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Adapting Scottish agriculture to a changing climate - assessing options for action

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1 Executive summary

1.1 Aims

The Climate Change Risk Assessment 3 (CCRA 3) identifies a risk of serious climate impacts in Scotland. The Climate Change Committee (CCC) 2022 Report to the Scottish Parliament made recommendations on adaptation opportunities for agriculture, such as the potential to grow a broader range of crops which will support domestic food security, mitigating the risks of some common food crops becoming less suitable.

This report maps the current major agricultural activities in Scotland and examines Scotland's rainfall and temperature projections up to 2030, 2050 and 2100 using UK Climate Projection (UKCP) 18 data to create a picture of current agricultural activity and future climate. We located regions that currently have a similar climate to what Scotland expects in the future, to identify potential agricultural products that could be adopted or expanded in Scotland. We also explored published evidence to examine the options for climate change adaptation for farmers in Scotland.

Farmers are already experiencing changing weather patterns and extreme events due to climate change and consideration of adaptation actions is very timely.

1.2 Key findings

- We found that Scotland is predicted to have wetter and warmer winters and drier and warmer summers, alongside a higher frequency of extreme events.
- Due to latitude (a critical element as it effects day length and frost occurrence) and the relative warmth of Scotland compared to other parts of the world at a similar latitude, we found very few climatically comparable regions in the world. These were limited to: northern Europe, parts of western Canada, southern Alaska, southern Chile and Auckland Island.

    - We found some suggestions for cropping activity, such as sugar beet, apples, oats and hops, based on current activity in Denmark, Germany and British Colombia.
    - Livestock are more adaptable than cropping, so it will be more important to adapt management and improve both natural/green and hard infrastructure, such as shade, shelterbelts and buildings, rather than requiring a complete change in breeds and/or species.
- The evidence review identified around 50 adaptation actions suitable for Scottish agriculture that would be feasible in all regions of Scotland before 2030 and are also applicable to 2050 and 2100. These include adjusting planting and harvesting dates, selecting crop types resilient to extreme weather, adjusting pasture and soil management practices.
    - Some of the actions lacked detail, for example, on the species of crops or livestock that are more resilient. This is a reflection of the availability of data, and perhaps limited progress of adaptation in agriculture.
- We also found that adaptive actions are not limited to physical practices on-farm, but also include knowledge transfer and management changes, such as advice provision, early weather warning systems and farmer co-operatives. There are also cross-over actions which support mitigation and adaptation in agriculture and can support biodiversity, for example:
    - Changes to fertiliser application frequency to improve both inorganic and organic fertiliser use efficiency.
    - Improved soil management to better respond to wetter and drier conditions, which in turn can support carbon sequestration/ retention and agroforestry.
    - Use of agroforestry - which can sequester carbon, stabilise at-risk soils, provide shade and shelter to livestock, provide diverse income streams and support biodiversity through habitat and green corridor creation.

1.3 Recommendations

The full list of recommendations is available in section 7 of this report. We recommend the following next steps.

- Undertaking case studies for the proposed adaptation actions, looking at effectiveness and practicalities in a variety of Scottish contexts. The case studies should highlight lessons learnt and the potential to replicate them in Scotland.
- Providing on-farm advice to help farmers understand the impacts of climate change on their business and to assist the implementation of relevant actions, with an emphasis on building on and improving existing practice. These could be integrated with climate mitigation advice to produce robust outcomes. If this is carried out, outcomes should be monitored to see what is successful. Farmers are constantly adapting their practices to the weather, without it being considered adapting to climate change. For example, planting and harvesting dates adjust each year, and we recommend building on this common practice already embedded within Scottish farming.

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2 Glossary of terms

Term	Definition
Adaptation	Measures proposed or taken to address climate change and variability
Agrivoltaics	The use of agricultural land to produce agricultural products and generate photovoltaic electricity simultaneously
Agroforestry	Multifunctional land use by integrating trees with crops or pastureland
CCC	Climate Change Committee
CCRA3	Climate change risk assessment 3
Extreme weather	Occurrences of unexpected, severe weather events that can impact communities, agriculture, and natural ecosystems
Fallow	Soil left unseeded for a period of time
INNS	Invasive and non-native species
Intercropping	Growing two or more crops in close proximity at the same time.
IPM	Integrated Pest Management
Irrigation	Supply of water to crops to aid growth
Latitude	An angle that ranges from –90° at the south pole to 90° at the north pole, with 0° at the Equator.
Mitigation	Reducing severity
Mob grazing	More Intensive type of rotational grazing (high intensity, short duration grazing)
Pathogens	Microorganism that can cause disease
REA	Rapid Evidence Assessment
Rough grazing	Uncultivated land used to graze livestock
Shelterbelts	Planting a line of trees/shrubs to reduce windspeed and provide shade and shelter
Tillage	Agricultural preparation of soil by mechanical manipulation for the purpose of crop production
Transhumance	The movement of livestock in a seasonal cycle

UKCP18	UK Climate Projections 18 (Climate projections based on different representative concentration pathways)
RCP6.0	Representative Concentration Pathways 6.0 (emission scenario pathways created and used for climate modelling for climate modelling)
Köppen Climate zones	Five main climate groups (Tropical, Dry, Temperate, Continental and Polar) which make up the basis of the Köppen Climate Classification System
Climate hazard sensitivity	Level of sensitivity and therefore risk to a climate hazard such as a heat wave
Adaptive capacity	The ability to adjust or respond to certain events
Exposure of hazard/ opportunity	The level to which an element has not taken any protective measures to a hazard or put in place ways of optimising an opportunity

3 Introduction

The Climate Change Risk Assessment 3 (CCRA 3)[1] identified a risk of serious climate impacts in Scotland. Identifying the risks and opportunities within these climate impacts and acting on them now, would improve the resilience of Scotland's farmers, rural areas and related industries.

In the 2022 report 'Is Scotland Ready?'[2], the Committee on Climate Change (CCC) referred to agricultural productivity and farmland birds and habitats as two agriculturally relevant areas for adaptation action. This included optimising opportunities, such as the potential to grow a broader range of crops to support domestic food security and mitigating the risks of some commonly grown crops becoming less suited to Scotland's climate.

Our research looked at the current climate and agriculture in Scotland and made recommendations for how farmers can adapt to a changing climate in Scotland.

4 Mapping

It is important to understand the spatial distribution of current agricultural activity in Scotland to appreciate the context of the impacts of climate projections. Scotland was mapped through three tasks used to inform the feasibility of adaptation actions across time and area:

- We evaluated Scottish agricultural activity to provide a current snapshot as a baseline.
- Rainfall and temperature data were evaluated to provide climate projections up to 2030, 2050 and 2100 (the time periods requested in the proposal).
- Comparable regions around the world were located to help to inform the adaptation actions and agricultural activity feasible in Scotland in the future.

4.1 Mapping current agricultural activity

The annual Scottish agricultural census data provides a picture of agricultural activity across Scotland. The census is broken down by agricultural region, providing data on different aspects of agriculture, including number of holdings, livestock numbers and crops grown by hectare. To better correlate with the climate projections, we grouped high level land-use activities from the 2021 census into land cover categories by UKCP18 region[3] as shown in Figure 1. The analysis of census data shows what Scotland produces and where, providing an activity baseline for consideration of future changes in response to climate change (but noting there are many other drivers for change, and barriers, for example demand for products and availability of infrastructure).

Key findings are:

- Within all regions 'rough grazing' takes up the largest area, particularly in the north region.
- In the west and east regions 'grazing' covers the second largest amount of land .
- In the east region, 'crops and fallow' is far larger than other regions in Scotland and the focus of Scottish arable farming.

[1] https://www.ukclimaterisk.org
[2] https://www.theccc.org.uk/publication/is-scotland-climate-ready-2022-report-to-scottish-parliament/
[3] UKCP18 data provides climate change projections up to 2100 in the UK. For comparison of UKCP18 regions against agricultural census regions, please see Appendix 1: Mapping methodology.

- ‘Woodland and other’ is of a similar percentage of land cover within all three regions. Further detail is provided on land cover in Table 1.

Livestock numbers are presented in Table 2 by agricultural region and UKCP18 region. Key findings by region are:

- The north region holds the fewest numbers of livestock, dominated by sheep in the Highlands. This is related to low population and large distances to larger markets, as well as the high proportion of rough grazing, which is less productive land.
- The east region has the highest numbers of livestock. This is likely to be related to the proximity to grain and vegetables for animal feed. Within this region, the Scottish borders has the highest numbers of livestock, dominated by poultry (indoors) and sheep.
- The west region is dominated by sheep and poultry (indoors) in Dumfries and Galloway, and the number of dairy cattle is the highest here, by some margin, compared to the rest of Scotland. This will be due to the current climate producing excellent grass growing conditions, as well as the structure of the dairy industry becoming more concentrated over time with fewer dairy farms and larger numbers of cows per farm.

It is important to note that agricultural activity such as most poultry and pigs and some suckler beef and dairy, will be taking place indoors. This is out of scope of this project as it can be possible to control indoor climates regardless of external impacts (notwithstanding extreme events). The ratio of livestock head to land-use also becomes arbitrary when analysing the importance of particular land-use types.

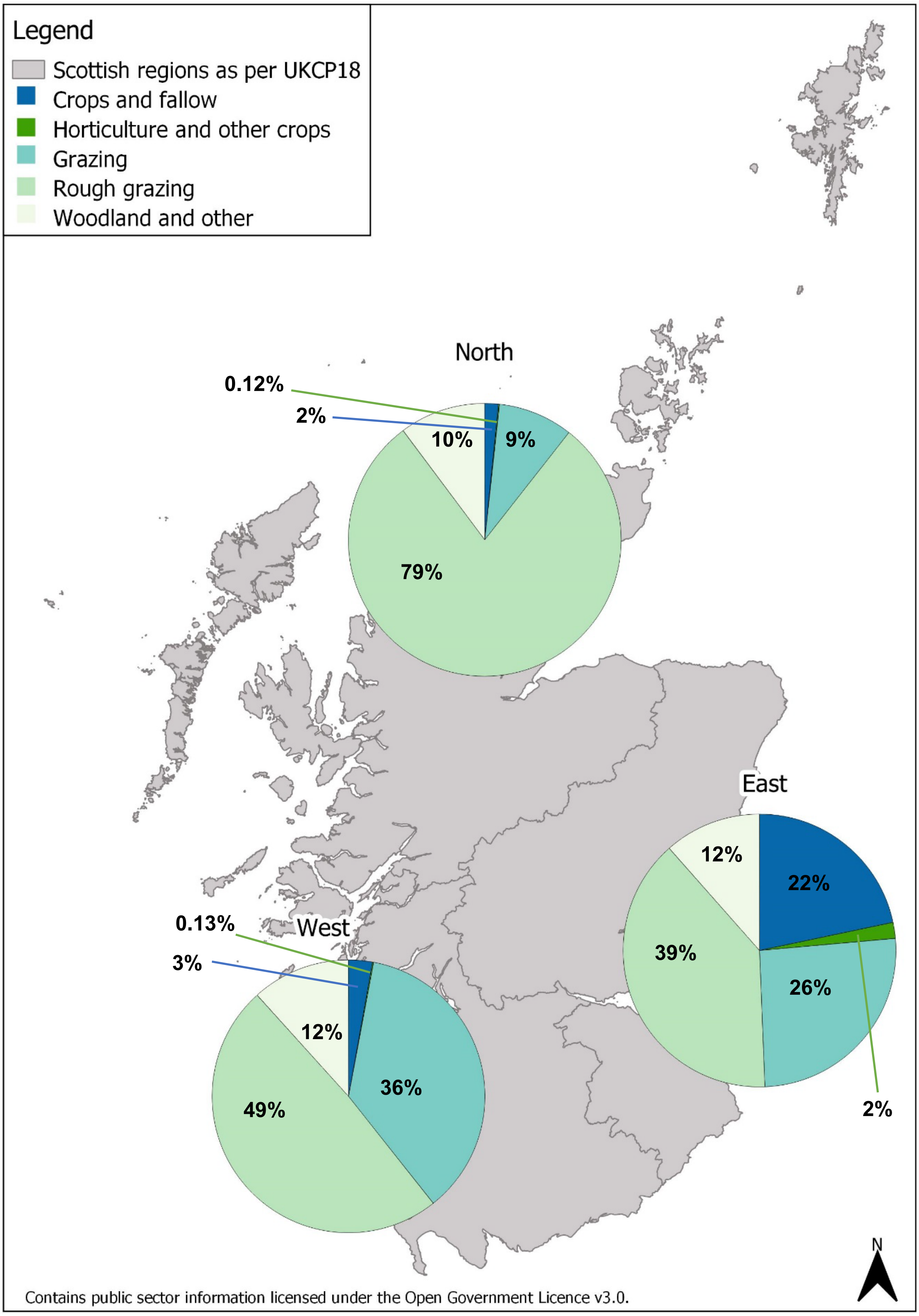

Figure 1: Agricultural land cover in Scotland split by UKCP18 climate regions

Table 1: Total hectarage of crops in Scotland by agricultural region, clustered into UKCP region.

