School of Geography and the Environment

Options Extended Essay

Essay Title: How will climate change impact apple production in Herefordshire, and what adaptation options are needed for this?

Option title: Climate Change Impacts and Adaptation

Word count: 4487

Abstract

In the UK, agriculture is an essential sector because of its importance in the food system and its economic value. Herefordshire is a major farming county in the UK and produces 25% of England's fruit crop, predominantly apples. The agricultural sector is highly vulnerable to the impacts of climate change, and these impacts are not evenly distributed globally. This means studying the regional impacts of climate change on local agricultural sectors is important to investigate impacts and assess potential adaptation options so that crop yield can be protected. This study provides a critical assessment of the projected impacts of climate change in Herefordshire using UKCP18, and how this is likely to impact apple crop production. Following this, several adaptation strategies are evaluated to determine the best steps to protect the apple crops. This essay concludes that climate changes and subsequent impacts cannot be determined conclusively, and therefore adaptation planners in Herefordshire need to look to 'no regrets' or 'win-win' adaptation policies.

KEYWORDS

Agriculture - Apple Crops - Herefordshire - Climate Change - Impacts - Adaptations

1. Introduction

Herefordshire is a major farming county in the UK. The county is located in the West Midlands, where fruit is one of the biggest agricultural crop outputs, with a value of £168 million (DEFRA, 2020). The region produces approximately 25% of England's fruit, with apples being the most predominantly grown crop (Herefordshire Council, 2009). Apple orchards have developed in this area as a result of geology, tradition, and an established infrastructure (Thomas et al., 2016). Farming in Herefordshire accounts for 6.7% of the county's employment (Herefordshire Council, 2009), and thus apple crop yield is important for livelihoods.

A major factor that is likely to affect crop yield is climate change. Since industrial times, human activities have resulted in an exponential increase of greenhouse gas (GHG) concentrations in the atmosphere. By 2017 the planet had already seen a 1°C temperature rise (0.8 to 1.2 at 66% confidence (Allen et al., 2018)) since pre-industrial times because of this (IPCC Special Report, 2018). Climate change, both in means and extremes, is likely to impact meteorological factors in the future. These factors will have widespread and complex impacts on agriculture worldwide (Vermeulen et al., 2012; Gaupp et al., 2019; Ray et al., 2019). These impacts are not evenly distributed across the world, and different regions experience impacts differently. It is therefore important to study the regional impacts of climate change to get an understanding of what the future will look like at the regional scale.

Agriculture as a sector will experience some of the greatest negative impacts from climate change, and in some regions, this has already been the case (Stern, 2007; Porter et al., 2014; Gaupp et al., 2019). In the UK agriculture is an essential sector to maintain because of its importance in the food system and its economic value. It is therefore vital to understand and address the impacts of climate change on crop yield so that appropriate adaptation strategies can be implemented to reduce the negative impacts of such changes. This includes the development of local policies to protect the success of crop growth. As a key region of agriculture in the UK, it is important to understand how climate change will impact Herefordshire and its dominant apple crop, and how such impacts can be prepared for.

This study provides a critical assessment of the projected impacts of climate change in Herefordshire using UKCP18, and how this is likely to impact apple crop production. Based upon previous literature of factors determining the success of the crop, it is likely that apple orchards in the region will experience increased risks and benefits from a changing climate. To follow on from this, several adaptation strategies are evaluated to determine the best steps to protect the agricultural sector and its apple crops.

2. Background: factors affecting apple crop production

To determine how apple crops in Herefordshire are likely to be impacted by climate change, it is necessary to understand the main meteorological factors determining yield in temperate climates. This study looks at the findings of several papers (Table 1) with results from a range of locations (Figure 1) to evaluate the determining meteorological factors.

