogged for <15 days, the estimated average yield loss for winter wheat was 20% and winter oilseed rape was 15%. For fields waterlogged >15 days, losses of winter wheat, winter oilseed rape and winter field beans were all estimated at 100%. Additionally, stakeholder consultation in Somerset highlighted that 50% of land planted with winter cereals (1,336 ha) and oilseed rape (155 ha) was rendered unviable, while 75% of the 50 ha of winter field beans (50 ha) was rendered unviable. 100% of spring cereal planting was delayed, while failed winter cropland could not be re-drilled in a timely fashion, leading to further yield impacts (estimated at 10%).

Future potential for wet periods

A 2024 study found that climate change had increased both the frequency and intensity of heavy rainfall during autumn and winter storms in the UK and Ireland from October 2023 to March 2024[293]. It found that, in a pre-industrial climate, rainfall from storms as intense as the 2023-24 season would have had an estimated 50-year return period. In today's climate, with 1.2°C of warming, these events are expected to occur once every 5 years and be 20% more intense. In a 2°C world, storm events of this magnitude could occur once every 3 years and be around 4% more intense. Similarly, for wet periods such as the

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[288] https://ui.adsabs.harvard.edu/link_gateway/2015Wthr...70...40K/doi:10.1002/wea.2465

[289] https://assets.publishing.service.gov.uk/media/5a74a46d40f0b61df47774b1/RFI7086_Flood_Impacts_Report__2_.pdf

[290] https://cyberleninka.org/article/n/653944.pdf

[291] ITEM%205a%20ii%20Annexe%205b%20-%20Environment%20Agency%20Briefing%20Note.pdf

[292] https://assets.publishing.service.gov.uk/media/60354990e90e0740b7caac90/The_costs_and_impacts_of_the_winter_2013_to_2014_floods_-_non_technical_report.pdf

[293] https://www.metoffice.gov.uk/about-us/news-and-media/media-centre/weather-and-climate-news/2024/climate-change-drives-increase-in-storm-rainfall

October 2023-March 2024 season, the estimated return period in a pre-industrial climate was once in 80 years. In today's climate, such an event is at least four times more likely to occur. Scientists estimate that climate change has increased total rainfall by about 15%. If global warming reaches 2°C, similar periods of rainfall - capable of saturating soils and causing significant agricultural losses - are expected to become much more frequent, occurring roughly every 13 years.

Potential Adaptation Strategies

Effective prevention and management strategies are crucial to mitigate waterlogging. Below are some examples of measures that can improve the resilience of agriculture to waterlogging.

- **Soil Management Practices:** Deploy a combination of soil management measures to improve soil structure and water holding capacity (including cover cropping; minimum tillage; crop rotation; maintained surface cover, increases soil organic matter; reduced machinery traffic). Improvements to root health can also support heat tolerance and other co-benefits such as improving soil shear strength and reducing susceptibility to erosion.
- **Crop selection:** Select crop varieties with high tolerance to waterlogging conditions (e.g., early maturing cereals), noting that this may require trade-offs between tolerance and yield / quality. A number of tree species are tolerant / moderately tolerant to waterlogging and may contribute to alternative land use strategies. These include several willow (*Salix*) and alder (*Alnus)* species, as well as Bird Cherry (*Prunus padus*) and Pedunculate Oak (*Quercus robur*)[294].
- **Drainage:** Effective drainage techniques play a crucial role in mitigating waterlogging. Already wet weather and low crop prices in the UK have prompted an increase in drainage operations on arable land, resulting in yield increases of up to 35%[295]. Problems such as delayed drainage of flooding and waterlogging may occur when conventional subsurface drainage is used alone, whether through pipe drains, mole drains or tile drains. Ditches, outfalls and pipes should be regularly cleared and periodic jetting of the drainage network may be necessary to optimise water flows. Costs to install new drainage systems may range between £2,500 and £3,500 per hectare, comprising perforated plastic pipe installed at a depth of around 0.8m in a trench that is normally back-filled with aggregate to maintain permeability[296].
- **Bio drainage** removes excess soil water by relying on evapotranspiration by deep-rooted fast-growing trees such as willow and poplar. Plant water consumption can vary between 6500 and 28000 m^3 ha^{-1} yr^{-1} and an ideal tree plantation can lower groundwater levels by 1-2 m over 3-5 years[297]. Evapotranspiration rates will be lower in winter (or nil for deciduous species).
- **Flood defence:** Raise riverbanks to reduce river overtopping onto land.
- **Irrigation systems:** Drip irrigation reduces evaporation and prevents waterlogging, allowing plants to receive exactly the amount of water they need, instead of watering the entire cropped surface.

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[294] https://www.forestresearch.gov.uk/publications/tree-species-guide/

[295] https://www.fwi.co.uk/arable/land-preparation/soils/tackle-poor-drainage-raise-crop-yields

[296] https://library.rvc.ac.uk/Record/17667

[297] https://doi.org/10.1002/ird.2252?urlappend=%3Futm_source%3Dresearchgate.net%26utm_medium%3Darticle

Case studies

Molescroft Farm (East Yorkshire, UK) - Drainage overhaul on heavy clay soil[298]

Molescroft Farm is a large arable farm located on low-lying, heavy clay soils just below sea level near Beverley in East Yorkshire. The farm's fully tiled drainage system was installed over 30 years ago, and in recent years its performance declined. After an exceptionally wet 2012 season, the farm began experiencing persistent waterlogging - with standing water "wet patches" in some fields - and a surge in weed problems (notably blackgrass, which thrives in damp conditions) that drove up herbicide costs. The waterlogged soils also shortened the workable cropping window: the farm struggled to drill winter crops early enough in autumn without getting stuck, yet delaying sowing to drier conditions reduced revenues.

In response, farm managing director Tamara Hall decided to modernise the field drainage infrastructure across the affected land. Starting in 2013, Molescroft Farm undertook a phased drainage overhaul:

- Installing New Subsurface Drains: The old clay tile pipes were excavated and replaced with modern perforated plastic piping on a closer spacing. These new lateral drains efficiently lower the water table after heavy rain and are far more durable (expected to last as long as the decades-old ones they replaced - 40+ years). In very heavy clay areas, additional mole draining was used to complement the main pipes, creating subsoil channels that funnel water into the pipe network.
- Ditch and Outfall Rehabilitation: Alongside new pipes, all the field ditches and drainage outfalls were checked and cleared of silt or blockages. Often a neglected outlet can incapacitate an entire drainage system - simply unblocking an outfall or ditch can "rejuvenate an entire field" by allowing water to escape freely. Overgrown ditches were re-dug and outlets properly set to ensure collected water flowed off the farm without obstruction.
- Staggered Implementation: Given the high cost (a new comprehensive drain system can cost ~£2,000-£2,500 per hectare), the farm updated the drainage in stages over several years, prioritising the worst fields first. By rotating drainage works from field to field, the farm managed cashflow and minimized disruption, replacing the defunct drains across about 485 ha of arable land by around 2015-2016.