	North					East							West				
Category	**Shetland**	**Orkney**	**Na h-Eileanan Siar**	**Highland**	**North Total**	**Grampian**	**Tayside**	**Fife**	**Lothian**	**Scottish Borders**	**East Central**	**East Total**	**Argyll & Bute**	**Clyde Valley**	**Ayrshire**	**Dumfries & Galloway**	**West Total**
Crops	169	4,663	319	34,453	39,604	168,685	105,779	44,199	41,963	64,764	10,738	436,128	1,997	7,603	8,129	18,335	36,065
Horticulture and other crops	62	193	92	2,793	3,140	8,619	16,007	6,018	3,289	5,621	427	39,981	76	418	434	923	1,851
Fallow	113	318	588	3,005	4,025	11,390	6,082	2,432	1,881	1,554	922	24,260	503	1,821	623	801	3,747
Grazing	28,510	51,146	25,036	133,970	238,661	191,659	100,017	32,403	40,857	131,782	50,190	546,907	66,748	102,023	115,473	227,089	511,332
Rough grazing	117,506	34,746	274,135	1,704,587	2,130,974	225,899	322,474	3,744	28,138	141,011	108,105	829,371	372,260	74,640	89,747	151,463	688,110
Woodland and other	951	941	6,786	266,014	274,692	86,451	68,197	9,335	14,403	40,641	25,055	244,082	67,558	20,846	24,937	50,830	164,171
Sum of crops	**147,311**	**92,007**	**306,956**	**2,144,822**	**2,691,095**	**692,702**	**618,556**	**98,131**	**130,531**	**385,372**	**195,437**	**2,120,730**	**509,141**	**207,350**	**239,342**	**449,442**	**1,405,275**

Table 2: Total number of heads of livestock in Scotland by agricultural region, clustered into UKCP region.

	North					East							West				
Category	**Shetland**	**Orkney**	**Na h-Eileanan Siar**	**Highland**	**North Total**	**Grampian**	**Tayside**	**Fife**	**Lothian**	**Scottish Borders**	**East Central**	**East Total**	**Argyll & Bute**	**Clyde Valley**	**Ayrshire**	**Dumfries & Galloway**	**West Total**
Dairy	807	2,938	538	3,838	8,120	8,355	5,138	8,023	4,076	11,127	12,505	49,224	10,293	34,994	65,962	153,921	265,170
Beef	3,986	74,133	5,403	115,587	199,108	323,849	92,273	45,509	44,050	127,722	38,259	671,662	49,658	92,685	113,527	272,223	528,093
Sheep	289,566	130,134	143,247	858,222	1,421,169	715,197	644,042	100,672	222,336	1,131,007	269,503	3,082,757	424,134	435,492	451,209	1,016,944	2,327,779
Pigs	116	165	159	13,739	14,179	190,268	27,858	7,270	18,950	52,609	250	297,205	1,400	10,248	1,541	16,641	29,830
Poultry	4,868	8,745	7,424	216,576	237,613	1,740,783	2,313,573	1,186,680	2,226,656	2,960,864	631,595	11,060,151	15,248	208,635	878,362	1,554,195	2,656,440
Goats	69	191	66	774	1,100	1,798	1,001	210	670	353	126	4,158	208	593	664	1,113	2,578
Deer	0	0	0	1,886	1,886	3,519	2,776	966	0	2,677	898	10,836	0	0	0	1,520	1,520
Other[4]	1,023	579	453	4,661	6,716	7,684	4,785	2,316	3,337	3,500	1,935	23,557	1,236	3,653	3,337	3,847	12,073
Sum of livestock	**300,434**	**216,885**	**157,289**	**1,215,283**	**1,889,891**	**2,991,453**	**3,091,446**	**1,351,646**	**2,520,075**	**4,289,859**	**955,071**	**15,199,550**	**502,177**	**786,300**	**1,514,602**	**3,020,404**	**5,823,483**

[4] **horses, donkeys, camelids, beehives**

4.2 Establishing future scenarios

The UKCP18 dataset was used to model rainfall and precipitation projections for Scotland. It provides climate change projections up to 2100 in the UK to equip decision makers with information to help adapt to the challenges and opportunities presented by climate change (Met Office, N.D.). UKCP18 has a governance board[5] as part of their peer review process. UKCP18 provides probabilistic projections as a spatially coherent global dataset. The UK focused dataset provides projections at a 2.2 km scale allowing realistic simulation of high impact events, for example heavy rainfall in summer.

The UKCP18 dataset presents climate projections based on different representative concentration pathways (RCP), which are emission scenario pathways created and used for climate modelling (Met Office, 2018). This project has used RCP6.0[6] projections in line with the RCP pathway presented within the CCRA3 2021 technical report for Scotland and following discussions upon project inception. The UKCP data is presented as ranges of change in daily average summer and winter temperature and precipitation for three regions in Scotland: north, east and west. The split of these regions is shown in Figure 1. For the purposes of this project we are looking at data ranges from 2020-2039, 2040-2059 and 2080-2099 to represent the date periods up to 2030, 2031 to 2050 and 2051 to 2100, as closely as possible with the available data.

The box plots (Figure 2) present the lower (5^{th} percentile of the 5^{th} percentile projection) and upper (95^{th} percentile of the 95^{th} percentile projection) projections to capture the projected range of weather in each of the three regions in Scotland. The lower, median and upper (5^{th}, 50^{th} and 95^{th} percentile) percentiles of the median (50^{th}) data are presented as crosses and squares within the box plots. It is important to note the median shows the direction of where the models sit, but should not be considered an average nor the most likely outcome. Baseline data is represented by dashed lines in the box plots for comparison.

Climatic events, such as the 2022 summer heat waves, are occurring sooner and to larger degrees than previous projections indicated, revealing the conservative nature of the predictions. The Intergovernmental Panel on Climate Change (IPCC) makes it clear that the frequency and intensity of some extreme weather and climate events have increased as a consequence of global warming and are predicted to continue to increase under current emission scenarios. However, there is still low confidence in predictions of extreme events.

Figure 2 shows that within all regions, winter rainfall (mm) and temperature (ºC) are predicted to increase, presenting a movement towards wetter and warmer winters. Data for the summer projections show decreased rainfall and increased temperatures, with the 95^{th} percentile showing upper limit temperature increases of 3-4ºC in all three regions. The graphs in Figure 2 show daily average rainfall and temperature so do not show the frequency of extreme events such as drought or flooding. Comparing the three regions:

- The east is projected to remain the driest region.
- The north is projected to remain the wettest region, with upper increases of over 1500mm in winter rainfall in 2080-2099.
- The west is projected to have the warmest summer temperature range with projections of 12-20 ºC for average summer temperature in 2080-2099.

[5] Including The Department for Environment, Food and Rural Affairs (Defra), the Met Office, The Department for Business, Energy and Industrial Strategy (BEIS), the Environment Agency and a peer reviewed panel.

[6] Representative Concentration Pathways (RCPs) present scenarios for four changes in temperature by 2081-2100, these are averaged at 1.6ºC (RCP2.6), 2.4ºC (RCP4.5), 2.8ºC (RCP6.0) and 4.3ºC (RCP8.5). The RCP values are linked to targets for the total radiative forcing (the difference between the incoming and outgoing radiation at the top of the atmosphere) with targets for the year 2100 set at 2.6, 4.0, 6.0 and 8.5 watts per square meters (W m-2).

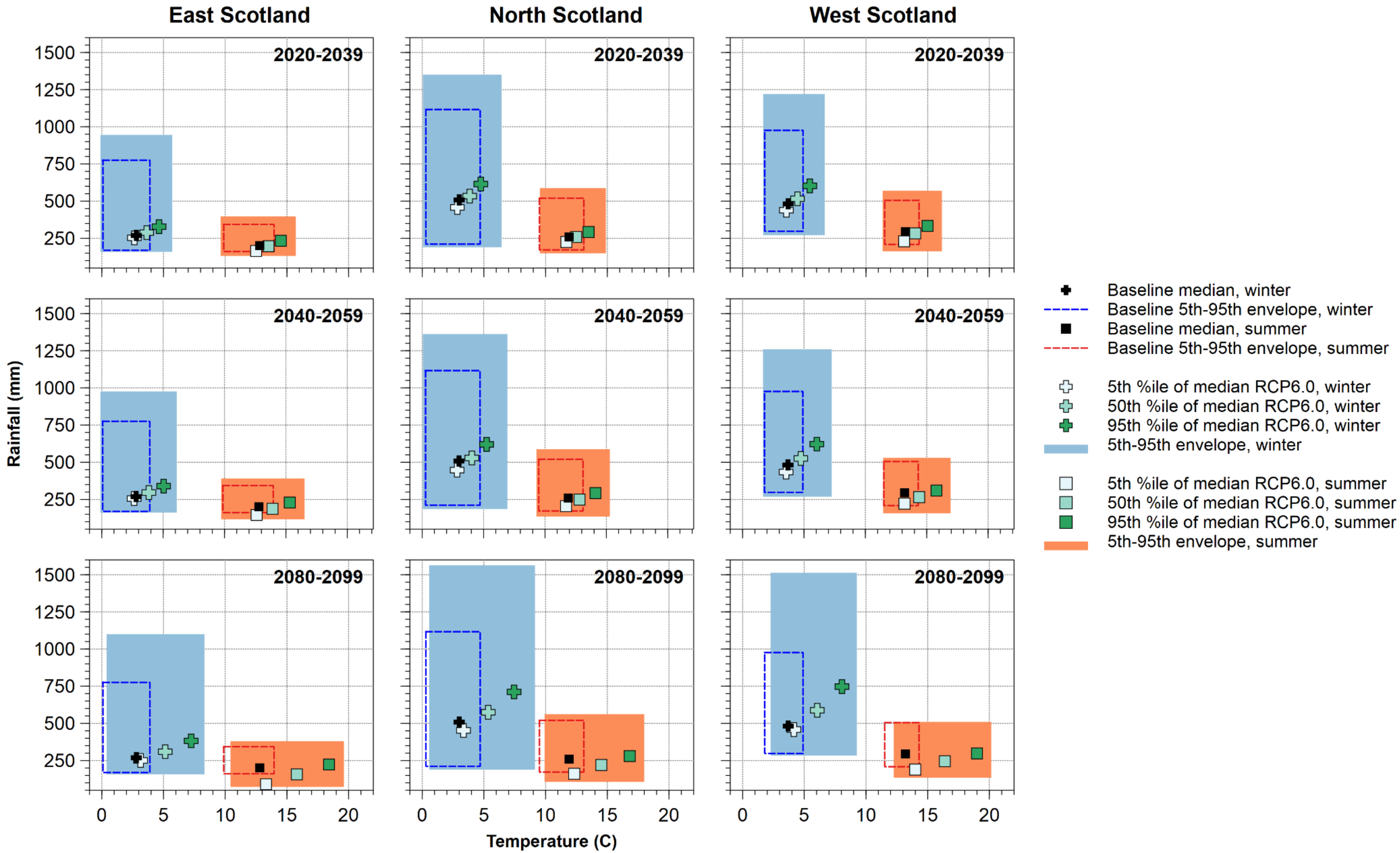

Figure 2. *Box plots showing the daily average range of precipitation and temperature for the East, North and West UKCP18 regions of Scotland. Baseline data is shown by dotted lines for comparison.*

4.2.1 Future scenario implications on farming types

It is likely that future temperature and rainfall will continue to support the same types of agricultural activities as that which are currently practiced. For example wetter and warmer weather will increase grass growth, supporting the livestock industry in dominant areas such as the west and northern regions.

However, the risks of flooding, and severe storms will negatively impact farming businesses. In all regions, hotter, drier summers will impact current crop growing in particular and will provide opportunities for new types of crops to be grown. These opportunities can be optimised as long as adaptive actions are taken. In section 4.3 below, we look for suggestions of possible crops and products from comparable regions, and necessary adaptive actions are explored in section 5.

Extreme heat will provide further challenges for crops and livestock.

4.3 Locating comparable regions

This task located regions around the world currently experiencing climates forecast for Scotland up to 2100 to inform the feasibility of adaptation actions. We used the Köppen climate scale[7].

The Köppen climate scale divides climates into five major types: tropical, dry, temperate, continental and polar which are then sub-divided into Köppen climate classes based on precipitation and heat. The climate projections for Scotland at 2020 (baseline), 2030, 2050 and 2080 (representing 2100) are shown in Appendix 1 (section 9), the Köppen climate classes present in these maps are:

- Cfb: Temperate, without dry season, warm summer
- Cfc: Temperate, without dry season, cold summer
- Dfc: Boreal, without dry season, cold summer
- ET: Polar, tundra

As the maps in Appendix 1 (section 9) show, the majority of Scotland's land cover up to 2030, 2050 and 2080 is temperate, without dry season, warm summer (Cfb), with small areas at a higher latitude largely as temperate, without dry season, cold summer (Cfc). Therefore, the Köppen climate classes Cfb and Cfc were chosen to locate comparable regions.

To identify the regions of interest, we took account of climate (using Köppen climate classes) and latitude. Latitude is critical because it determines daylength characteristics (how daylength varies through the year), which influences suitability for crop production because:

- Daylength influences frost risk, and average timing of first and last winter frosts. For example bananas need 10-15 months of frost free days.
- Daylength change influences the length of the growing season that is suitable for production of a specific crop.
- Plants and animals respond to daylength (photoperiodism).