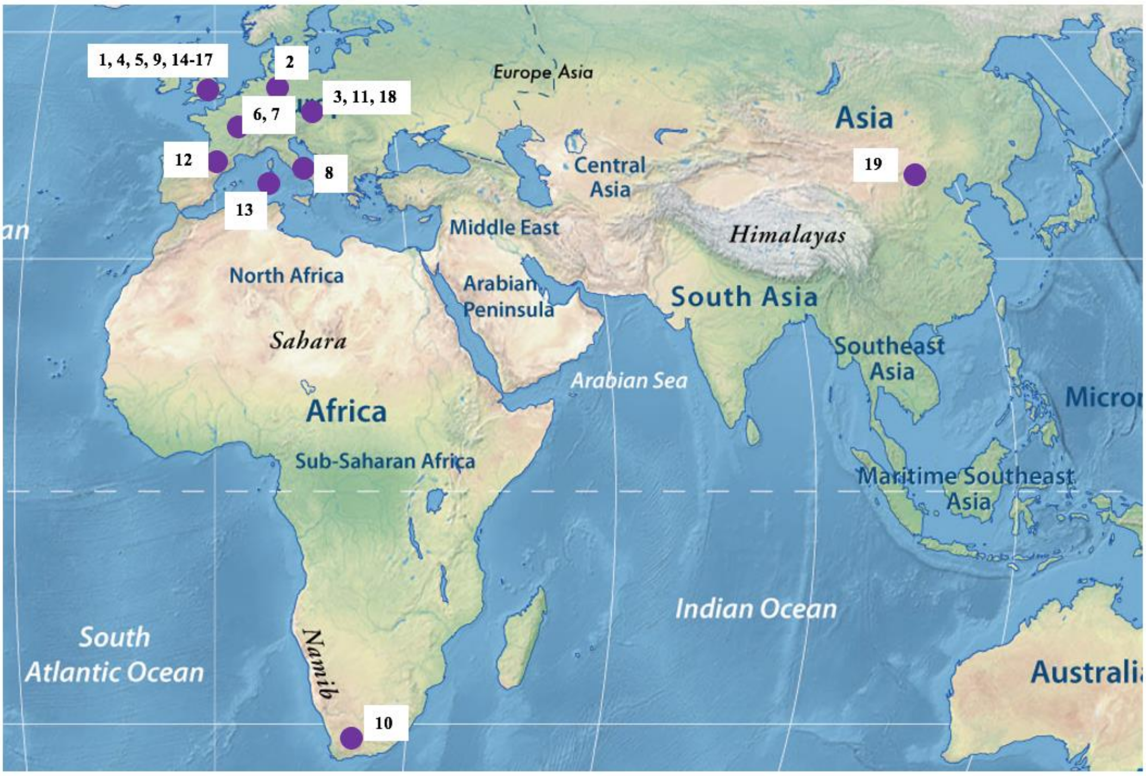

Figure 1 – Map of the different locations considered in this study. The purple dots represent the locations of study sites found in the literature. The site number corresponds to the site number in Table 1. Figure created by the author.

Site	Success Factor	Author	Year	Region	Conclusions
1	Spring frost	Cannell and Smith	1986	UK	Earlier bud blooming may increase the risk of frost damage to trees.
2	Changes to tree pheno-phases	Chmielewski et al.	2003	Germany	Increasing air temperatures of 1°C result in advanced growing and blossoming of trees by 5 days.
3	Changes to tree pheno-phases	Menzel et al.	2006	Europe	Spring/summer advances by 2.5 days per °C.