The drainage improvements have been transformational for this farm:

- Dramatic Yield Increases: Crops on previously waterlogged fields now thrive. For example, a field of second winter wheat (variety *Grafton*) yielded 12 t/ha after new drains - far above the ~8.5 t/ha that had become the norm (roughly a 40% yield increase). Across the farm, typical wheat yields rose from ~7 t/ha to 8.75 t/ha on drained land, unlocking an estimated extra £175/ha per year in grain revenue. These gains validate expert estimates that addressing poor drainage can increase yields by about a third.
- Extended Field Access & Timeliness: Better drainage means fields dry out faster, making the land accessible for field work much sooner after rain. The farm can now plant and harvest on schedule, even in wet seasons. Key operations like sowing, spraying and fertiliser applications are no longer delayed by waterlogged ground, ensuring optimal timing (for instance, crucial autumn fungicide sprays can be applied when needed, despite less-than-ideal weather). This extended working window was one of the primary goals and has been achieved.
- Better Weed Control & Soil Health: With soils no longer perpetually wet, troublesome weeds like blackgrass have fewer wet patches to exploit. Crops now "look generally much cleaner", requiring less herbicide usage. In fact, herbicide costs are expected to be reduced by ~£30/ha on the drier

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[298] https://www.fwi.co.uk/arable/land-preparation/soils/how-to-improve-soil-and-yields-with-effective-field-drainage

soils. The drainage interventions also improved soil structure and reduced the need for deep cultivations - the farm cut subsoiling passes by ~25%, saving on fuel and labour. Overall soil health has improved with better aeration and less surface run-off (the drainage overhaul also decreases nutrient losses and slug pressure in wet years).

- Economic Payback: Although the drainage project required upfront investment, the benefits in yield and cost savings are paying this back. Summing up the gains (extra grain, fewer herbicides, simpler cultivations) gives an estimated benefit of £229 per hectare per year on the rejuvenated land. At that rate, the payback period for the new drainage is about 10-12 years. As Tamara Hall anticipated, *"the investment will be paid back in 10 years through better-yielding crops and less need for herbicide…"*. Land that was once "too wet to farm" is now prime arable land again, securing the farm's long-term viability in the face of wetter weather cycles.

Fownhope Farm (Herefordshire, UK)[299] – Adaptive cropping and soil management after flooding

Location & Problem: This case study covers an arable farm near Fownhope along the River Wye in Herefordshire, western England. In the winter of 2019-2020, the River Wye burst its banks after prolonged heavy rainfall, inundating about 34 ha of the farm's low-lying fields. The preceding potato crop had just been harvested from the affected land - fertile alluvial soil by the river - which was due to be sown with winter wheat. But autumn flooding within two weeks of lifting the potato crop prevented any wheat from being drilled. Those fields remained under water or waterlogged for much of the winter, with repeated flood episodes. Farmer Martin Williams quickly recognised that if he tried to sow winter wheat as planned, the crop would have drowned: *"It would have been wheat, and we would have lost it because of the floods,"* he noted. Even though the floodwaters tend to recede fairly quickly on the Wye, the window for establishing a winter crop had clearly closed - by the time the ground drained and became accessible, it would be too late (approaching April) to get a viable winter wheat stand. In short, the farm faced a potential total crop loss on 34ha due to the severe waterlogging and an impossibly delayed planting season.

Instead of writing off the flooded fields or attempting to drill a very late winter wheat, Martin Williams opted to sow a different spring crop once conditions allowed:

- Crop Substitution (Spring Peas): The farmer decided the best recovery option was to plant large blue peas in spring on the 34ha floodplain parcel. Peas were already part of his rotation (grown as a break crop alongside maize and others) and can be sown relatively late (March/April). By switching to peas he "bought time" until the land dried out. This tactical change meant the farm could still produce a crop on those hectares in 2020, rather than leaving them fallow.
- "Pump Out" Water with a Crop: Planting a crop in waterlogged soil can help dry it out, since growing plants will transpire significant moisture out of the ground. By getting peas established as soon as feasible, their roots would help recover the soil by extracting excess water and improving soil structure as they grew.[142] (Had the land been left bare, it would have stayed wetter for longer and become prone to slumping.)
- Soil Remediation Before Drilling: The farmer also took the opportunity to remediate the soil once the floodwater retreated. Before drilling the peas, he went in with a Sumo subsoiler to alleviate compaction and rutting left from the potato harvest and the flooding. He also checked and cleared the field's drainage channels, many of which had silted up during the floods. By deep tilling and maintaining the drainage prior to planting, the soil was in much better condition - with restored porosity and drainage - for both the pea crop and the following season's crops. (Agronomy

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[299] https://www.fwi.co.uk/news/weather/herefordshire-grower-hopes-to-drill-once-flood-recedes

advisors note that any deeper remedial work for drainage should wait until soils have dried sufficiently, as was done here in early spring[142])

Outcomes: By staying flexible and focusing on soil recovery, the Herefordshire farm mitigated the impact of an extreme waterlogging event:

- Salvaged a Productive Crop: The switch to spring peas meant that the 34ha of flooded land still produced a crop in 2020, avoiding a total loss. The peas were planted once the ground was workable and went on to establish normally. While peas generally have a lower yield and market price than winter wheat, this strategy ensured some return on the land instead of zero. In essence, the farmer averted a complete crop failure. As Mr Williams explained, farmers instinctively plan to stick with wheat, *"because that is what farmers do,"* but in this case adapting the plan was the only viable option. Thanks to that decision, *"there is nothing that we won't crop"* - virtually the entire farm remained under production despite the floods, with only a few small patches too damaged to crop.
- Restored Soil for Next Season: The flooded fields emerged from the ordeal in better condition than one might expect. By rectifying drainage and subsoiling compaction in spring, the farmer set the stage for improved performance in the following year. The soils had time to dry and were further "opened up" by the pea roots, helping to naturally restructure the soil. Come autumn 2020, those fields would be in a suitable state to revert to winter cereals again, now with less risk of waterlogging due to the repairs made. In short, the interventions not only yielded a one-time pea crop, but also rehabilitated the land for future seasons.
- Risk Management & Flexibility: This case demonstrates the value of agronomic flexibility in the face of unpredictable weather. By pivoting his rotation (even putting some other higher ground fields into wheat for a third year to make up area), the farmer spread his risks. He also avoided wasting seed and inputs on wheat that would likely fail and prevented the soil structure from being ruined by trying to work it while too wet. Although less of the farm's most profitable crop (wheat) was in the ground that year, the farm still met its cropping commitments and covered its costs. This pragmatic approach maximised overall farm resilience.