Daylength will not be influenced by climate change, and there is evidence that seasonal fluctuations in day length play an important role in changes to the distribution range of species (Saikkonen et al., 2012). For example, seasonal fluctuations in Scotland mean day length varies from around 7 to 17.5 hours per day depending on the time of year

[7] https://www.britannica.com/science/Koppen-climate-classification

(Sunrise, 2022). We did not find evidence that allowed us to define the latitude limits for world regions that could grow similar crops to Scotland in future climate scenarios.

Therefore, we restricted this research to the latitude range of the British Isles: between 50° north, in line with the southernmost point of the Isles of Scilly, and 62° north, in line with the northernmost point of Shetland. Details of the methodology are outlined in Appendix 1.

The following regions have been identified as being comparable (as presented at a global scale in Figure 2 and a European scale in Figure 3 below):

- Northern Europe including England, Northern Ireland and Wales, Northern France, Ireland, Belgium, Denmark, Germany
- Parts of western Canada and southern Alaska
- Parts of southern Chile
- Auckland Island, southwest of New Zealand (up to 2040)

Figure 2 shows that very few areas were identified on a world scale. It is our view that this is to be expected because Scotland is already warm relative to other parts of the world at similar latitude, due to the warming influence of the Gulf stream and the north-Atlantic current. Therefore, there are few, if any, world regions that are warmer than Scotland and at a similar latitude.

The food and drink grown in a particular region reflect the dominant cultures of that area. It is therefore important when looking for future crops and livestock that the social acceptance and/or demand of that crop is considered. Interestingly, the regions that have similar latitude also have similar food and drink cultures.

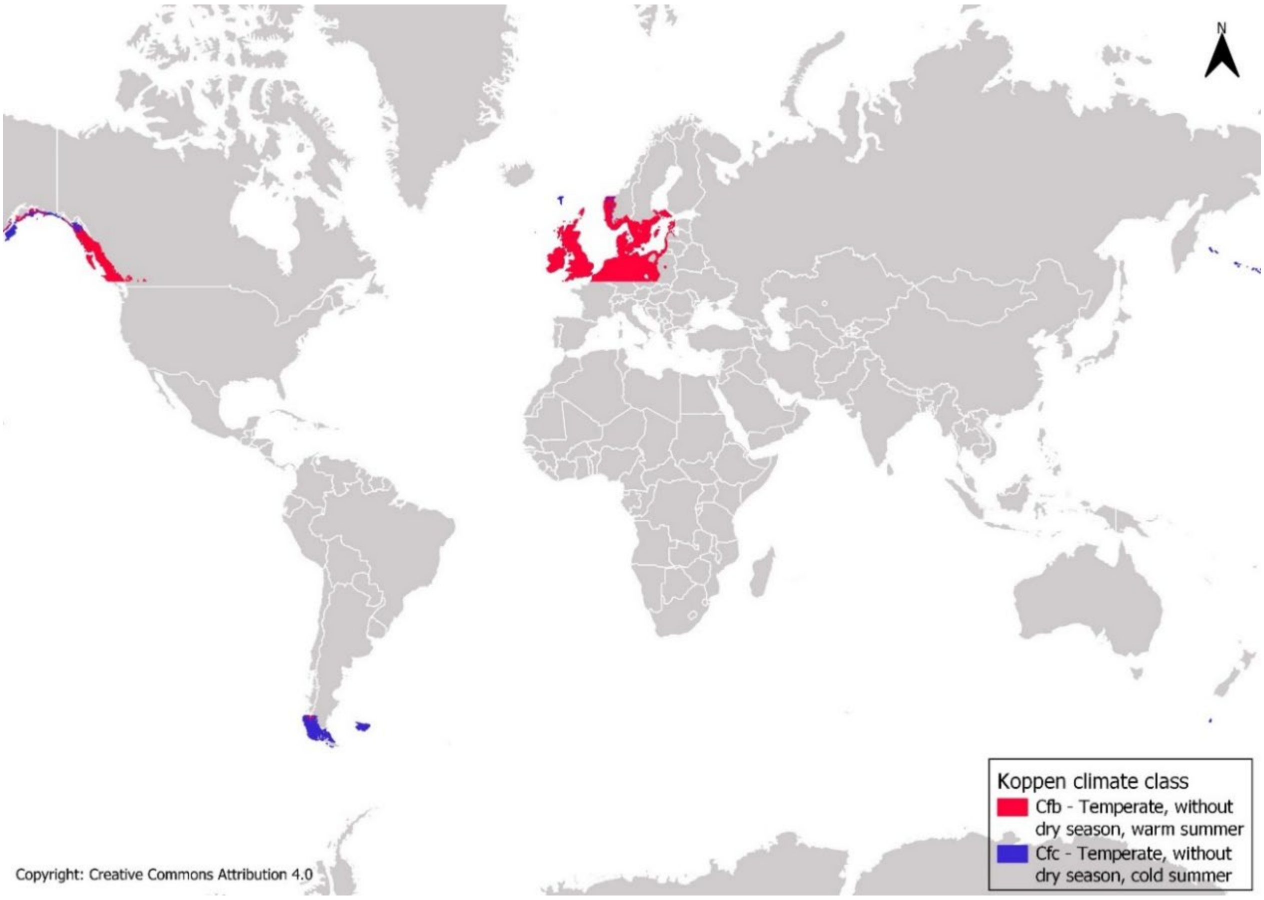

Figure 2: World map showing regions between 50° - 62° latitude which are in the Cfb and Cfc climate classes in the 1981-2010 baseline.

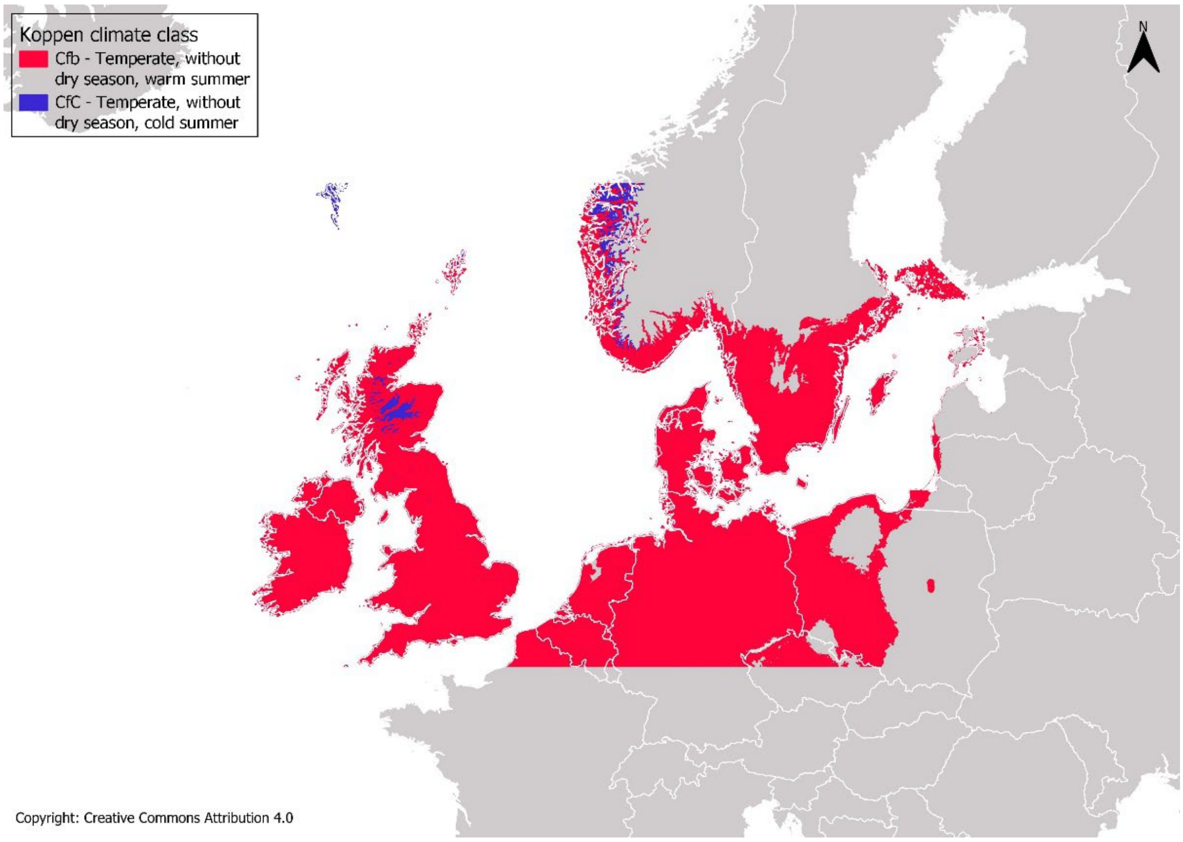

Figure 3: European map showing regions between 50° - 62° latitude which are in the Cfb and Cfc climate classes in the 1981-2010 baseline.

4.4 Agriculture in comparable regions

Denmark, British Columbia and Germany were found to currently have climates considered comparable to where Scotland is projected to be in the future, so can provide examples of agricultural activity that could be feasible in Scotland based on climatic characteristics. We have provided detail on a selection of potential new agricultural activities or products present in these regions that could be expanded in Scotland, alongside reasons of why they would or would not have potential.

Some of the activities are already taking place in Scotland, but there is potential for them to increase with the impacts of climate change. For example, British Columbia has productive beekeeping which could become more successful in Scotland, particularly where the conditions are predicted to become warmer and drier, for example, in the East region (Figure 2).

The success of changes in agricultural activities will not be driven only by climate, but will also be determined by other factors such as the availability of infrastructure, availability of suitable land and demand for products.

Changes to agricultural activity are more relevant to cropping sectors as livestock are more adaptable to a changing climate and actions can be introduced to support this, for example by introducing more shade or shelter. More detail on this is in the following section of the report.

Comparable region	Agricultural activity	Why it would have potential in Scotland	Possible restrictions
Denmark	Oats Denmark harvested 74,750 ha in 2020	Oat production in Scotland has been increasing in recent years. Oats are an alternative to diversify a rotation and as a break crop for control of disease such as Take All (SFAS, 2022). Increasing oat production would align with the increasing demand for plant based products such as oat drinks. Particularly with the opportunity to make oat drinks with Scottish oats and water.	Distance to oat processing facilities may restrict wide implementation.
	Sugar beet Denmark harvested 33,200 ha in 2020	Sugar beet was reintroduced to Scotland in 2021 for bioethanol. Other opportunities include sugar production and livestock feed. Successful trials have been undertaken in the East. For successful adoption, farmer co-operatives are encouraged (SRUC, 2021).	Distance and availability of processing facilities may restrict wide implementation.
	Seed production Denmark produces 50% of all grass and clover seed in the EU.	Production in Scotland would open opportunities for Scotland to be involved in the non-EU market. Seed produced in Scotland will be climatised to the conditions, so have the potential to be more successful (Seed Sovereignty, 2018).	Not suitable for wet conditions, so likely to be better suited to the East region.
	Farmer owned cooperatives (co-ops) make up major food enterprises in Denmark.	Shared investments help overcome challenges with availability to infrastructure and improve the community adaptive capacity. Several farmer co-ops already exist in Scotland, see: https://saos.coop/. Support for these could be further expanded to improve resilience of agriculture, therefore improving its adaptive capacity.	Some farmers are considered 'hard to reach' due to location and/or broadband availability, so may struggle to be involved.
British Columbia	Bees British Columbia's estimated market value from bee related products in 2021 was £21.4 million (GOV.BC, 2021).	Beekeeping, alongside fruit production, produces honey, wax, pollen and pollination. Beekeeping in Scotland is a relatively small and unsupported sector; building on this would create opportunities for the sector to be expanded and farmers to produce new products/diversify. Warmer, drier summers would produce more honey and support wider pollination.	Concerns over growing pests for bees and restricting invasive varieties would be key.

Comparable region	Agricultural activity	Why it would have potential in Scotland	Possible restrictions
Germany	Hops Germany is one of the largest hop producers in the world.	The James Hutton institute undertook hop trials in Scotland (2014-2018) concluding hops would be a feasible option for Scotland, particularly with the growing interest in craft beer (Hutton, 2018).	A very different type of agriculture to integrate into existing farming systems, may be a challenge to gain farmer acceptance.
	Apples Germany harvested 33,980ha in 2020.	70% of apples eaten in the UK are imported, estimated to be worth around £230 million. Orchards and soft fruit production is mostly in the East and is likely to remain suitable in this area in the future.	Permanent crops can be problematic for tenant farmers due to contract arrangements. High initial investment and processing costs.

5 The current state of confident knowledge - gathering data and evidence.

We found adaptation actions for agriculture in Scotland using a Rapid Evidence Assessment (REA) of peer-reviewed and grey literature (for methodology, see Appendix 2). This evidence was supported by expert knowledge of the project team.

The evidence review found recommendations for on-farm actions that are available and feasible for implementation in Scotland up to 2030, 2050 and 2100, to support climate adaptation. The CCRA3 report for Scotland was a key resource for this task. It identifies the climate change risks for Scotland, scoring the magnitude of these and identifying where more actions are required to address these risks. An example of this includes a high magnitude score against the increase in the range, quantities and consequences of pests, pathogens and invasive species.