4	Winter chill	Sunley et al.	2006	UK	There has been a declining winter chill in recent decades.
5	Spring frost	Sunley et al.	2006	UK	Reduced frequency and severity of spring frosts in recent decades.
6	Changes to tree pheno-phases	Legave et al.	2007	France	Global warming has slowed the rate of completion for the chilling requirement and increased the rate of completion for the heat requirement.
7	Changes to tree pheno-phases	Guedon and Legave	2008	France	Changes to flowering dates coincide with increasing temperatures.
8	Spring frost	Eccel et al.	2009	Italy	There is a lower exposure risk of tress to frost as mean temperatures increase.
9	Winter chill	Else and Atkinson	2010	UK	Chill losses might stop trees being able to break dormancy.
10	Changes to tree pheno-phases	Grab and Craparo	2010	South western cape, South Africa	Rising temperatures of 0.45°C/decade in early spring correlate to advances in full bloom of 1.6 days/decade.
11	Winter chill	Campoy et al.	2011	Europe	Advances in spring and summer can be seen as a result of climate change.
12	Changes to tree pheno-phases	Legave et al.	2012	Western Europe	Blooming advances were found in northern continental Western Europe due to global warming.
13	Winter Chill	Funes et al.	2015	Mediterranean subbasin	Increasing temperatures might result in insufficient chilling.
14	Drought	Thomas et al.	2016	UK	Drought in summer affects fruiting.
15	Temperature effects on apple flowering	Thomas et al.	2016	UK	Pollination affected by high and low temperatures. The initiation of flowers is sensitive to temperatures below 30°C.

16	Disease	Thomas et al.	2016	UK	Apple scab and fire blight risk of spreading increases with temperature rise in the summer.
17	Water logging	Thomas et al.	2016	UK	Warm wet winters can lead to tree rot.
18	Spring frost	Unterberger et al.	2018	Europe	Frost risk will remain and might even increase in a warmer climate.
19	Temperature effects	Li et al.	2019	Loess Plateau, China	Spring climate conditions and the effects of temperature are the most important factors in determining crop yield.

Table 1 – A list of literature sources investigated in this study, along with the meteorological factor being studied for the success of the apple crop and their main conclusions. Red conclusions represent risks to the apple crop as a result of climate change. Green conclusions represent benefits as a result of climate change. Yellow conclusions represent impacts of climate change that could be risks or benefits. The site numbers are in chronological order and correspond to the numbers on the map in Figure 1. Table compiled by the author.

From Table 1, the key factors for the success of apple crop production have been identified and summarised into three main themes: phenological phase (pheno-phase) changes, winter chill, and spring frost. There are several other factors that are also potential impacts of climate change, for example, increased apple scab disease in summer (Thomas et al., 2016), but these will not be addressed in this section.

2.1 Pheno-phase changes

Rising temperatures and altered precipitation patterns resulting from climate change have considerably changed the timing of the pheno-phases of apples (Grab and Craparo, 2010). Pheno-phase changes can affect the balance and productivity of ecosystems and has direct and indirect implications that extend to factors including pollination and pest control (IPCC, 2007a; Grab and Craparo, 2010). In general, temperate regions have seen earlier springs and milder autumns because of climate change, which has allowed longer growing seasons for apple crops (Dey et al., 2016).

Mean temperature increases have meant trees now flower several days earlier than previously (Grab and Craparo, 2010). This has been supported by studies across the world and is demonstrated in Figure 2. Chmielewski et al. (2003), Menzel et al. (2006), Legave et al. (2007), Grab and Craparo (2010), and Legave et al. (2012) all provide results from temperature regions showing advances in apple pheno-phases because of earlier springs. The largest advance in spring flowering is presented by Legave et al. (2007) who shows advancement of 7-8 days in France since the late 1980s. While the clear benefit of this is an extended growing season, early spring can cause some indirect risks. For example, it could lead to bees emerging before there is enough food for them, which could cause pollination problems (Thomas et al., 2016).