Comparison

Both case studies dealt with excess water in fields but employed different solutions - one largely an infrastructure upgrade, the other a change in farming practice - reflecting the specific nature of the waterlogging problem. Table 61 compares the interventions and outcomes:

Table 61. Comparison of interventions and outcomes

Farm Case	Waterlogging Issue	Intervention Implemented	Outcomes Achieved
Molescroft Farm *Large arable farm on heavy clay lowlands (East Yorkshire)*	- Aging 30-yr-old field drains were failing on heavy clay soil. - Persistent ponding ("wet patches") in fields after rain. - Weed outbreaks (e.g., blackgrass) due to damp soil; rising herbicide	- Drainage system overhaul: Installed new subsurface plastic drains to replace old clay tiles (improving capacity & longevity). - Cleared and re-dug ditches/outfalls to remove blockages (a quick ditch clean can "rejuvenate" a whole field). - Added supplemental	- Yield restoration: Grain yields rebounded by ~30-40% on drained land (e.g., wheat from ~8 → 12 t/ha on one field), unlocking ~+£175/ha/year in extra output. - Extended workability: Fields dry faster, allowing on-time sowing and agrochemical applications even in wet seasons. Farming operations are timelier and more efficient.

Farm Case	Waterlogging Issue	Intervention Implemented	Outcomes Achieved
	costs. - Very short planting window in autumn; struggled to sow winter crops on time because ground stayed wet.	mole drains in clay subsoil to aid water flow into main drains. - Staggered the drainage work over several years (post-2012) to manage costs, eventually covering ~485 ha.	- Lower weed pressure: Drier soils have fewer water-loving weeds; the farm projects cutting herbicide use by ~£30/ha as crops stay cleaner[300]. - Economic gains: Improved yields and lower costs add ~£229/ha/yr benefit. Upfront costs (~£2k/ha) should be recouped in ~10 years, after which profitability on those acres is much higher.
Fownhope Farm *Mixed arable farm on river floodplain (Herefordshire)*	- Severe river flooding in winter drowned ~34 ha of arable land. - Winter wheat could not be sown at all (fields under water in autumn). - Risk of complete crop failure on those waterlogged fields (wheat would have died). - Soil left with silt, compaction, and damaged field drains after floodwaters receded.	- Cropping change: Abandoned autumn sowing. Switched the 34 ha from winter wheat to a spring crop (large blue peas) that could be sown in April once land dried. - Soil repair: Once floodwater fell, cleared drainage channels of silt and ran a subsoiler (Sumo) to break up compaction from flooding/potatoes. - Staggered planting: Rescheduled cropping so wetter low fields went into peas (later), while maximizing wheat on higher ground that was dry enough. - Used the pea crop itself to help dry the soil via transpiration and restore soil structure (a natural "biological drainage" approach).	- Avoided lost land: The threatened 34 ha still produced a harvest (of peas) instead of yielding nothing. This safeguarded farm income and cropping targets despite the floods. - Recovered soil health: Post-flood remedial actions improved field conditions - compaction was alleviated and drainage function restored - setting up the land for a return to normal winter cropping by the next season. - Minimal fallow area: With flexible planning, almost the entire farm was cropped (only a few small patches stayed bare for recovery), showing resilient use of land. - Adaptive success: By matching crop choice to field conditions, the farmer reduced potential losses. He demonstrated that *"doing something is better than doing nothing"* - planting peas was agronomically and economically smarter than either risking a wheat or leaving land idle.

These two examples highlight that different waterlogging problems demand different solutions. On slowly drained heavy soils, investing in better field drainage infrastructure can dramatically improve productivity

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[300] https://www.fwi.co.uk/arable/land-preparation/soils/how-to-improve-soil-and-yields-with-effective-field-drainage.

and prevent chronic waterlogging. On the other hand, when faced with sudden flood-induced waterlogging, an adaptive agronomic strategy - like changing crops and remediating soil when conditions allow - can save a season. Notably, both approaches are complementary: good infrastructure provides long-term resilience, while flexible management provides immediate resilience. In practice, farmers may need to combine both engineering fixes and crop/soil management tweaks to combat waterlogging. By doing so, they can protect their crops, maintain yields, and improve soil health even as extreme weather events become more frequent.

Conclusions

Waterlogging poses a significant challenge to UK agriculture, historically leading to reduced crop yields, lower harvests, and economic losses for farmers. Seasonal and subsoil waterlogging, driven by heavy rainfall, high groundwater levels, inadequate drainage, and certain farming practices, can severely affect plant growth and productivity, while also increasing disease and mortality in livestock. The exceptionally wet winter of 2023/24 highlighted the vulnerability of farming systems, with widespread financial impacts. Looking ahead, high-rainfall periods capable of saturating soils could occur more frequently - although this may take place within a context of drier and warmer summers which depress soil moisture and underlying groundwater levels, reducing subsequent waterlogging risks. Nonetheless, proactive adaptation will be essential, drawing on measures such as improved drainage, optimised irrigation, tolerant crops and robust flood defences, to mitigate waterlogging impacts and support sustainable management of the UK’s farmed landscapes.

Appendix J - Shortlisted REA resources

The following reports and papers were analysed as part of Task 1.2, providing insights into climate risks, impact thresholds and adaptations.

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Appendix K - The calculation of economic losses

Methodology, contextual information, data and assumptions used

This document sets out the rationale for the approach taken to quantifying economic losses within the Climate Change Committee's (CCC) Farmed Landscape Deep Dive Project, including (1) how economic losses are calculated from climate modelling results and (2) what underlying assumptions were made (and what data were collected to evidence those assumptions). It also contains the results of a literature review to contextualise the findings of the results.

It covers the following;

1. The theory and assumptions underpinning the calculations
2. Unit prices used in the analysis
3. The use of discount factors
4. The calculation of economic losses and Net Present Values (NPVs)
5. Considerations for the estimation of economic losses

The theory and assumptions underpinning the calculations

Economic losses are calculated as the losses incurred by producers, through analysing some representative agricultural products. Farmers' revenues depend on the following main components:

- the production unit (Q): area (A – in hectares) or the number of livestock (N – in number of livestock)
- the yield (Y): productivity, reflecting the quantity produced in a given area or by animals – e.g., in t/ha for crops
- the producer price (P): reflecting the quality of the same amount of product – e.g., in GBP/tonne for crops

The units of measure for different agricultural products are included in Table 62.