5.1 Adaptation actions relevant to Scotland

Agriculture is affected by climate change in many ways. The CCC recommends that "(adaptation) actions should respond to risks from flooding, more intense rainfall and higher temperatures, and improve the technological capability of the sector to respond to threats such as changing pest and disease risks."[Error! Bookmark not defined.]

The impacts of these climatic changes will have much cross over between sectors. For example, cropping and livestock will both be impacted by heat stress and increases in pest and disease associated with wetter and warmer conditions. Wetter conditions will impact crop yields through water logging, and livestock will be impacted by reduced animal welfare, affecting fertility and yields of outputs such as milk.

Because of the high number of adaptation actions found in the evidence review, we grouped them based on their similarities. For example, the action group 'Select crop types resistant to extreme weather' includes selecting crop types that are more heat, drought and flood tolerant. Table 3 summarises these action groups by sector, with examples of specific actions. The full list of actions is in Appendix 3, with detail of the feasibility by UKCP18 region and by time period. We analysed the feasibility of actions in Scotland by 2030, 2050 and 2100 for the UKCP18 regions using the results of the mapping task 1, namely output from the Scottish agricultural census and the projected rainfall and temperature data.

The actions found in the evidence review for dairy and sheep sectors are more detailed, reflecting the available data. Actions for livestock more broadly, and for crops, were often vague and did not provide specific detail, such as the species that could be introduced due to their heat tolerance.

We assessed the actions and found most are relevant to all years analysed for this project and all regions of Scotland (more detailed analysis is in Appendix 3, section 11). It is important to be better prepared and to introduce these actions early to increase Scotland's adaptive capacity.

Using the Cairngorms as an example, the maps in Appendix 1 (section 9.1) show it will lose the polar and boreal climate classes as the climate changes. Despite this warming, we assume that the area would not suddenly become suitable for cropping. This is because the success of cropping also depends on the geology and aspect of the area, much of which is hilly, making machinery operations difficult. Therefore, this land would remain suitable for livestock farming. This is likely to apply across Scotland, where land capability is driven by morphology as well and climatic considerations.

We found livestock to be more adaptive than crops. For example, highland cattle adapt their coats depending on climatic conditions, with evidence of them growing shorter coats or shedding more in warmer regions such as Australia. Instead of changing the breed or type of livestock, it would be recommended to make their managed environment more suitable. This includes shearing sheep earlier, improving natural and hard infrastructure to deal with drought by ensuring sufficient water is available in fields, and using tree-belts, wind breaks or buildings to provide shade and shelter.

Figure 1 shows the majority of land cover in the north is used for rough grazing, which is likely to remain the case despite the changes in climate, again linking to the geology and aspect of the land. Existing crops such as barley, which is successfully grown in comparable regions, is not likely to expand due to increased risk profile and reduced resilience to disease and lack of available land. However, other crops found in comparable regions such as oats, sugar beet or apples may be successful instead and in addition.

Adaptation in agriculture is not limited to the individual actions listed here, but also applies to the systems supporting these actions. For example, creating adaptation strategies, appropriate insurance and business resilience plans that link with on-farm mitigation action. The CCC (2022a) made this clear when they recommended that the Scottish Government should:

- **develop a long-term strategy to prepare the agricultural sector for the range of risks and opportunities from climate change.** This would be helpful alongside climate mitigation strategies.
- **develop a structured approach to incorporating the potential impacts from a changing climate into long-term land use planning is essential for land managers to successfully adapt to climate change.** This could include all relevant stakeholders to ensure community engagement and increase the potential for a fair and just transition (CCC 2022b).
- **help increase awareness through owning and supplying necessary information and providing a mechanism for landowners to use it.** This would be helpfully achieved through climate mitigation and adaptation advice being provided in tandem.

Table 3: Actions to support climate adaptation for farming in Scotland showing feasibility for the three time periods. 2030, 2050, 2100 and three UKCP18 regions of Scotland. More detail on the actions is in Appendix 3.

Sector	Action grouping	Feasibility by 2030, 2050, 2100	Feasibility (UKCP region)
Cropping (arable and horticulture)	Select crop types resistant to extreme weather	All years	All
	Adjust management strategies (changes to intercropping and crop area, crop diversification, introducing fire precautions)	All years	All
	Changes to inputs (fertiliser, herbicides, and pest/disease treatments)	All years	All
	Adjust planting/harvesting dates (altering timing to suit weather conditions, planting short-season varieties)	All years	All
	Adjusting water management (low-cost water management, improving drainage)	All years	All
	Adjusting soil management (changes to tillage, introducing soil conservation)	All years	All
	Off-farm actions (climate risk management, genetic breeding, insurance, advice)	All years	All
	Diversity of farm outputs (agroforestry, agri-voltaics, growing legumes)	All years	All
General livestock	Adjusting livestock handling to suit climatic conditions (moving/handling in the mornings or evenings when it’s cooler, modify stock routes and moving distance and consideration of land conditions to reduce wider impacts of soils)	All years	All
	Adjust housing design to suit climatic conditions (housing during extreme weather when they are not typically housed, installing cooling systems such as fans or sprinklers)	All years	All
	Adjust pasture management to suit climatic conditions (providing shade, moving livestock away from flood or drought tolerant areas, mob grazing, lower intensity)	All years	All
	Selecting resilient species more tolerant to pests and diseases.	All years	All

Sector	Action grouping	Feasibility by 2030, 2050, 2100	Feasibility (UKCP region)
	Off-farm actions to strengthen climate resilience (genetic breeding for desirable traits, pest/disease monitoring, introducing insurance schemes)	All years	All
	Adjusting feeding strategies (improving access to water, position feeders in the shade, match stocking rates to available resources)	All years	All
	On-farm monitoring to strengthen climate resilience (increased frequency of checking herds for signs of illness or stress)	All years	All
	Changes to the farming system (introducing a mixed system and/or agroforestry)	All years	All
Dairy	Timed insemination protocol to avoid times of heat stress	All years	All
	Pasture-based dairy systems, or increased duration of grazing	All years	All
Sheep	Fly-spraying pre-sheering	All years	All
	Weaning lambs earlier	All years	All
	Early shearing to avoid blowfly peak in warmer conditions	All years	All
	Introducing whole flaxseed into sheep diet has been shown to help immune function and physiological responses	All years	All

5.2 Key gaps in the evidence

Climate adaptation research has typically focused on urban areas in the global north and on agricultural production in global south countries, with less information available for countries that have agricultural economies similar to Scotland. There is much to be learnt from this research, but due to the implications of different latitudes and therefore day length and frost on agricultural production, comparisons must be made with caveats. These caveats would depend on the individual farming system and testing of the adaptation actions with on-farm pilot trials before widely implementing them. The effectiveness of adaptation actions will also depend on the regional conditions, as detailed in Section 4.2. We have made some analysis on the feasibility of actions in the UKCP18 Scottish regions, and the priority region in Appendix 3, Section 11.

There is information on recommended or proposed adaptation actions, but less on actions that have been implemented and succeeded. As climate change continues to impact both with extreme events and more continuous change, it makes measurement of success of adaptive measures difficult as the base continually shifts. Some adaptation actions may also not be implemented as farmers and others continue to deal with more immediate pressures.

The risk of pests, parasites and disease due to warmer, wetter winters is of particular concern. Avian flu in 2021/22 for example, has had a pronounced impact on both the wild bird population and on the logistics and day-to day activities of poultry farming across Scotland. The CCRA3 identify 'important knowledge gaps' in this area, while pointing out that invasive and non-native species (INNS) costs could be around £240 million/yr. At the same time, there are pests and diseases that have not made it to Scotland but are limiting agricultural production in England. For example, the Bruchid Beetle is a problem for growing field beans and broad beans in England and is likely to come to Scotland as temperatures warm further.

Food and beverages is financially the largest sector of Scotland's international exports, worth £6.6bn in 2019[1], revealing the importance of international trade to the success of the industry. The sector is characterised by long distribution networks, including limited transport hubs and processing opportunities which further compound the sector's climate sensitivity. The implications of climate change on international trade are not well studied which leads to a low adaptive capacity as there are few adaptation actions identified or in place.

We were surprised not to find more information on soils and their contribution to climate adaptation. There is potential to expand on our understanding of Scottish soils in this context, and this would also support biodiversity adaptation and climate mitigation due to improved carbon sequestration and retention.

According to the CCRA3, sufficient data is not currently available on direct water abstractions by businesses (across all economic sectors) in Scotland. Water scarcity risks across all sectors require further investigation due to significant gaps in analysis with the magnitude of risk being low now, but medium to potentially high in the future. This can also be extended to problems that will arise due to heavy precipitation events and water quality issues.

5.3 Areas of active debate

Many adaptation actions have been identified in Europe for arable and horticulture (e.g. Zhao et al., 2022), showing the variability of climate change impacts. Some actions had conflicting outcomes. For example, some parts of Europe reduced tillage, whilst others were increasing tillage (including deep tillage). Changes to inputs were also variable, with introducing, increasing and decreasing inputs of fertiliser, irrigation, herbicide and pest/disease treatments found across different parts of Europe.

As detailed in the CCRA3, some adaptation measures conflict with achieving net zero land optimisation targets. It mentions conflicts such as intensification vs extensification, or land sharing vs land sparing. The CCRA3 mentions a net zero measure of 'sustainably increasing productivity of crops and grazing to make space for woodland expansion and growing bioenergy crops'. This potentially contradicts others' advice of reducing stocking densities to match livestock numbers to available resources (Renaudeau et al., 2012; Gaughan et al., 2019), or integrating agroforestry in existing farming systems.

The CCRA3 also details conflict between sectors. For example, ecosystem-services solutions such as natural water storage and tree planting are recommended to reduce flooding risks. Yet, farmers are increasing field drainage to reduce field flooding, and evidence suggests that lack of effective artificial drainage in agricultural areas may be increasing flood risk.

The whole of the UK is currently lacking in specific policies to address the implications of climate change for food safety or food security. The magnitude of future risk is high, hence further investigation is required.

6 Adapting Scottish agriculture to a changing climate

6.1 Sectoral analysis

We undertook a sectoral analysis of adaptation in cropping and livestock, showing the strengths, weaknesses, opportunities and threats (SWOT). The analysis is not tied to a specific action, however, where a point is linked to a specific action or action group, this is mentioned. This is due to a high level of cross over between actions within the sectors. For example, in cropping, many of the actions will benefit soil health, water and air quality, whilst for livestock, many actions will benefit animal welfare. A weakness for some actions is the need for time and money to plan the implementation, which some farmers may struggle to do without support. For more detail on the actions and action groups, please see the analysis in Appendix 3, section 9.

The SWOT analysis shows interactions between elements. For example, a threat to adaptation is reluctance from farmers having to adapt themselves to farm in new and unfamiliar ways. However, the opportunity for strategic climate risk management could reduce this by informing and educating farmers about climate change mitigation and adaptation.

We did not find evidence for actions that need to be stopped or replaced. Instead, there are opportunities to expand existing cropping such as oats, or introduce production methods, such as agroforestry, to provide shade for livestock to support their adaptation.

Table 4. Analysis of adaptation in the cropping sector

Strengths	Weaknesses
• Farmers may already be adopting some adaptation actions; further actions can build on what is already being done. • **Adjusting planting/harvest dates and selecting crop types resistant to extreme weather** o allows continued production of crops important to Scotland. o has positive impacts for soil health, water and air quality. • **Fire precautions** create a safer working environment	• **Selecting crop types resistant to extreme weather** may require different processing, such as additional drying with higher energy demands. • **Increasing inputs** increases costs and has negative impacts for soil health, water and air quality and potential GHG emissions.
Opportunities	**Threats**
• Introducing innovative practices will move Scotland to the forefront of climate adaptation. • Generate income stream diversity as different crop species or varieties are selected. • **Selecting crop types resistant to extreme weather** could introduce new food types with a positive impact on food security. • **Strategic actions such as climate risk management** will improve farmers' understanding of climate risks and may encourage uptake of adaptation and mitigation actions.	• It may be challenging for farmers to adapt in ways that are new and unfamiliar. • **Crop types resistant to extreme weather** may not be suitable for all Scottish soil types. • If not already grown in Scotland, seed may be expensive or difficult to access. • **Adjusting planting/harvesting dates** risks misalignment with time of market demand, affecting income. • Adaptation actions require planning to effective and many farmers are already working at full capacity. • Selecting new **crop types resistant to extreme weather** may not align with consumers' tastes or preferences.

Table 5. Analysis of adaptation in the livestock sector

Strengths	Weaknesses
• Farmers may already be adopting some adaptation actions, already increasing resilience; further actions can build on what is already being done. • Improved animal welfare, for example, due to improved shelter from heat and extreme weather, will lead to improved fertility and daily liveweight gain, and greater output of products such as milk. • **Adjusting timing of handling** can create a more comfortable environment for farm workers. • Adaptation actions such as more timely movement of livestock away from flood prone areas will have benefits for soil, water and air quality.	• Many actions require investment. Farmers may not choose to do this without additional support. • Retrofitting **cooling strategies** to existing livestock housing is challenging and costly for old buildings.
Opportunities	**Threats**
• Introducing innovative practices will move Scotland to the forefront of climate adaptation. • Uptake of some adaptation actions can help meet Scotland's GHG emissions goals (e.g. improved animal welfare can lead to increased production efficiency and lower emissions intensity). • **Providing shade through agroforestry** can generate new income streams through selling timber, fruits, nuts etc. • **Strategic actions such as climate risk management** will improve farmers' understanding of climate risks and may encourage uptake of adaptation and mitigation actions.	• It may be challenging for farmers to adapt to ways that are new and unfamiliar. • Adaptation actions require planning to be most effective and many farmers are already working at full capacity with limited time for planning.