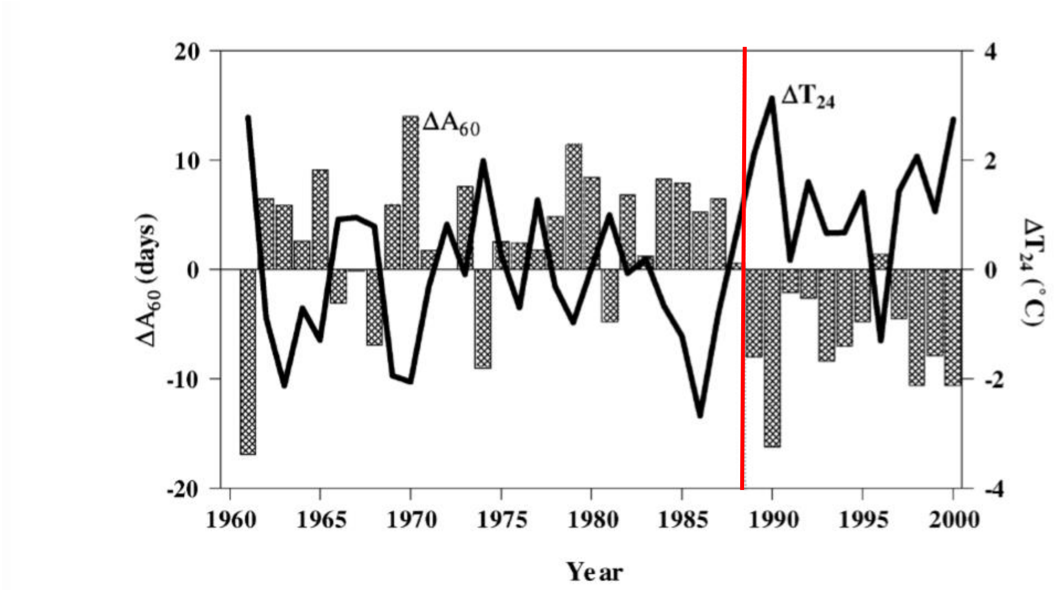

Figure 2 – Anomalies of the start of apple flowering (A_{60}) and the average air temperature from February-April (T_{24}). Results from Germany, 1961-2000. The red line indicates the start of constantly advanced flowering dates and a clearer pattern of regularly warmer temperatures as a result of climate change. There is a clear relationship between years with warmer air temperatures (implying earlier spring) and early dates of flowering. Adapted from Chmielewski et al., 2003.

Previous literature also explores climate change resulting in milder autumns (e.g., Dey et al., 2016). Increased temperatures enhance biochemical reactions within the apple trees and thus extend the growing season of the crop (Chmielewski et al., 2004). This prolonged season enables a higher crop yield, which is beneficial for farmers and has significant economic importance. Although pheno-phase changes to apple crops provide the benefit of extended growing seasons, the changes also present risks. These include issues relating to winter chill and spring frost.

2.2 Winter chill

Apple crops require winter chilling to break full dormancy (Sunley et al., 2006; Else and Atkinson, 2010; Luedeling, 2012; Funes et al., 2015; Thomas et al., 2016; Moser et al., 2020). Dormancy is a phase of development in the annual cycle that protects the tree from unfavourable winter conditions by protecting sensitive tissues (Faust et al., 1997; Campoy et al., 2011). The phase needs to be broken after winter to allow the crop to flower and grow in spring (Moser et al., 2020).

For full dormancy to be broken, winter chilling temperatures need to be met. The literature suggests the crop needs to be at a temperature of approximately 0- 7.2°C for several hours each day (Bennett, 1949; Byrne and Bacon, 1992; Sunley et al., 2006; Luedeling, 2012). Increasing temperatures as a result of climate change can lead to insufficient chilling and therefore crops may not be able to overcome dormancy. A common impact of inadequate chilling is a delay in bud break (Funes et al., 2015). Among other things, this can shorten the growing season and limit the crop yield. This is likely to counteract the longer growing seasons resulting from early springs and mild autumns.

In the UK, winter chill has been studied by Sunley et al. (2006) and Else and Atkinson (2010). Sunley et al. (2006) use chill accumulation models to show a trend of declining winter chill in the UK since the 1950s. Else and Atkinson (2010) also suggest the UK will experience reduced chilling temperatures, which might impact fruit trees to sufficiently break full dormancy. However, they use a chilling requirement of 3-7°C rather than the 0-7.2°C suggested by other literature and provide no quantitative projections of future change.