Table 62. Unit of measures applied to different agricultural products

Agricultural product	**Unit of measure of**		
	Production (Q)	Yield (Y)	Price (P)
Crops: wheat, barley, oats	Area: hectare	Yield: tons/ha	Producer price: GBP/ton
Milk	Number of animals affected Number of days affected	Yield: litre/cow/day	Producer price: GBP/litre
Egg	Number of hens affected Number of days affected	Yield: weight of egg (gram/egg/day)	Producer price: pence/gram
Lamb[301]	Number of lambs	Cost: number of lambs affected by parasites	Cost: the cost of treatment per lamb

Based on this, revenue is calculated as:

$$Revenue_{C,R}^{Base} = Q_{C,R}^{Base} * {Y_{C,R}}^{Base} * P_{C,R}^{Base}$$

where C, R reflect the type of the agricultural product (C) and the region (R) (England or devolved administration) of the UK and 'Base' reflects the revenues without considering the impact of climate change ('baseline').

Losses can be attributed to two factors: changes in quality (L^{qual}) and changes in yield (L^{quant}) (i.e., quantity). The economic loss can be expressed as the losses of farmers, by considering the change in quality and quantity (assuming that the production units are fixed):

$$Rev^{climate\ change} = Q^{Base} * [Y^{Base} * (1 + L^{quant})] * [P^{Base} * \left(1 + L^{qual}\right)]$$

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[301] In the case of lamb, it was not the loss in revenue that was assessed, but the cost of treating animals infected by parasites. However, the calculation of economic losses is broadly similar to the loss of revenue

Due to a lack of robust data for estimating impacts, the methodology assumes **no change in quality**, and therefore $L^{qual} = 0$;

Prices are kept constant over time. This reflects and is consistent with our assumption of no change in quality ($L^{qual} = 0$).

This analysis assumes that all the economic losses are born by producers, while consumers are unaffected by higher prices. This assumption was made to simplify the calculation of welfare losses: although it is realistic to assume that lower yields would lead to higher producer prices (counterbalancing some of the losses of producers), this loss would simply be transferred to consumers. The implication of this assumption is discussed further in the main report. For example, the price elasticity of demand, trade, and the substitution of different products can all affect prices, among other factors.

As a result, losses occur only due to reductions in yields: $Q^{Base} * [\boldsymbol{Y^{Base}} * (\mathbf{1} + \boldsymbol{L^{quant}})] * P^{Base}$

The total loss in revenue in a given year (t) is:

$$R_t^{loss} = R_t^{cc} - R_t^{Base} = Q_t^{cc} * P_t^{cc} * Y_t^{cc} - Q_t^{Base} * P_t^{Base} * Y_t^{Base};$$

$$as\ Q_t^{cc} = Q_t^{Base} = \overline{Q_t}\ and\ P_t^{cc} = P_t^{Base} = \overline{P_t}\ \ [production\ units\ and\ producer\ prices\ are\ fixed\ in\ given\ year]:$$

$$R_t^{loss} = \overline{Q_t} * \overline{P_t} * (Y_t^{cc} - Y_t^{Base}) = \overline{Q_t} * \overline{P_t} * (Y_t^{Base} * (1 + L^{quant}) - Y_t^{Base}) = \overline{Q_t} * \overline{P_t} * (Y_t^{Base} * L^{quant})$$

where R is the Revenue, 'cc' (climate change) refers to values considering heat stress and 'Base' refers to baseline values

The climate modelling calculates the *total* losses in yields in a given year (e.g., tonnes per year for each crop), which equals to: $\overline{Q_t} * Y_t^{Base} * L^{quant}$

Note: The climate modelling does not assume any further adaptation compared to today.

There are three scenarios modelled, as described in the section *Land use scenarios*.

Prices

This analysis only focuses on producer prices (i.e. farmgate prices), and the calculation of economic loss accordingly focuses on lost revenue to producers. Such losses are used as a proxy for welfare losses. In this analysis, it is assumed that all losses are borne by producers, while in reality the reduced yields modelled in this analysis would likely result in higher farmgate prices (as a result of greater scarcity of these products). This would limit any loss of revenue to the producers, and instead result in consumers (either directly or indirectly) paying higher prices for related goods and services. However, these are still welfare losses – so by holding prices constant, this methodology ensures that welfare losses are still captured, rather than being lost through being imposed on consumers rather than producers.

These prices reflect the quality of the agricultural products, expressed in GBP per unit of production (e.g., GBP/tonne for cereals, or in GBP/litre for milk). In the analysis, it is assumed that there are no changes in quality over time. However, within each agricultural product, there is variance in the price due to different *subproducts* (e.g., milling and feed wheat in the case of wheat).

To calculate the **average price** of a given agricultural product (e.g., the average price of 1 tonne of wheat), the following factors can be considered:

- How many **subproducts** are available? (e.g., taking the example of wheat: there is milling wheat and feeding wheat, which may have significantly different prices)
- What is the **share** of different subproducts within the agricultural production? (e.g., what percentage of wheat is milling and feeding wheat?)
- Is there a significant **variance in the share** of different subproducts over time? (e.g., does the proportion of land harvested for milling and feeding wheat vary from year to year?)
- Are there significant **differences across devolved administrations**? (e.g., Does Scotland produce significantly more feeding or milling wheat than England or the UK?)

In order to consider all these factors, data was collected on the following (as far as it was available[302]):

- the price and relative share of all subproducts
- by devolved administrations and
- took the 5-year average price (to overcome any price fluctuations) and relative shares.

The price of a given agricultural product is proportional to the subproduct based average price (e.g., reflecting the share of land area used for harvesting feeding and milling wheat)

For example: $P_{wheat}^{England} = Share_{milling\ wheat}^{England} * P_{milling\ wheat}^{England} + Share_{feed\ wheat}^{England} * P_{feed\ wheat}^{England},$
$where\ Share_{milling\ wheat}^{England} + Share_{feed\ wheat}^{England} = 1$

Nominal prices were converted to real prices (based on the 2024 price level) using the yearly average economy-wide consumer price index (CPI).

In the following sections, the data sources identified and selected for each product are set out, along with an assessment of the limitations of the data, how it varies from the classifications that are used in the final analysis, how these issues have been addressed and the implications.

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[302] Please note that, in most cases, data could not be sourced to cover all dimensions, so some simplifying assumptions were made. These are listed as limitations below.

Wheat

Prices

Data used: Defra, 2024[303]

- This source has only UK-wide prices for two subproducts of wheat (milling and feed).

Alternative data (not used): AHDB, 2025[304]

- This source includes some data at DA-level and uses crop years (e.g., 2023/24); it has three subproducts of wheat (bread milling, other milling, feed wheat)
- This data is not used due to missing data on prices in some nations – in order to remain consistent, UK-wide prices from Defra are used
- For example, this source has no data on NI; there are missing figures for Scotland; England and Wales are not differentiated.

Limitations: UK-specific prices are applied (for each subproduct) to all nations (i.e., assuming that $P_{UK}^{feed\ wheat} = P_{England}^{feed\ wheat} = P_{NI}^{feed\ wheat} = \cdots$)

- By using UK-level prices instead of nation-level prices, some granular information which is available is lost, and the estimation of economic losses is less precise. However, the calculation remains consistent and nation-level losses sum up to UK-level losses: $L_{UK} = L_{England} + L_{Wales} + L_{Scotland} + L_{NI}$.