6.2 Adapting agriculture – the wider context

Each of the adaptation actions suitable for Scottish agriculture are underpinned by the need to reduce climate change risks. Agriculture does not sit in a vacuum. Therefore, a PESTLE[8] analysis has been done for adaptation to climate change for agriculture in Scotland, and is aligned with the risks identified in the CCRA3 report for Scotland. The full table is shown in Appendix 4.

The CCRA3 identifies the main risks associated with climate change for Scotland and our PESTLE analysis provides context against the following elements:

- The sensitivity to the climate hazard/opportunity: the magnitude to which Scotland is affected by the risk, on a high-low scale.
- Adaptive capacity: off-farm actions providing the ability to adapt.
- Exposure to hazard/opportunity: direct impacts of on-farm risks.

[8] PESTLE - Political, economic, social, technological, legal, environmental

The table below is the outcome of scrutinising each of these three elements through political, economic, social, technical, legal and environmental lenses and against the climate change risks identified in the CCRA3. More detail on these can be found in Appendix 4, alongside the adaptation actions associated with the risks.

Many adaptation actions require a mix of factors to be in place. In this table we have simplified items to one area of focus, but this should not be at the expense of others. The implementation of these actions will then underpin the implementation of the adaptation actions we have already explored.

Political	**Prioritising climate adaptation** is fundamental to the achievement of any of the actions as this underpins the development of system-level forces. This can stimulate the maximising of opportunities, such as longer and warmer growing seasons. **Procurement** has the potential to shorten supply chains, reducing the exposure to international climate events.
	Governance structures can drive provision and use of appropriate insurance, weather warning systems and relevant advice and training. 'Support' can include public regulation or backstops for insurance, financial support for weather warning systems and procurement requirements for advisory services.
	Political support at local and national levels through **funding and encouragement** of the development of decentralised processing and storage facilities and other related infrastructure would support shorter supply chains. It may further increase the potential for product diversity.
	At local, regional, and national scales political support for integrated land-use and community engagement can facilitate larger scale options such as multi-functional land use including temporary floodplains. Governance structures could facilitate this **community dialogue**, building on existing conversations around integrated land-use planning and partnerships.
	Climate mitigation is currently an important feature of government funding and policies. Action on adaptation will be most effective if **mitigation and adaptation are considered together** and with equal importance in policy discourse, as well as when formulating incentives to integrate climate planning within usual farm business planning.
	The combination of these factors points to appropriate **food system planning** to protect businesses, biodiversity and the poorest in society at city, regional and national levels.
Economic	Informed selection of crop and livestock **types more resilient** to adverse weather by farmers and supply chain actors is key to adaptation. This includes **increasing diversity** of processing, finished products and broadening of customer bases.
	Supply chain and government development of appropriate **insurance** and sharing responsibility would provide a safety net for farmers to relieve the worst impacts of intense events.
	Supply chain support for the **integration of adaptation planning** – including water and soil management – within risk analysis and climate mitigation reporting would provide holistic business planning and risk analysis.

Social	**Farming community acceptance** of the need for adaptation planning and implementation has social implications, as some common practices and crop and livestock choices will need to be adjusted.
	Wider society changes to core product demand, such as willingness to replace traditional ingredients with different varieties and/or types of food would support farmers growing a wider range of products, reducing their risk profile and diversifying their income both within seasons and across years
	Individual landowners and farmers increasing their openness to **community engagement** may support increased rural economy and social resilience through shorter supply chains, joint effort on climate issues and better understanding of needs of both parties. This could increase the speed of new practice adoption and reduce the risks of maladaptive practices. This needs to be approached by both bottom up and top-down approaches such as with Integrated Land Partnerships, engaging all relevant stakeholders. The CCC recommends an assessment of the distributional consequences of climate impacts and adaptation in Scotland to assist local authorities and others to consider **fairness** in their climate policies. This can include detail on agricultural production following on from this study.
	For adaptation to be fair and effective, extensive and regular engagement is needed throughout the policy cycle. Scotland's **Just Transition** Commission includes agriculture and should include adaptation within the agriculture context.
	International **food price spikes** are an expected result of climate change. Shorter supply chains with a reduced reliance on imported inputs could support this, particularly since the UK is not expected to experience issues with food availability due to climate change.
Technical	**Further technical development** by farmers and research institutes particular to Scotland's context is crucial. This applies to research of social and economic impacts, provision of advice and knowledge transfer services, implementation of actions on-farm and through supply chains. There is particular need to address the risk of pests, weeds, diseases and invasive species.
Legal	No distinct examples of legal barriers were found during the evidence review, however, there may be barriers such as limited access to better adapted varieties or **intellectual property** rights around climate breeding indices.
Environmental	It is crucial for farmers to **maximise opportunities** when weather conditions are favourable by implementing relevant actions such as water saving practices and protecting soil health. This includes adjusting planting and harvesting times, testing new varieties, creating strategies to save and/or use less water, and integrating renewables and storage into the normal business mix. These activities will create resilience when environmental conditions are less supportive.

7 Conclusions and recommendations

This project analysed Scotland's rainfall and temperature projections up to 2030, 2050 and 2100. Scotland is projected to have wetter and warmer winters and drier, warmer summers, alongside a higher frequency of extreme events.

During the mapping task, we identified that:

- latitude is a critical element for locating world regions comparable to Scotland's projected climate. This is because latitude determines daylength, which in turn, impacts frost occurrence and length of growing season.
- it is important not to consider median values (50th percentile) of climate projections to be averages. This is because the climate is not changing in a linear way. Rather the whole range of values should be taken into account, whilst also considering that extreme events occur outside of these ranges.

In line with the objectives of this project, nearly all of the adaptation actions found during the evidence review have the potential to be available, feasible and implemented before 2030, 2050 and 2100. Examples of actions include selecting crop types resistant to extreme weather, adjusting planting and harvesting dates and adjustment to feeding strategies, pasture management and housing design. Our analysis found the actions would also be feasible in all regions of Scotland. As shown in the mapping task, Scotland is already at the warmer end of the scale relative to its latitude, so it is important to act early to increase its adaptive capacity.

We recommend that adaptation plans are promoted amongst the farming community to better prepare them for the changing climate, that there is a focus on testing and trialling new crops and varieties of crops that are resilient to extreme weather.

The evidence review highlighted many actions are already being done by farmers as they constantly have to adapt to the weather. Adaptive actions are not limited to on-farm actions, but include knowledge transfer and management changes, such as advice provision and early weather warning systems.

We looked at Germany, British Colombia and Denmark to find potential products that Scotland could invest in to work better in a changing climate. These include hops, fruit trees, seeds production, sugar beet and expanding the oat product market into oat drinks. In terms of livestock, these have wider adaptive capacity but sufficient and appropriate on-farm infrastructure such as trees for shelter, sufficient and well placed water and where necessary buildings should be invested in. Further, there is potential to expand bee and honey production.

Climate change is the environmental driver that underpins all the adaptation actions that farmers need to take. Some of the expected climatic changes may have positive impacts on crop and livestock yields but extreme events will have major negative impacts. These both need to be planned for to protect Scotland's agricultural future. It is important to act now to increase Scotland's adaptive capacity, the climate is already changing.

7.1 Recommendations

We recommend the following:

- It is vitally important to integrate adaptation with climate mitigation strategies at national, regional, local and on-farm levels now, given that we are already experiencing extreme weather events and changing weather patterns. This can help to ensure that Scotland can optimise any possible opportunities from warmer weather and longer growing seasons.

- There are opportunities for a wider variety of crops to be grown and longer growing seasons, but they need to be acted on now to maximise their potential.
- Diversity of production systems and products is key to counter invasive pests, weeds, diseases and plants, to increase the adaptive capacity of biodiversity, soil and farming businesses. More varied production systems must be supported with diverse processing opportunities at different scales which would support shorter, more local supply chains and a more resilient food system.
- Case studies for the proposed actions can help farmers look at effectiveness and practicalities in a Scottish context. Case studies would highlight lessons learnt and potential to replicate the actions from other places in Scotland.
- On-farm advice is needed to help farmers understand the impacts of climate change particular to their context, to assist the speedy implementation of relevant actions and avoid maladaptation. Combining this with support for adaptation throughout the supply chain would integrate action within other business priorities and reduce risk throughout the supply chain.
- Community engagement is key to creating a resilient food system and ensuring a just transition when considering adaptation actions. We recommend that wider community engagement occurs on adaptation at the same time as climate mitigation and the broader risks to community are included when thinking about international food price spikes, flooding risks and other relevant issues.
- The CCC recommends an assessment of the distributional consequences of climate impacts and adaptation in Scotland to assist local authorities and others to consider fairness in their climate policies. We would recommend that such a study includes detail on impacts on and of agricultural production following on from this project. Impacts could include water, soil, communities, trade, local food systems, energy use and more, particularly identifying maladaptive risk factors.
- More study is needed on the impacts of climate change on Scotland’s international food and drink trade.

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9 Appendix 1: Mapping methodology

9.1 Agricultural census data

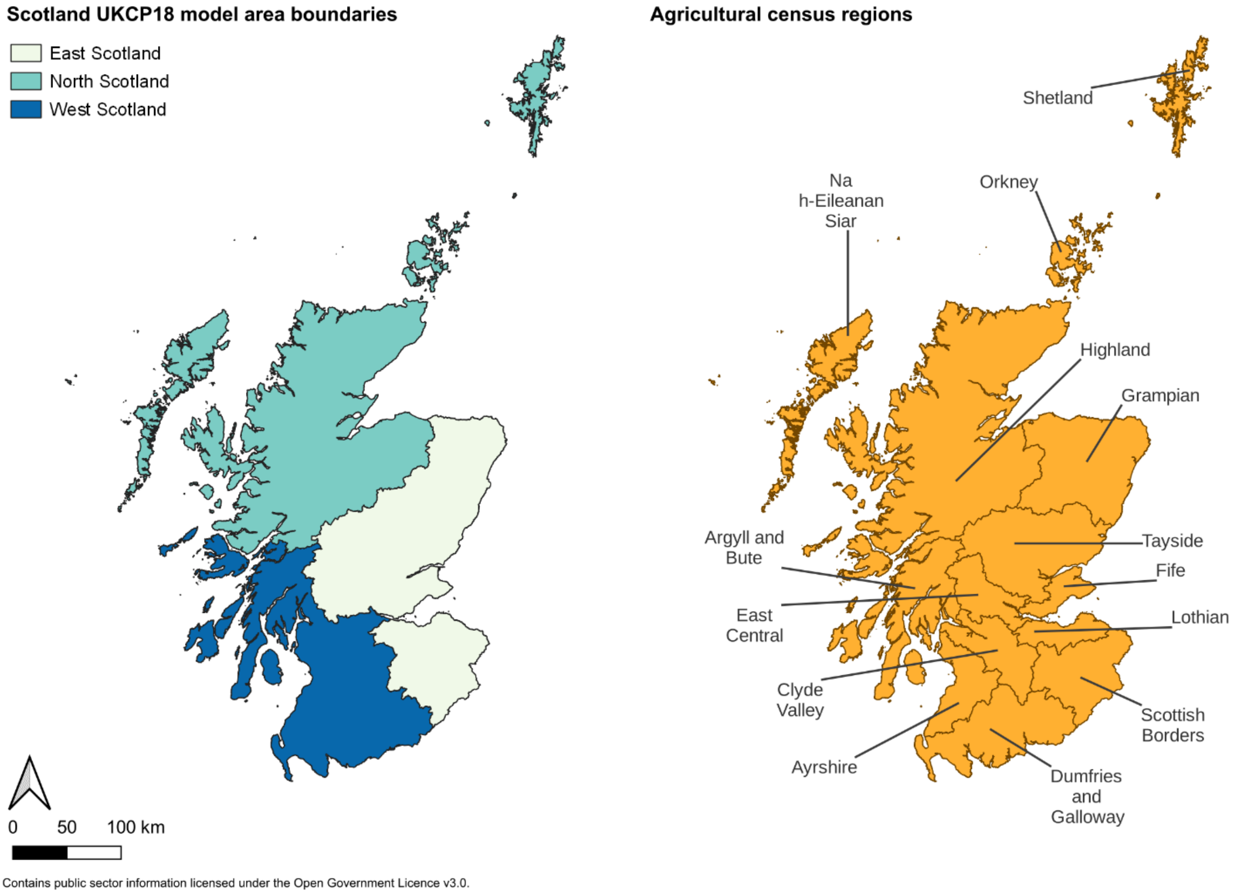

Figure 4: Representation of the Scottish UKCP18 regions, against the agricultural census regions

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9.2 Locating comparable regions

The Köppen Climate Classification categorises the world into five climatic zones (tropical, arid, temperate, boreal and polar). These are then sub-divided based on precipitation type and level of heat.