2.3 Spring frost

Early flowering ensuing increased mean temperatures may increase the risk of damage to apple trees by late spring frosts (Cannell and Smith, 1986; Chmielewski et al., 2003; Legave et al., 2012). Damage from light frosts can lead to the degradation of fruit quality, while severe frost damage may cause the crop to fail completely (Eccel et al., 2009). In April 2016, Styria, the main apple-producing region in Austria, experienced warmer temperatures leading to advanced flowering in early spring (Unterberger et al., 2018). This was followed by a severe spring frost, which caused almost 80% of the regional apple crops to fail (Unterberger et al., 2018).

The literature provides ambiguous conclusions as to how frost risk will change in the future. Eccel et al. (2009) identify “light” and “moderate” frost risk thresholds for apple buds of -1°C and -3°C respectively, and from this show that in IPCC scenario A2 frost episodes mainly increase, and in scenario B2 they decrease. Eccel et al. (2009) conclude that the risk of frost to apple crops in northern Italy will remain the same as in the present day or will decrease slightly in the future. Meanwhile, Unterberger et al. (2018) propose that with increasing temperatures the risk of frost damage to apple crops will remain and or even increase.

2.4 Commentaries on identifying factors affecting apple crop success

This section has focused on the direct and indirect impacts of pheno-phase changes, which are related to mean temperature change. But it is important to note that as a result of climate change, apple crops also have to deal with meteorological extremes. For example, extreme hot weather impacts plant growth as crops have critical average temperature thresholds during the growing season, and if these are exceeded biochemical activities within the crop, such as photosynthetic processes, can be negatively affected (Moretti et al., 2010). Furthermore, extreme low or high precipitation events can lead to drought conditions, causing issues such as root stress (Dey et al., 2016; Thomas et al., 2016), or flooding, causing waterlogging (Vermeulen et al., 2012).

In addition, Primack et al. (2009b) caution generalising pheno-phase changes between sites. Regional differences occur in the impacts of climate change and the responses of apple crops. Therefore, although looking at several sites in temperate regions provides a clear understanding of factors affecting the success of apple crops, the factors in Herefordshire may not be the same or may have different effects. To more accurately assess how climate change is going to impact apple crop production in Herefordshire, the future climate of the area needs to be projected.

3. Climate projections for Herefordshire

In this section UKCP18 (UK Climate Projections 2018) is used to look at the future climate projections for temperature and rainfall in Herefordshire. UKCP18 is part of the Met Office Hadley Centre Climate Programme and provides climate change projections for the UK until 2100 (Met Office, 2021). This study uses the 2.2km scale projection for realistic simulations at a localised area. The RCP8.5 forcing is used, which is a pathway that approximately results in radiative forcing of $8.5Wm^{-2}$ at 2100 relative to pre-industrial conditions (IPCC, 2013). Each plot shows twelve 'members' within the set of local projections. Projections are presented for the periods of 2021-2040 and 2061-2080, with a baseline period of 1981-2000.

3.1 Limitations of UKCP18

Models provide the best available way of studying the climate and making projections about the future (Tyson and Preston-Whyte, 2000). However, models are imperfect tools, and to use them appropriately their limitations must be acknowledged.

Climate projections are based upon future scenarios and future greenhouse gas emissions (van Vuuren et al., 2011). However, the future is extremely hard to predict and therefore all projections have high levels of uncertainty. This study uses the RCP8.5 pathway, however, there is no guarantee that this is the pathway the planet will end up on. Furthermore, UKCP18 does not capture all the possible future outcomes. This is especially true of the local 2.2km projections used in this study, and thus the models have limitations in their simulation of the real world (Met Office, 2021). The local 2.2km projections are convection-permitting models that use downscaling to increase the spatial and temporal resolution of the projections. However, this increases the uncertainty and bias in the models (Kendon et al., 2017).