Land area

Relevance: In order to calculate the weighted average of different subproducts, data on the land area on which they are produced is required.

- For example, this information shows whether milling wheat production has a higher share in one nation than in another.

Data used: AHDB, 2024[305]

- This source reports the share of different flour groups in several UK regions
- Much data are not reported due to confidentiality – Great Britain is the only aggregate where all information is available.

Variance: Wheat is categorised based on flour groups and not based on the two subproducts for which other data is available (i.e., milling and feed wheat). Therefore, flour groups are matched to wheat subproducts:

- Group 1 and 2 are assumed to be bread milling wheat

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[303] https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fassets.publishing.service.gov.uk%2Fmedia%2F665da1297b792ffff71a8638%2FAUK-chapter7-06jun24.ods&wdOrigin=BROWSELINK

[304] https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fprojectblue.blob.core.windows.net%2Fmedia%2FDefault%2FMI%2520Reports%2FD%26A%2520Arable%2FDaily%2520and%2520Weekly%2520Price%2520Reports%2FCorn%2520Returns%2520prices%2520month_year.xlsx&wdOrigin=BROWSELINK

[305] https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fprojectblue.blob.core.windows.net%2Fmedia%2FDefault%2FMarket%2520Intelligence%2Fcereals-oilseeds%2Fsurvey-results%2Fplanting-survey%2F2024%2520results%2Fahdb-planting-and-variety-survey-historical-results-2024.xlsx&wdOrigin=BROWSELINK

- Group 3, 4 and other are assumed to be other milling wheat and feed wheat (poorer quality in gluten and/or protein).

Limitations: Great Britain-specific figures are applied for all nations and for the UK:

$$\frac{Land_{GB}^{feed}}{Land_{GB}^{total\ wheat}} = \frac{Land_{UK}^{feed}}{Land_{UK}^{total\ wheat}} = \frac{Land_{England}^{feed}}{Land_{England}^{total\ wheat}} = \cdots$$

- This is due to missing data at nation level (mainly due to confidentiality).
- However, based on the available data, there are significant differences between whether feed or milling wheat is the dominant subproduct within a nation. This variance does not occur in calculations due to the application of GB-specific figures. The shares are reported below to illustrate the impact that is **not** captured:

DA	Share of milling wheat	Share of feed wheat	Share of area reported (compared to 100%)	Note
GB	**42%**	**58%**	**100% (no missing data)**	This figure is applied to each nation and the UK
England	40%	41%	81%	Weighted share of regional data, based on 2022 shares of regions
Wales	57%	41%	98%	West Midlands and Wales are reported jointly
Scotland	0%	94%	94%	
NI	21%	74%	95%	
UK	19%	43%	61%	

Barley

Prices

Data used: Defra, 2024[303]

- This source has only UK-wide prices for two subproducts of barley (malting and feed barley)

Alternative data (not used): AHDB, 2025[304]

- This source includes some data at DA-level and uses crop years (e.g., 2023/24); it has three subproducts of barley (premium malting barley, other malting barley (and the average malting barley price) and feed barley)
- This data source was not used due to missing data on prices in some nations – in order to remain consistent, UK-wide prices are applied.
- E.g.: no data on NI; there are missing figures for Scotland; England and Wales are not differentiated.

Limitations: UK-specific prices (split by subproduct) are applied to all nations (e.g., assuming that $P_{UK}^{malting} = P_{England}^{malting} = P_{NI}^{malting} = \cdots$)

- By using UK-level prices instead of DA-level prices, some granular information which is available is lost, and the estimation of economic losses is less precise. However, the calculation remains consistent and DA-level losses sum up to UK-level losses (i.e. $L_{UK} = L_{England} + L_{Wales} + L_{Scotland} + L_{NI}$).

Land area

Data used: AHDB, 2024[305]:

- 2024 barley variety at DA-level except Northern Ireland; Based on total area, NI has low production of barley compared to other DAs
- Total barley area historical: regional figures (more granular than nation level – e.g., North East, North West, etc.); latest available figures for all regions (including Wales separately from West Midlands) are from 2022; however there are no significant variations between years (i.e., the share of a given region within a nation is similar over time)

Variance: barley is categorised to 'Total malting, brewing and distilling' and 'Total feed and other', the same categories as used in the price data

Limitations: aggregated results for England and Wales are not available, only more granular (regional) data

Calculation: the land-weighted average of barley varieties is applied to get nation-level figures

- This means that $Share_{malting}^{England} = \sum_{region\in England} share_{region}^{malting} * weight_{region}^{malting}$

$$where\ weight_{region}^{malting} = \frac{A_{region}^{malting}}{\sum_{region\in England} A_{region}^{malting}}\ and\ A\ stands\ for\ Area$$

Weights are the share of barley area within England

- Note that due to missing barley variety data in Northern Ireland, GB-specific figures are used for NI. For example, this means that $Share_{malting}^{NI} = Share_{malting}^{GB}$
- UK-wide results are calculated based on the share of barley area in 2022 (a year when there is no missing data)

$$\begin{aligned} Share_{malting}^{UK} = {} & w_{England} * Share_{malting}^{England} + w_{Wales} * Share_{malting}^{Wales} + w_{Scotland} \\ & * Share_{malting}^{Scotland} + w_{NI} * Share_{malting}^{NI}\ where\ w_{England} + w_{Wales} + w_{Scotland} \\ & + w_{NI} = 1 \end{aligned}$$

w refers to the weight: the share of total barley area in a nation compared to the UK: e.g., $w_{England} = \frac{Land_{total\ barley}^{England}}{Land_{total\ barley}^{UK}}$

Oats

Prices

Data used: Defra, 2024[303]

- This has only UK-wide prices for two subproducts of oats (milling and feed oats)

Alternative data not used: AHDB, 2025[304]

- This source includes some data at nation-level and uses crop years (e.g., 2023/24); it has two subproducts of oats (feed and milling)

- This data was not used due to missing data on prices in some nations – in order to remain consistent, only UK-wide prices are used. E.g.: no data on NI; there are missing figures for Scotland; England and Wales are not differentiated.

Limitations: UK-specific prices (by subproducts) are applied to all nations (i.e., assuming that $P_{UK}^{feed} = P_{England}^{feed} = P_{NI}^{feed} = \cdots$)

- By using UK-level prices instead of nation-level prices, some granular information which is available is lost, and the estimation of economic losses is less precise. However, the calculation remains consistent and nation-level losses sum up to UK-level losses (i.e. $L_{UK} = L_{England} + L_{Wales} + L_{Scotland} + L_{NI}$).