The map of Scotland below shows the baseline of where Scotland currently sits, largely in Cfb (Temperate, without dry season, warm summer) and Cfc (Temperate, without dry season, cold summer), with small areas of Dfc (Boreal, without dry season, cold summer) and ET (Polar, tundra) in the in the high altitude areas within the Cairngorms.

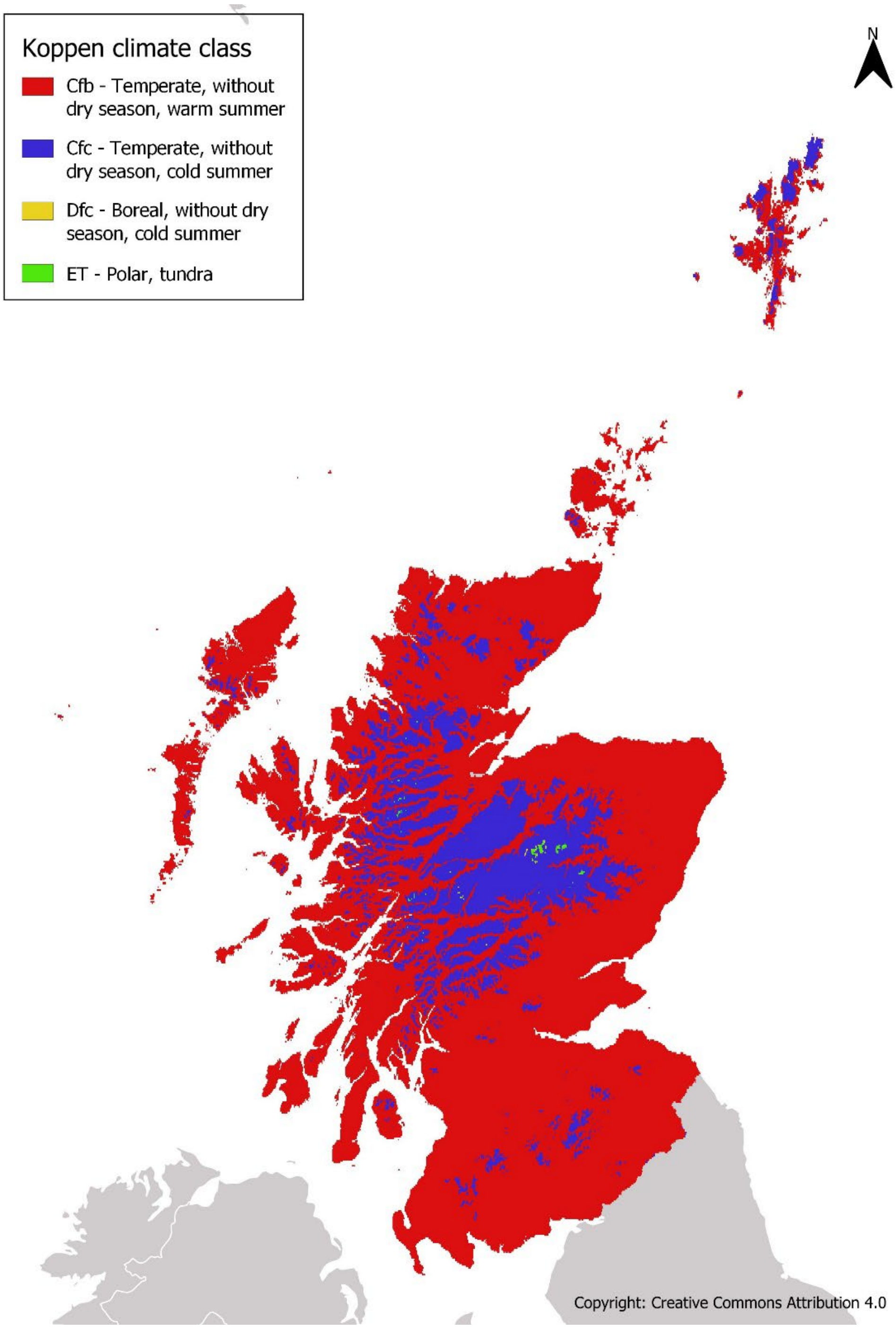

Figure 5: Baseline map of Scotland according to the Köppen Climate Classification System (1980-2010)

Figure 5 to Figure 7 shows the change in projected climate classes from 2030, 2050 and 2080. These projections are based on an RCP8.5 climate scenario, so are considered slightly more severe than the RCP6.0 scenarios analysed for this project. However, it can still be expected that Scotland will lose the Boreal (Dfc) and Polar (ET) classes with more areas of land moving into the Cfb climate class.

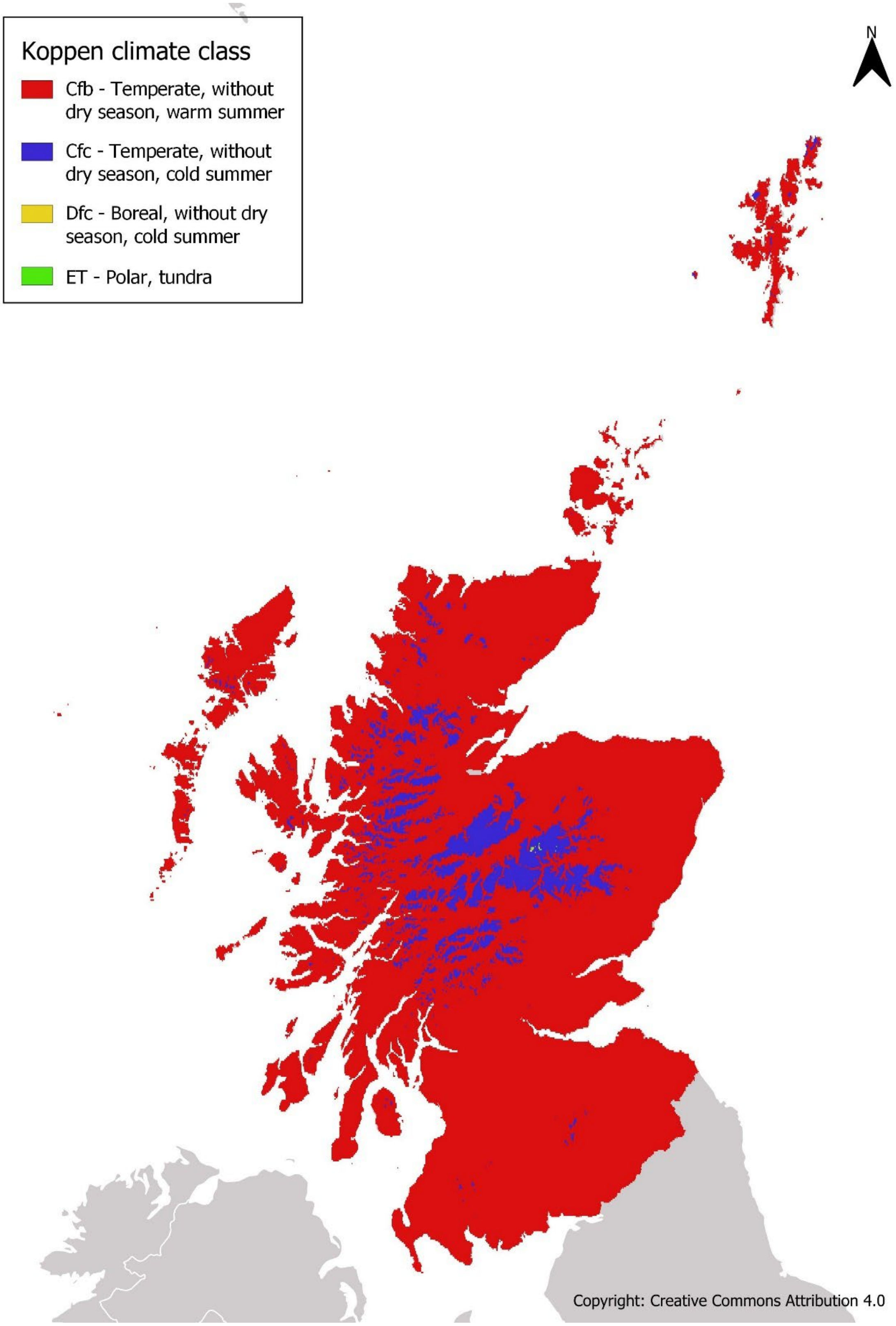

Figure 6: Map of Scotland according to the Köppen Climate Classification System with climates expected in 2030.

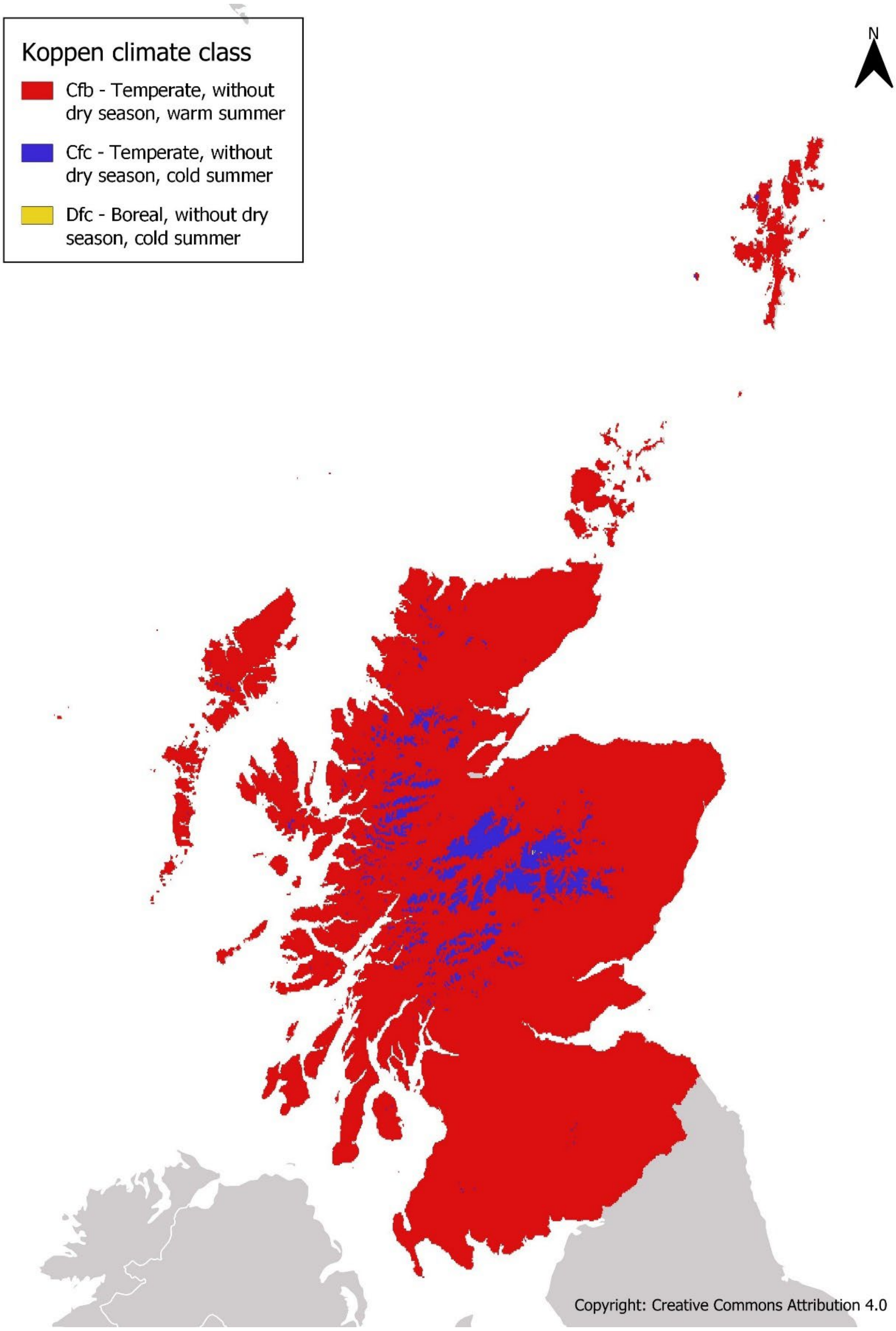

Figure 7: Map of Scotland according to the Köppen Climate Classification System with climates expected in 2050.

Figure 8: Map of Scotland according to the Köppen Climate Classification System with climates expected in 2080.

Through analysis of the current baseline of Köppen Climate classes and projections at 2030, 2050 and 2080 it was decided that Köppen Climate classes Cfc and Cfb should be the focus when looking for areas that have a similar climate to Scotland's projected climate. Climate classes Cfc and Cfb across the world are presented and shown in the world map below.