3.2 Baseline period

A baseline period of 1980-2000 is used to compare future projections to the recent past climate. In this sub-section, plots are produced in Python using ERA5 reanalysis data to show seasonal temperature and precipitation composites for the baseline period. ERA5 is the most recent climate reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020). The dataset uses advanced modelling and data assimilation systems to amalgamate historical observations into global estimates (ECMWF, 2020).

3.2.1 Temperature

Figure 3 shows that mean temperatures differ significantly between seasons in Herefordshire. In winter months, temperatures are 4-5.5°C. Coming into spring temperatures rise to 7- 9°C. Summer months have the highest temperatures of 14-16°C. Temperatures then decrease in autumn to approximately 10°C. Similar patterns can be seen for maximum and minimum temperatures in Figures 4 and 5. For maximum and minimum temperatures, values stay fairly similar to those seen in the mean composites for spring and autumn. However, in winter, maximum temperature ranges from 5-7°C and minimum from 1.5-3.5°C. Furthermore, in summer, maximum temperature is 17-20°C while minimum is 13-15°C.

3.2.2 Precipitation

Mean total precipitation values are presented in Figure 6. Precipitation remains fairly constant all year round, with autumn seeing the highest levels of 180-210mm during the season. Meanwhile, summer has the lowest precipitation, with values from 130-170mm.