Land area

Data source: AHDB, 2024[305]

- Data is only available for Great Britain (with no nation-level distinction).

Variance: oat varieties are reported, which are grouped to feed and milling oats

- Feed oats: 'WPB Isabel' and half of 'other'
- Milling oats: 'Mascani', 'Merlin', 'Canyon Oats' and half of 'other'

Due to the lack of more granular data, GB shares are applied for all nations. For example, the share of milling oats: $Share_{milling}^{England} = Share_{milling}^{Wales} = Share_{milling}^{Scotland} = Share_{milling}^{NI} = Share_{milling}^{GB}$

Eggs

Two data sources are used:

- Defra, 2025[306] [Source 1]: Average UK farm-gate egg price by production method
- IndexBox, 2025[307] [Source 2]: Production of eggs for human consumption

Variance in egg prices:

- Type of production: enriched cage, barn, free range, organic
- Type of use: shell eggs (directly sold, class A), and processed egg
- Size of egg: eggs of different sizes (S, M, L, and XL) have different prices; the size depends on weight
- Only hen eggs are considered.

Assumption: losses due to climate change are expressed as a reduction in egg weight (in grams)

- It was not possible to source data which evaluated the price and volume of eggs produced by their size
- therefore the price of 1 gram of egg (taking into account the type of egg) is calculated, and losses are expressed according to the total weight lost.

The calculation of average prices:

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[306] https://www.gov.uk/government/statistics/egg-statistics

[307] https://www.indexbox.io/blog/table-egg-united-kingdom-market-overview-2024-2/

- Source 1 includes the weighted average of shell egg prices by production between 2019 and 2024 (in pence per dozen) ($P_{shell\ egg}^{average}$), but has data only for the UK, not by nation.
- Source 1 also includes information on the total number of eggs produced in the UK for use as shells or for processing, in millions of dozen.
- From source 1, the total revenue of the UK egg industry can be estimated from shell eggs: $Revenue^{shell\ egg} = P_{shell\ egg}^{average}\left[\frac{pence}{dozen}\right] * \left(Production^{shell\ egg}\right)[million\ dozen]$ (it only consider shell eggs)
- Source 2 includes information on the production of chicken table egg in tons ($Production_{egg}^{shell\ egg}$ $[ton\ or\ gram]$) (table egg and shell egg are assumed to be the same)
- From this, the average price of shell egg per gram is calculated: $Price_{egg}^{shell}\left[\frac{pence}{gram}\right] = \frac{Revenue^{shell\ egg}}{Production_{egg}^{shell\ egg}}\left[\frac{pence}{gram}\right]$

Limitation: there is no information on the producer prices of processed eggs. Only the revenue from shell egg production is evaluated.

- This means: $Revenue^{egg} = Revenue^{shell\ egg}$
- Note: the production of processed eggs is 9-12% of all egg production (processed + shell)

Limitation: Please note that it is not possible to differentiate prices at the nation level. Economic losses are calculated based on the number of eggs produced in each nation, and applying a single UK-level price.

An alternative calculation of the price per gram of eggs was carried out, to attempt to verify the primary method;

- It assumed that the average weight of one egg is 58 grams (assuming an average egg size of M, which weighs between 53 and 63 grams)
- Source 1 includes information on the price of eggs per dozen (e.g., 130.8 pence in 2024)
- From this, the average price of an egg per gram is 0.188 pence per gram:
- $\frac{Price\ per\ dozen}{Weight\ of\ 1\ egg*dozen} = \frac{130.8\ pence}{58g*12} = 0.188\frac{pence}{gram}$
- This is close to the value calculated based on the first method (0.166 pence per gram), suggesting that the primary method is providing a reasonable estimate.
- If the average size of egg is assumed to be 68 grams, the price per gram is 0.160 pence/gram.

Milk

Data source: AHDB, 2025[308]

- This source describes milk production in terms of price and volume in the UK, Great Britain and Northern Ireland

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[308] https://view.officeapps.live.com/op/view.aspx?src=https%3A%2F%2Fprojectblue.blob.core.windows.net%2Fmedia%2FDefault%2FMarket%2520Intelligence%2Fdairy%2FFiles%2FPrices%2FFarmgate%2520milk%2520prices%2FUK%2520GB%2520and%2520NI%2520Farmgate%2520prices.xlsx&wdOrigin=BROWSELINK

- Data is available by month, and the 5-year average can be calculated without imputing missing data (for the period 2020–2024)

The calculation of average prices:

- The data source gives average monthly farmgate milk prices and volumes for the UK, GB and NI (e.g., P_t^{UK}, V_t^{UK}, the price and volume in the UK in a given month)
- Yearly prices are calculated as the weighted average of monthly prices where the weights are the monthly production:
- For example: $P_{2024}^{UK} = \frac{Revenue_{2024}^{UK}}{V_{2024}^{UK}} = \frac{\sum_{t\in 2024}(V_t^{UK} * P_t^{UK})}{\sum_{t\in 2024} V_t^{UK}}$ (over all months in 2024)

Limitation: UK-specific prices are applied in all nations due to a lack of more granular data

- Data on GB and NI is available, but for consistency just a single UK price is used.

Lamb

Relevance: in the case of lambs, the risk metric calculates the number of lambs projected to be infected by parasites (*Haemonchus contortus*). The loss due to infection is equal to the cost of treating infected animals.

Data source: Jones et al., 2020[309]

- The authors reference Nieuwhof and Bishop (2005) who calculated the losses incurred by the sheep industry in Great Britain in 2005. The average cost of treating a parasite infection per lamb is estimated to be £4.63 (at the 2005 price level). This equates to 7.93 GBP per lamb at the 2024 price level.

Variation: As the cost of treatment is assumed to be the same for all lambs in all parts of the UK, therefore nation-level data were not collected.

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[309] https://www.ukclimaterisk.org/wp-content/uploads/2020/07/Thresholds-in-the-natural-environment_CEH.pdf

Discount factors

In this analysis, a discount rate is applied to express future economic losses in present value terms. Discounting is done in this analysis to represent social discount rates - the principle that a unit of cost or benefit occurring in the future should carry less weight than the same amount today in decision-making, due to the opportunity cost of capital (and, more broadly, reflecting that due to economic growth a pound today is worth more than a pound in the future when incomes will be higher) and a pure time preference (i.e. that people prefer money today to money tomorrow). By converting multi-year losses into a Net Present Value (NPV), results are comparable across time horizons and provide a consistent measure of the economic burden of climate change impacts.

Based on the UK Green Book (Annex A: Discounting, Table 6), the annual discount rate is assumed to be 3.5% in the first 30 years of the analysis, and 3.0% between year 31 and 61. The discount factors are calculated within the table of the UK Green Book based on:

$$discount\ factor^{y} = \prod_{t=1}^{y} \frac{1}{1 + r_t}$$

Where y is the end year and r_t *is the discount rate in year t (i.e., 3.5% in the first 30 years, 3.0% later).*

Calculating annual economic losses and NPVs

Economic losses are calculated in four steps, as set out below.