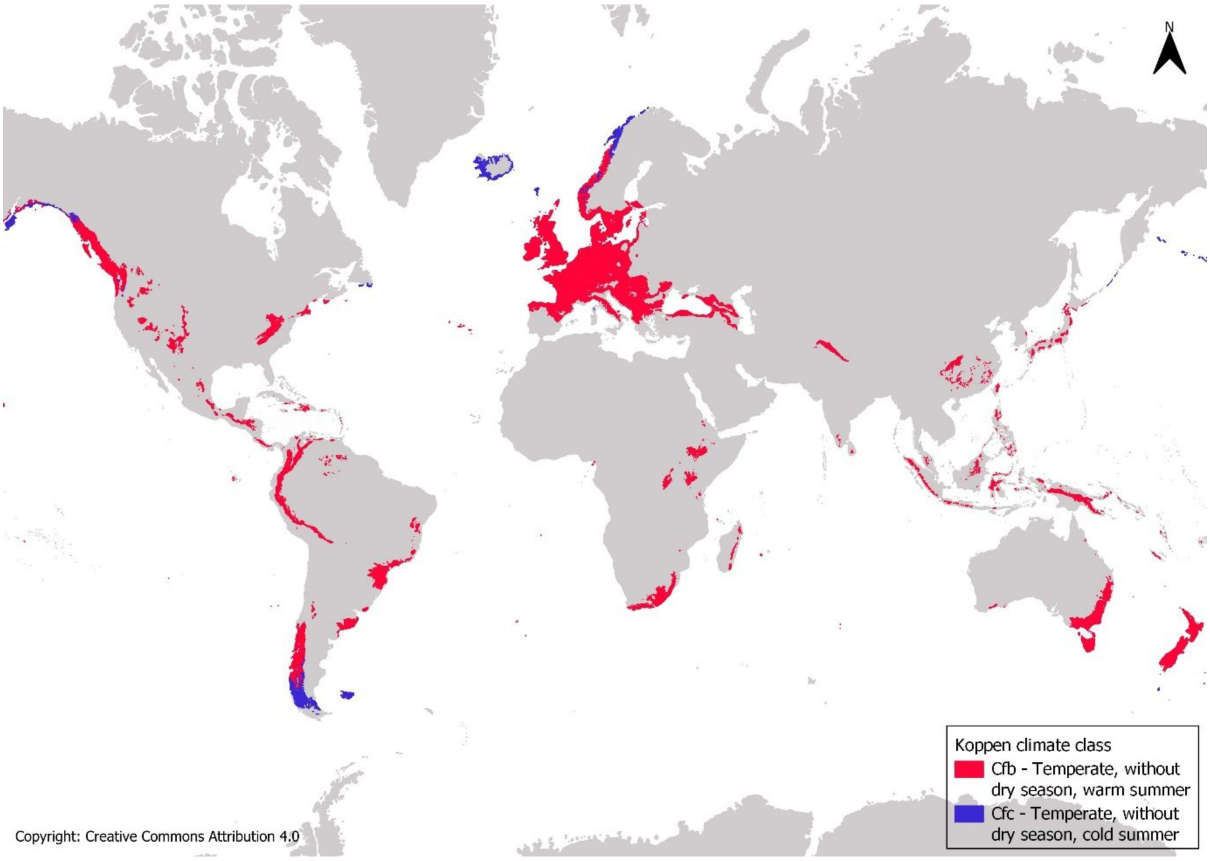

Figure 9: World map showing regions with a comparable climate according to the Köppen Climate Classification System (without latitude exclusions).

As agricultural production is also dependant on length of growing season and prevalence of frost, we further restricted the comparable regions by latitude. We chose the latitude that covers the whole of the UK – from the Scilly Isles to Shetland, providing the final map included in section 1.3 of the report.

10 Appendix 2: Rapid Evidence Assessment methodology

The Rapid Evidence Assessment (REA) methodology used for this project aligns with NERC methodology[9] and comprised of the following steps.

1. **Define the search strategy protocol, identify key search words or terms, define inclusion/exclusion criteria.** To focus the review on the most relevant sources, a list of search terms was created and reviewed by the project steering group (as seen in the supporting spreadsheet). Exclusion criteria was also defined, this included papers relevant to farming systems in the global south or that were greatly different to systems found in Scotland. We also chose to exclude any literature older than 10 years, however, if it was from a credible source, or was felt to add value to the project, it was included. Examples of these are reports from the FAO or UNFCC.
2. **Searching for evidence and recording findings.** Due to the short timescales of this REA, we searched for literature using Google Scholar, utilising our accounts with Science Direct and Research Gate to access restricted pdfs where required**.** For each search, we recorded the date, search string and number of results found, each search string was assigned a reference number. Examples of search strings include:
    a. agriculture practices "adaptation" climate volatility livestock tolerance

[9] https://nora.nerc.ac.uk/id/eprint/512448/1/N512448CR.pdf

b. beef OR cattle drought resistant trials Europe climate resilience case study
c. climate change resilience arable OR cereals farming Europe extreme weather.

The results were recorded in a spreadsheet, with information extracted on the sector, region and adaptation actions. A RAG (red, amber, green) rating was also assigned for each source, based on the following criteria:

Description	Rating
Quality	
Peer reviewed journal, sound data sources and methodology	**Green**
Government funded research reports, sound data sources and methodology	**Green**
Research funded by NGOs (e.g. AHDB), sound data sources and methodology	**Amber**
Work is unreliable because of unreliable data sources, or limited sources, or because the method is not robust	**Red**
Information from websites, blogs etc., of unknown quality	**Red**
Relevance	
Timeframe: within last 10 years	**Green**
Timeframe: within last 20 years	**Amber**
Timeframe: older than 20 years	**Red**

3. **Screening.** Evidence was then screened, initially by title and a selection of sources were screened by the abstract, applying the criteria developed in step 1. This step ensures the relevance and robustness of the evidence that was included in the study.
4. **Extract and appraise the evidence.** Evidence was then extracted from the papers after screening, this included relevant adaptation actions to Scottish agriculture. The literature also helped to shape the views of the project team, supporting information included in the SWOT and PESTLE tables.

11 Appendix 3: Full list of adaptations actions

The following tables present the full list of adaptation actions found during the evidence review, grouped and split by sector. We have indicated the region where an example was found in the literature and stage of implementation. The stage of implementation is represented by a key, showing if there is evidence of the action being done (E), if the action is proposed (P), or if based on expert view there is a high likelihood of the proposed action being done on farm (EV). This is because farmers are constantly adapting to weather impacts and over time, this becomes a climate adaptation action without necessarily being noticed or labelled as one. For example, harvest dates are generally different each year and livestock may be housed for longer if the conditions require it.

We have provided an assessment on the feasibility of the action taking place in Scotland up to 2030, 2050 and 2100 and the feasibility of the action in each of the UKCP18 Scottish regions (north, east, west). Alongside this, we detail if there is a priority region for the action, determined by the Scottish agricultural census data and rainfall and temperature projects as detailed in Section 2. For example, the north and west are projected to be wetter, so would be considered a priority for flooding actions, whilst the east will have lower rainfall, therefore a priority for drought related actions.

Table 6. Full list of adaptation actions for arable cropping.

Action grouping	Action	Example found in	Stage of implementation	Reference	Feasibility (years)	Feasibility (region)	Priority UKCP region
Select crop types resistant to extreme weather	Use of cultivars or crop type with higher temperature requirements and heat resistance	Europe	E	Zhao et al., 2022; Anderson et al., 2020	All	All	East
	Introducing more drought resistant cultivars or crop type (such as fodder beet)	Europe	E	Zhao et al., 2022; Charles, 2013	All	All	East
	Introducing more cultivars or crop type resistant to stagnant water/flooding	Europe	E	Zhao et al., 2022; FAO 2012	All	All	North, West
	Introducing more pest/disease resistant cultivars or crop type	Europe	E	Zhao et al., 2022	All	All	
	Switch to/from Spring/Winter cultivars or crop type	Europe	E	Zhao et al., 2022	All	All	
Adjust manage ment strategies	Changes to intercropping[10]	Europe	E	Zhao et al., 2022	All	All	
	Changes in crop area (increase/decrease)	Europe	E	Zhao et al., 2022	All	All	
	Abandonment in growing the crop	Europe	E	Zhao et al., 2022	All	All	
	Crop diversification	Zimbabwe	E	Mutekwa, 2009	All	All	
	Fire precautions, such as clearing harvesting equipment of chaff, having water available nearby and having phone signal to contact emergency services	UK	E	Salmoral et al., 2020	All	All	
Changes to inputs	Changes to fertilisation frequency[1010]	Europe	E	Zhao et al., 2022	All	All	
	Changes to herbicide frequency[1010]	Europe	E	Zhao et al., 2022	All	All	
	Changes to frequency of pest/disease treatments[1010]	Europe	E	Zhao et al., 2022	All	All	
	Further expanding the uptake of Integrated Pest Management (IPM) rather than rely on current voluntary uptake schemes.	Florida, Scotland	E, P	Sniffer, 2021; Fraisse, 2009	All	All	

[10] Introduced, increased or decreased depending on local climate conditions.

Action grouping	Action	Example found in	Stage of implementation	Reference	Feasibility (years)	Feasibility (region)	Priority UKCP region
Adjust planting/ harvesting dates	Changing sowing dates	Europe	E	Zhao et al., 2022	All	All	
	Changing harvest dates	Europe	E	Zhao et al., 2022	All	All	
	Quicker sowing/planting required if fewer suitable days	Europe, Zimbabwe	EV	Zhao et al., 2022; Mutekwa, 2009	All	All	
	Wider window for sowing/harvest	Europe	E	Zhao et al., 2022	All	All	
	Quicker harvest required if less suitable days	Europe	E	Zhao et al., 2022	All	All	
	Change in amount of post-harvest drying required	Europe	E	Zhao et al., 2022	All	All	
	Planting short season varieties	Zimbabwe	E	Mutekwa, 2009	All	All	
	Altering time of planting/harvesting to better suit soil warm-up rates, soil moisture conditions and water availability	Not specified	EV	McCarl, 2007	All	All	
Adjust water management	Low-cost rainwater harvesting	Not specified	EV	Driedonks, 2016	All	All	East
	Changes to water management[10]	Europe	E	Zhao et al., 2022	All	All	
	Altering tillage practices to conserve water	Not specified	EV	McCarl, 2007	All	All	East
	Improving drainage and sewer systems to reduce flood damage to crops	Taiwan	P, EV	Li et al., 2021	All	All	North, West
	Add flood control such as heightening ridges	Taiwan	P, EV	Li et al., 2021	All	All	North, West
Adjust soil management	Changes to tillage pattern[10]	Europe	E	Zhao et al., 2022	All	All	
	Introduce soil conservation	Europe	E	Zhao et al., 2022	All	All	
Off-farm actions	Climate risk management: provide farmers with timely climate information and/or index based agri-insurance.	China, India, Kenya, and Mexico	E	Loboguerrero, 2018	All	All	
	Genetic breeding for desirable traits	Germany	P	Snowdon et al., 2021	All	All	
Diversity of outputs on farm	Agroforestry can reduce erosion, reduce vulnerabilities from flooding and benefit soil structure and biodiversity.	Europe	E	Mbow et al., 2014a	All	All	
	Agrivoltaics: using solar panels to provide shade for crops and generate energy	Germany	E	Trommsdorff et al.,2021	All	All	
	Growing legumes towards the end of the rainy season when cereals fail due to excessive rainfall.	Zimbabwe	E	Mutekwa, 2009	All	All	North, West
	Growing crops on floating beds. In Bangladesh this is done on beds constructed of materials such as hyacinth. This is possible in places that are known to be waterlogged for 5-6 months at a time.	Bangladesh	E	Chowdhury, 2017	All	All	North, West

Adaptation actions for livestock include changes to handling, housing, pasture, feeding and species or breed selection.

In the case of selecting or breeding breeds to suit warmer temperatures, we found the example of Bonsmara cattle. This breed was created by crossbreeding trials between British beef bulls (including Herefords and Shorthorns) and Afrikaner cows to create a breed suitable for grazing in a sub-tropical climate such as South Africa. The trials began in the late 1930s and over 20 years, the Bonsmara was created. The breed is suitable to harsh, drought tolerant conditions, and said to have a calm temperate for easy handling and providing a high quality meat output[11]. Bonsmaras are found in South Africa, Australis and North America and are not found in comparable regions to Scotland. It is unlikely they will be suitable for these regions, but it does provide an example of successful genetic breeding.