1 Climate modelling outputs are fed into the economic loss calculations. The specific indicators used are the total annual yield losses (or the number of lambs affected) split into scenarios by land use (BAU, CB7a, CB7b) and climate scenarios (central, high), by period (i.e., present day, near-term and mid-term) for the four nations and the agricultural products. These results are available for 16 different model members, representing the mean of 20 modelled years at a given warming level.

2 Initial estimations of economic losses were calculated by multiplying the total annual yield losses (from the previous step) by prices (with an adjustment in the case of lamb: the number of lambs treated by the cost of treatment).

3 Model member selection was carried out to focus in on a single set of outcomes for each combination of inputs. This involved selecting either a single model member or averaging across model members (as set out in Table 63) in order to derive a single set of economic losses for the central climate scenario, and a further set for the high climate scenario.

Table 63. Model member selection by period and climate scenario

Period	Central Climate Scenario	High Climate Scenario
Present day	Average across all model members	Average across all model members
Near-term	Member 9	Member 13
Mid-term	Member 12	Member 13

Period	Central Climate Scenario	High Climate Scenario
Notes	*Model members with the median economic losses*	*Model members with the highest economic losses*

In the central climate scenario, the relevant model member was selected by calculating the economic losses for all model members at a given level of global warming (equivalent to a given a period in one climate scenario) and then identifying the member which reported the median outcome, when ordered according to cumulative economic losses (i.e. summed across all analysed products, and at the UK level). In the high climate scenario, the model member with the largest cumulative economic losses was selected at a given level of global warming (equivalent to a given a period in one climate scenario), in order to highlight the most severe outcome across the different model members.

4 Annual undiscounted economic losses were constructed using the loss figures calculated in the previous steps. Based on discussion with the CCC's secretariat, the mean of results for 20 modelled years for the selected model member were allocated to a single 'central' year. Table 64 outlines how different combinations of inputs were used to construct three separate data points for the central and high climate scenarios.

Table 64. Mapping modelled outcomes to central and high climate scenarios

Climate scenario	Period	Global Warming Level (compared to pre-industrial)	Central year that mean values were allocated to
Central / High	Present day	1.1°C	2024
Central	Near-term	1.5°C	2035
Central	Mid-term	2.0°C	2055
High	Near-term	2.0°C	2035
High	Mid-term	2.5°C	2055

Annual time series for each scenario were then constructed through linear interpolation between these central years (i.e. between 2024 and 2035, and 2035 and 2055). Extrapolation was then applied up to 2059, using the same rate of change as seen between 2035 and 2055.

For example, if the average annual yield loss in 2024 and 2035 are $Loss^{2024}\ and\ Loss^{2035}$, the linearly interpolated result for year *y* (which is between 2024 and 2035) is: $Loss^{y} = Loss^{2024} + \frac{y-2024}{2035-2024} * Loss^{2035}$

5 Net Present Values (NPVs) were calculated by multiplying the undiscounted economic losses by the discount factor, to calculate the annual discounted economic losses, and the summed over time.

Formally: the discounted annual losses can be described as

$$Discounted\ Loss\ (DL)^{year} = Loss^{year} * discount\ factor^{year}$$

The annual discounted losses are summed up across the relevant periods to calculate NPV

$NPV^{y_{t_0},y_t} = \sum_{t_0}^{t} DL^t$ (the net present value between year t_0 and t)

NPVs were calculated for the whole time period (2025-2059), but also for a number of subsets of years: 2025-39 and 2025-59, for reporting in the final analysis. In all cases, the application of discount rates starts from 2025.

Considerations for the estimation of economic losses

Considerations for the estimation of economic losses

A high-level literature review was conducted to assess the potential impact of climate-related stressors on the price of different agricultural products. Estimates of own price elasticities were identified to assess the flexibility of demand for the good. The relationship between producer and consumer prices was also taken into account. Where UK specific information was unavailable, literature from other comparable regions or countries were used.

The aim of this synthesis is to provide a view on two key aspects that are not well represented in the quantitative analysis that has been carried out: the extent to which changes in yields would lead to changes in prices (and therefore the extent to which welfare losses are borne by consumers, rather than producers), and the extent to which these agricultural products are traded, and therefore any reduction in domestic production might be addressed through imports (noting that while this would still represent a loss to producers, it would limit impacts on consumers).

The impact of price changes on domestic demand

The price elasticities of demand for eggs, fruit and vegetables, cereals, meat and dairy are negative and below 1, indicating that demand for these products is inelastic (i.e. demand changes by less than prices, in percentage terms). DEFRA (2012) estimated the elasticity of demand for food in the UK and found that all food products assessed have negative and inelastic own price elasticities. For example, the price elasticity of eggs is estimated to be -0.66.[310] This indicates that a 1% increase in the price of eggs will result in a reduction in consumption of 0.66%. The implication of this is that yield reductions that lead to greater scarcity will lead to economic losses that fall substantially on consumers, not just on producers. Accordingly, any estimation of economic losses arising from climate change should be constructed in a way that includes impacts on both producers and consumers.

Other papers that have a global scope have similar findings for high income countries and for the European region as summarised in the table below. Overall, the literature indicates that in the case of rising prices, demand for food prices will be largely unaffected, but in the case of large price increases, demand will fall. Consumer demand for cereals and potatoes is the least sensitive to changes in consumer price, whilst eggs, milk, meat and fruit and vegetables are more sensitive to changes in price.

Table 65. Summary of demand elasticities from the literature

Food product	Region	Source	Estimated elasticity
Lamb	UK	DEFRA (2012)[311]	-0.55

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[310] https://assets.publishing.service.gov.uk/media/5a759170e5274a545822c86d/defra-stats-foodfarm-food-price-elasticities-120208.pdf

[311] https://www.gov.uk/government/publications/food-and-drink-elasticities

Food product	Region	Source	Estimated elasticity
Meat	EU	Femenia (2019)[312]	-0.53
	Europe other	Femenia (2019)[312]	-0.54
	High income countries	Green, et al. (2013)[313]	-0.60
	High income countries	FAO (2014)[314]	-0.42
	Summary (total range in literature)		[-0.42; -0.60], inelastic, negative
Milk	UK	DEFRA (2012)[311]	-0.83
Dairy	EU	Femenia (2019)[312]	-0.53
	Europe other	Femenia (2019)[312]	-0.62
	High income countries	Green, et al. (2013)[313]	-0.61
	High income countries	FAO (2014)[314]	-0.371
	Summary (total range in literature)		[-0.47;-0.83], inelastic, negative
Eggs	UK	DEFRA (2012)[311]	-0.66
	High income countries	Green, et al. (2013)[313]	-0.36
	Summary (total range in literature)		[-0.36;-0.66], inelastic, negative
Starches (flour, bread etc)	UK	DEFRA (2012)[311]	-0.798
Cereals	EU	Femenia (2019)[312]	-0.19
	Europe other	Femenia (2019)[312]	-0.42
	High income countries	Green, et al. (2013)[313]	-0.43
	High income countries	FAO (2014)[314]	-0.036
	Summary (total range in literature)		[-0.036;-0.789], inelastic, negative

Producer and consumer prices

Producer prices refer to the amounts paid to producers for the goods they generate. In agriculture, this is the price a farmer receives – whether from a merchant, broker, miller, feed manufacturer or other party. Consumer prices are the final amounts paid by consumers for agricultural products, including both unprocessed and processed items, as set by retailers. Increases in production costs that raise producer prices may ultimately lead retailers to adjust consumer prices to maintain profit margins, once the costs for the primary produce have cascaded through the value chain. These two types of prices are interconnected through the value chain and the roles of producers, merchants, manufacturers, distributors, retailers, and consumers. Additionally, shifts in consumer prices can influence producer prices; for example, if demand for a product rises sharply and retailers increase consumer prices, producers may also raise their prices.

The literature indicates that, while the relationship can theoretically occur in both directions, producer prices are generally set first and influence consumer prices (see Caporale, Katsimi and Pittis, 2002[315]). Changes in producer prices are transmitted to consumer prices after a delay through the value chain. Producers may experience fluctuations in input costs, which subsequently affect the prices charged

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[312] https://hal.science/hal-02103880/document
[313] https://www.bmj.com/content/bmj/346/bmj.f3703.full.pdf
[314] https://openknowledge.fao.org/server/api/core/bitstreams/aa6175f4-2359-4daf-b634-b183dc39ca72/content
[315] https://doi.org/10.2307/1061728

downstream, with ultimate consumer prices adjusted accordingly. The effect of producer prices on consumer prices tends to be more pronounced with price increases, whereas decreases in producer prices have a smaller impact on consumer prices.

There is also evidence suggesting that future food prices may become less responsive to agricultural production costs. This is attributed to agricultural production costs constituting a declining portion of total food prices, with added-value components such as transport, processing, marketing, and catering gaining greater significance. This trend is particularly notable in high-income countries, including the UK. As a result, producer prices may exert a diminishing influence on consumer prices in the future, potentially limiting changes in consumer prices – although this will vary between agricultural products. There is (normally) a long value chain between harvested cereal crops and final (domestic) consumers, but this chain will be much shorter for eggs and milk.

Inflation affects how much changes in producer prices (PPI) influence consumer prices (CPI). When inflation is low, producers have less ability to pass on higher costs, reducing their profits. High inflation allows producers to adjust prices more easily and protect margins. Consumer food prices generally rise with producer prices, but the impact varies with inflation levels. Climate change and extreme weather are expected to increasingly disrupt agricultural production, lowering supply and raising producer prices, which can then push up consumer prices depending on inflation and value-added cost shares. Although food demand is inelastic, it still falls as prices rise - especially for meat, dairy, and eggs compared to cereals. As the share of producer prices in overall food costs declines, future price increases may be less pronounced.

Tradability and reliance on domestic production

Cereals - wheat, barley and oats

The UK primarily produces the wheat, barley, and oats that are used domestically. Based on AHDB data, the proportion of imports contributing to the total supply of these grains has been calculated and summarised in the table below. Total product availability is defined as the sum of opening stocks, production, and imports.

Table 66. Imports as a percentage of the total product availability

Product	2019/20	2020/21	2021/22	2022/23	2023/24
Wheat	6%	17%	11%	7%	13%
Barley	1%	1%	1%	1%	2%
Oats	1%	2%	1%	1%	2%
Raw milk	1%	1%	1%	1%	1%
Egg	13%	11%	12%	15%	14%
Lamb	19%	17%	18%	17%	24%
Note: For crops, years indicate crop years (e.g., 2020 means 2019/2020)					

The UK generally meets domestic demand through its own production, with imports playing a minor role. Over the past five years, barley and oat imports have accounted for just 1-2% of total product availability. In contrast, wheat imports have contributed a larger share, ranging from 6-17%. The fluctuations in wheat import percentages indicate that changes in domestic wheat production are easily supplemented by imports under prevailing conditions. With respect to exports, a higher proportion of barley and oats is exported compared to wheat. This indicates that domestic production of barley and oats frequently surpasses domestic demand, resulting in minimal import requirements for these grains.

Table 67. Exports as a percentage of total UK production

Product	2020	2021	2022	2023	2024
Wheat	7%	2%	3%	9%	2%
Barley	20%	14%	10%	13%	9%
Oats	10%	4%	10%	15%	12%
Raw milk	5%	6%	5%	5%	5%
Egg	8%	3%	4%	3%	3%
Lamb (meat)	33%	28%	29%	33%	31%

Notes: For crops, years indicate crop years (e.g., 2020 means 2019/2020). Crop values are compared to total production plus opening stocks

Raw milk

Overall, the UK imports a small proportion of raw milk, accounting for less than 1% of total milk availability in recent years, except for 2021 when imports rose to just over 1%. Exports have shown a slight decline, from 5.8% in 2020 to 5.5% in 2024. The proportion of exports remains higher than that of imports, indicating that domestic production generally meets consumption needs. Imports have remained relatively stable over the past five years.

Eggs

A small proportion of eggs are exported each year, while the percentage share of imported eggs is higher than exports. This indicates that egg imports contribute to meeting domestic demand in the UK. Over the past five years, the proportion of imported eggs has remained relatively stable, ranging from 11% to 15%. Exports have also shown stability and have not exceeded 3% since 2020. The figures in Table 66 and Table 67 include both processed and shell eggs.

Lamb meat

Approximately one-third of domestic lamb production in the UK is exported, and around 20% of lamb consumed domestically each year is imported. Compared to other products, the volume of lamb exports is relatively large, indicating notable activity in the lamb meat market. Imports are also substantial, which may relate to the seasonal aspects of lamb production.

Summary

Most modelled products are not widely traded, as UK agriculture generally supplies domestic demand, and only a small portion of production is exported, with the exception of lamb. Low import shares indicate that a potential decrease in yields could result in *higher* consumer prices in the short term, since domestic production is not easily replaced by imports (e.g., due to potential regulatory limitations or the lack of established trade relationships). Consequently, consumers may experience greater impacts from yield reductions, especially those sectors purchasing raw agricultural products (e.g., the food industry). If climate-related hazards cause lasting declines in yields, the UK may need to increase imports over time.

In addition, agricultural products are diverse, so different sub-products might be affected to varying degrees, leading to large range of impacts.