Table 7. Full list of adaptation actions for general livestock

Action grouping	Action	Example found in	Stage of implementation	Reference	Feasibility (years)	Feasibility (region)	Priority UKCP region
Adjusting livestock handling to suit climatic conditions	Change timing of operations, for example, avoiding moving/handling in the mornings or evenings when it is cooler to avoid heat stress.	Not specified	EV	Renaudeau et al., 2012; Hassen and Dawid, 2021	All	All	East
	Modify stock routes and distances	Not specified	P, EV	Hassen and Dawid, 2021	All	All	
	Transhumance (moving livestock in a seasonal cycle)	Africa	E	Idrissou et al., 2020	All	All	
	Alter the timing for finishers to avoid heat stress	USA	P, EV	Janowiak et al., 2016	All	All	East
Adjust housing design to suit climatic conditions	Housing livestock during periods of extreme weather when they are not typically housed	UK	P, EV	Wreford and Topp, 2020	All	All	
	Introducing cooling strategies to housing, such as: fans, sprinklers, cooling pads, misters and improved ventilation	UK	P, E	Wreford and Topp, 2020	2050	All	East
	Fitting LED lighting to reduce heat sources	USA	P	Janowiak et al., 2016	All	All	
	Alternative bedding material if drought reduces the availability of straw bedding	UK	E	Salmoral et al., 2020	All	All	East
	Extra livestock housing	UK	E	Wheeler and Lobley 2021	All	All	
	Building design, east to west to reduce sunlight and perpendicular to prevailing winds to better capture the breeze.	Europe	p	Pardo and DelPrado 2020	All	All	
Adjust pasture management to suit climatic conditions	Provide shade through tree planting or building shelter using materials such as white galvanised or aluminium	UK	E	Wreford and Topp, 2020;	All	All	

[11] https://www.thecattlesite.com/breeds/beef/70/bonsmara/

Action grouping	Action	Example found in	Stage of implementation	Reference	Feasibility (years)	Feasibility (region)	Priority UKCP region
	Move livestock grazing away from areas that are drought or flood tolerant	UK	P, EV	Wreford and Topp, 2020	All	All	
	Planting shelterbelts or introducing agroforestry to act as wind breaks and shelter belts	UK	P, EV	Wreford and Topp, 2020	All	All	
	Increase pasture drainage, benefits include reducing the habitat for liver fluke host snails.	Scotland	P, EV	ClimateXChange, 2016a.	All	All	North, West
	Reduce over grazing and land degradation by altering grazing patterns or timing of grazing	Europe/ North America	P, EV	Gaughan et al., 2019; Skuce et al., 2013; Jacobs et al., 2019; Climate hubs USDA Adaptation Workbook. (n.d.)	All	All	
	Spare fields with a good supply of grass to build resilience for potential hay and silage shortages	UK	P	Salmoral et al., 2020	All	All	
	Create cow tracks to reduce soil and grass compaction	UK	E	Wheeler and Lobley 2021	All	All	
	Mob grazing	UK	E	Wheeler and Lobley 2022	All	All	
	Fencing and multiple gateways to reduce poaching	UK	E	Wheeler and Lobley 2021	All	All	
	Keeping livestock off pastures to leave forage for dry periods	USA	P	Janowiak et al., 2016	All	All	
Selecting resilient species	Choosing livestock species/breeds that are, for example, more tolerant to heat	UK	P	Wreford and Topp, 2020	2050	All	East
	Choosing livestock species/breeds that are more tolerant to pests/diseases	Not specified	P	McCarl, 2007	All	All	
Off-farm actions to strengthen climate resilience	Genetic breeding or crossbreeding, for example for heat tolerant traits such as coat colour and thickness.	UK	P	Wreford and Topp, 2020	2050	All	East
	Using Artificial Insemination to control breeding and reduce cow size (so less forage is required)	UK	P	Wheeler and Lobley 2021	All	All	
	Pest/disease outbreak monitoring programmes	Not specified	P, EV	McCarl, 2007	All	All	

Action grouping	Action	Example found in	Stage of implementation	Reference	Feasibility (years)	Feasibility (region)	Priority UKCP region
	Climate risk management: provide farmers with timely climate information and/or index based agri-insurance.	China, India, Kenya, Mexico	E	Loboguerrero, 2018	All	All	
	Improving local genetics through crossbreeding with heat and disease-tolerant species	Not specified	E	Sejian et al., 2015	2050	All	East
	Introducing insurance schemes	Not specified	E	Sejian et al., 2015	All	All	
Adjusting feeding strategies	Improve access to water	UK	P, EV	Wreford and Topp, 2020	All	All	
	Nutritional interventions, such as: Feeding high quality forage, feeding in shaded areas, use of supplementary concentrates	Europe	P,E	Pardo and DelPrado 2020	All	All	
	Alter the timing of animal reproduction to match suitable temperatures and stocking rates to feed availability	North America	P, EV	Climate hubs USDA Adaptation Workbook. (n.d.)	All	All	
	Feeding silage earlier	UK	E	Wheeler and Lobley 2021	All	All	
	Supplementing feed for ruminant cattle with seaweed	Not specified	P	Duarte et al., 2017	All	All	
	Position feeders in the shade	Europe	P,EV	Pardo and DelPrado 2020; Manjunathareddy 2017	All	All	
On-farm monitoring to strengthen climate resilience	Improving animal health, ensuring sick animals are isolated and receive veterinary treatment as required.	Nigeria	E	Sejian et al., 2015; Onyeneke et al., 2019; Manjunathareddy 2017	All	All	
	Increased frequency of checking herds to identify and recognise early signs of illness.	USA	P, EV	Janowiak et al., 2016	All	All	
	Monitor animal temperatures to provide early warning of stress.	USA	P	Janowiak et al., 2016	All	All	
Changes to the farming system	Introducing a mixed crop-livestock system	Ethiopia	E	Hassen and Dawid, 2021; Gaughan et al., 2019	All	All	
	Introduce an agroforestry system to support soil health and biodiversity	Southern Nigeria	P, EV	Ozor et al., 2012	All	All	

Table 8. Full list of adaptation actions specific for dairy

Action	Example found in	Stage of implementation	Reference	Feasibility (years)	Feasibility (region)	Priority UKCP region
Timed insemination protocol to avoid times of heat stress	Not specified	P	Dash et al., 2016	All	All	
Pasture-based dairy systems, or increased duration of grazing to improve resilience.	France	E	Perrin et al., 2020	All	All	

Table 9. Full list of adaptation actions specific for sheep

Action	Example found in	Stage of implementation	Reference	Feasibility (years)	Feasibility (region)	Priority UKCP region
Fly-spraying pre-sheering	UK	E	Wheeler and Lobley 2021	All	All	
Weaning lambs earlier	UK	E	Wheeler and Lobley 2021	All	All	
Early sheering to avoid blowfly peak in warmer conditions	Europe	P, EV	Skuce et al., 2013	All	All	
Introducing whole flaxseed into sheep diet has been shown to help immune function and physiological responses	Europe	E	Pardo and Del Prado 2020	All	All	

12 Appendix 4: PESTLE analysis

A PESTLE analysis has been done for adaptation to climate change for agriculture in Scotland as a whole and rather than do it in a traditional sense, we have aligned it with the risks identified in the CCRA3 report for Scotland. This identifies the main risks associated with climate change for Scotland and we have provided context against the following:

- The sensitivity to the climate hazard/opportunity
- Adaptive capacity
- Exposure to hazard/opportunity
- Adaptive options

Where possible, the adaptation options have been linked to those in Appendix 3, however, some of the adaptation options involve wider, system changes such as strategies and technical support which are outside of the scope of on-farm actions.

Due to the integrated nature of climate change, many of the actions will not link to the themes in the PESTLE analysis, but actions have been assigned a theme where possible. More detail on the PESTLE themes is found in section 6.2.

Table 10. Risk and adaptation action assessment against PESTLE themes (Key: P: political Econ: economic S: social T: technology Env: environment)

CCRA3 Risk (directly or indirectly relevant to agriculture)	Sensitivity of Scottish agriculture to climate hazard/opportunity (magnitude of risk according to CCRA3)	Adaptive capacity (i.e., ability to adjust through use of: economic resources; institutions; technology; information and skills; infrastructure; equity)	Exposure of hazard/ opportunity (i.e., presence in places that could be affected)	Adaptation options (i.e. that reduce sensitivities, increase adaptive capacities, and/or reduce exposure)	PESTLE
Extreme events and changing climatic conditions: temperature change, water scarcity, wildfire, flooding, coastal erosion, wind	**Medium** degree, getting higher at more extreme levels of climate change.	**Low** due to narrow range of crops and livestock grown and products produced.	**High** due to large area of agriculture in Scotland	Select crop and livestock types resistant to extreme weather	**Econ, T**
				Increased diversity (Adjust management strategies)	**P, Econ, S, T**
				Diversity of outputs on farm	**Econ, S, T**
				Fire precautions	**Econ, S**
				Protection of coastal biodiversity to provide a buffer to farmland	**Econ, S**

CCRA3 Risk (directly or indirectly relevant to agriculture)	Sensitivity of Scottish agriculture to climate hazard/opportunity (magnitude of risk according to CCRA3)	Adaptive capacity (i.e., ability to adjust through use of: economic resources; institutions; technology; information and skills; infrastructure; equity)	Exposure of hazard/ opportunity (i.e., presence in places that could be affected)	Adaptation options (i.e. that reduce sensitivities, increase adaptive capacities, and/or reduce exposure)	PESTLE
Extreme events leading to disruption to business supply chains and distribution networks	**Medium at present**, **increasing to high in future** due to several factors including long distribution networks, including limited transport hubs and processing opportunities.	**Low** due to international supply chains are characterised by 'just-in-time' delivery, high efficiency but low redundancy, making them fragile and lacking resilience to disruptions. Given the projected and observed increase in disruptive events, this risk may become higher in the future.	**High** due to importance of international supply chains to Scottish food and drink and tourism industries, all crucial to Scottish agriculture	Selecting crop of livestock types resilient to extreme weather, improving product diversification.	**P, Econ S**
				Making use of early warning systems, to predict, monitor, record, measure, or report supply chain disruption solutions and communicate with suppliers.	**T**
				Expanding firm level insurance coverage of physical risks to supply chains, including innovative solutions such as non-damage supply chain insurance plans/ parametric insurance (e.g. when pay-outs are based on a drought duration index or rainfall data rather than losses) or captive insurance solutions.	**P Econ**
Changing climatic conditions, including seasonal aridity and wetness of soils	**Medium at present, increasing to high in future.**	**Medium** as awareness and availability of availability of technical information has improved. For example, development of improved indicator framework for soil health and soil risk maps. But significant adaptation shortfall needing more action.	**High**, total annual costs of soil erosion by water are ~ £31-50m/yr. Risks to soils will increase due to heavier rainfall events (resulting in erosion, compaction and pollution), and increased soil moisture deficits in summer (leading to loss of soil biodiversity and organic matter).	Integrated land use policy linking land management productivity with soil health and resilience.	**P**
				Integration of adaptation and mitigation strategies based upon long-term planning.	**P**
				Greater technical support on soil can lead to more bottom-up adaptation initiatives based on local contexts.	**T**
Fluvial flooding	**High** degree due to large numbers of water bodies and rivers in Scotland.	Currently **low** due to conflict between high use of land drains and lack of larger scale land use planning	Area of best quality land at risk increasing by 26% by 2050s and 31% by 2080. Crop such as wheat are impacted more by waterlogging than drier spells.	Multi-functional land use such as occasional flood plain areas	**P, S**
				Soil management such as soil conservation	**Env**
				Select crop types resistant to extreme weather	**T**
Increased wildfire risk	**Medium**	**Medium**, Scottish Wildfire Forum and regional wildfire networks help to increase capacity. Need to transfer actions being done in the forestry sector to the agriculture sector.	**Medium**	Fire precautions, such as clearing harvesting equipment of chaff, having water available nearby and having phone signal to contact emergency services	**S, T**
Potentially longer growing seasons	**Medium at present to high in future**	**Low**, there is a significant adaptation gap.	**High** across Scotland but limited by day length, this limitation increases further north.	Select crop types resistant to extreme weather and adjust housing practices	**Econ, S, T**
				Adjust planting/harvesting dates	**T**
				Climate risk management, integrating of climate adaptation skills in farm advisory services	**T**
				Combining mitigation & adaptation strategies	**P, Econ, S**
Drought risk including increased soil moisture deficits and variability in summer rainfall	**Medium**	Currently **low** due to narrow use of appropriate varieties. Creation of new International Barley Hub from 2024	**High** due to importance of malt barley and its low resilience to drought. Good quality arable land will become less suitable due to drought risk	Adjusting water management, particularly to counter or meet increased pressure for irrigation in E Scotland	**Econ, Env**

CCRA3 Risk (directly or indirectly relevant to agriculture)	Sensitivity of Scottish agriculture to climate hazard/opportunity (magnitude of risk according to CCRA3)	Adaptive capacity (i.e., ability to adjust through use of: economic resources; institutions; technology; information and skills; infrastructure; equity)	Exposure of hazard/ opportunity (i.e., presence in places that could be affected)	Adaptation options (i.e. that reduce sensitivities, increase adaptive capacities, and/or reduce exposure)	PESTLE
Increased pests, weeds, diseases and non-native species	**Medium** currently, too high in 2100. NatureScot consider INNS to be the second most serious threat to global biodiversity after habitat loss and one of the top five threats to Scotland's natural environment	**Low**, INNS could potentially cost the UK economy £1.8 billion per year.	**Low**, current strategies do not include sufficient consideration of future climate risks.	Further expanding the uptake of Integrated Pest Management rather than rely on current voluntary uptake schemes.	**Econ, S, T**
				Choosing species that are more tolerant to pest/disease	**Econ, T**
Decreasing yields from rising temperatures, water scarcity and ocean changes globally	**Medium**	**Medium**	According to the CCRA3, up to 2100, the UK is not likely to experience issues with food availability due to climate change. But, as the international food system becomes more exposed to climate related hazards, sharp increases in food prices become more likely. The poorest will suffer in particular.	The development of food systems that are resilient to disruption, rather than focusing on supply chain efficiency, which increases fragility.	**P, Econ, S**

climate X change

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