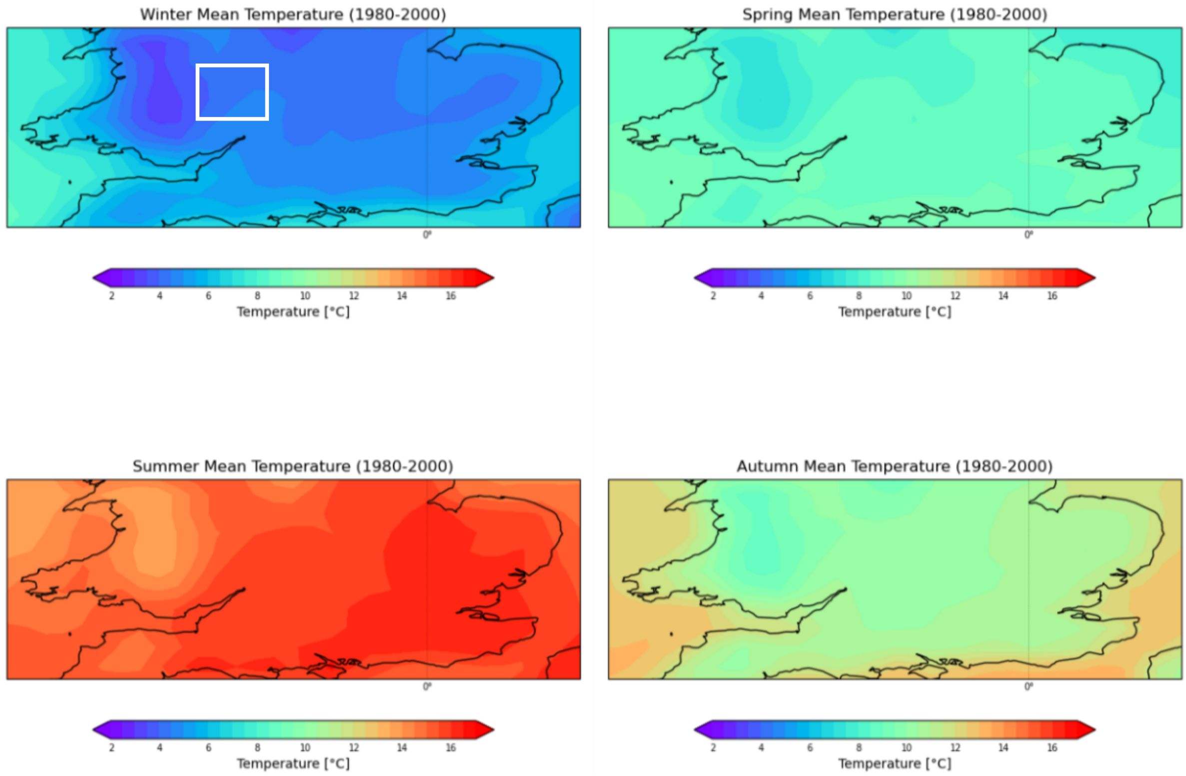

Figure 3 – Seasonal mean temperature (°C) composites for the period of 1980-2000. The white box indicates the county of Herefordshire.

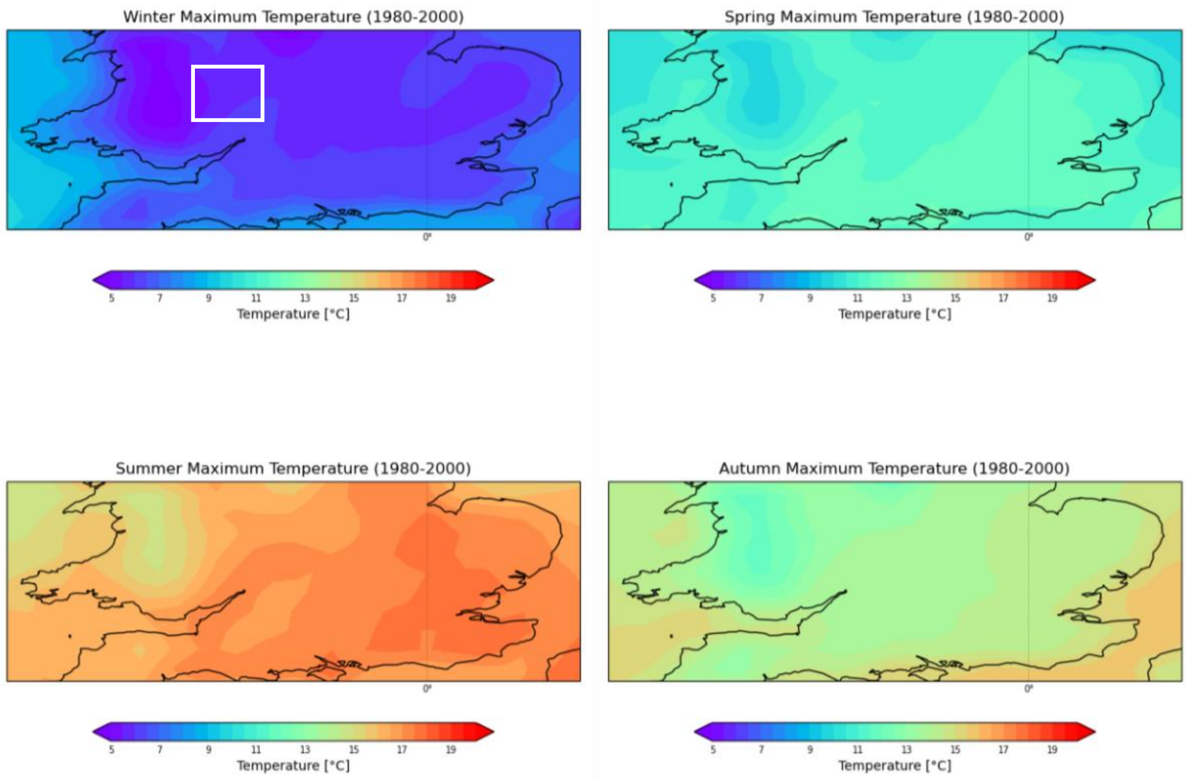

Figure 4 - Seasonal maximum temperature (°C) composites for the period of 1980-2000. The white box indicates the county of Herefordshire.

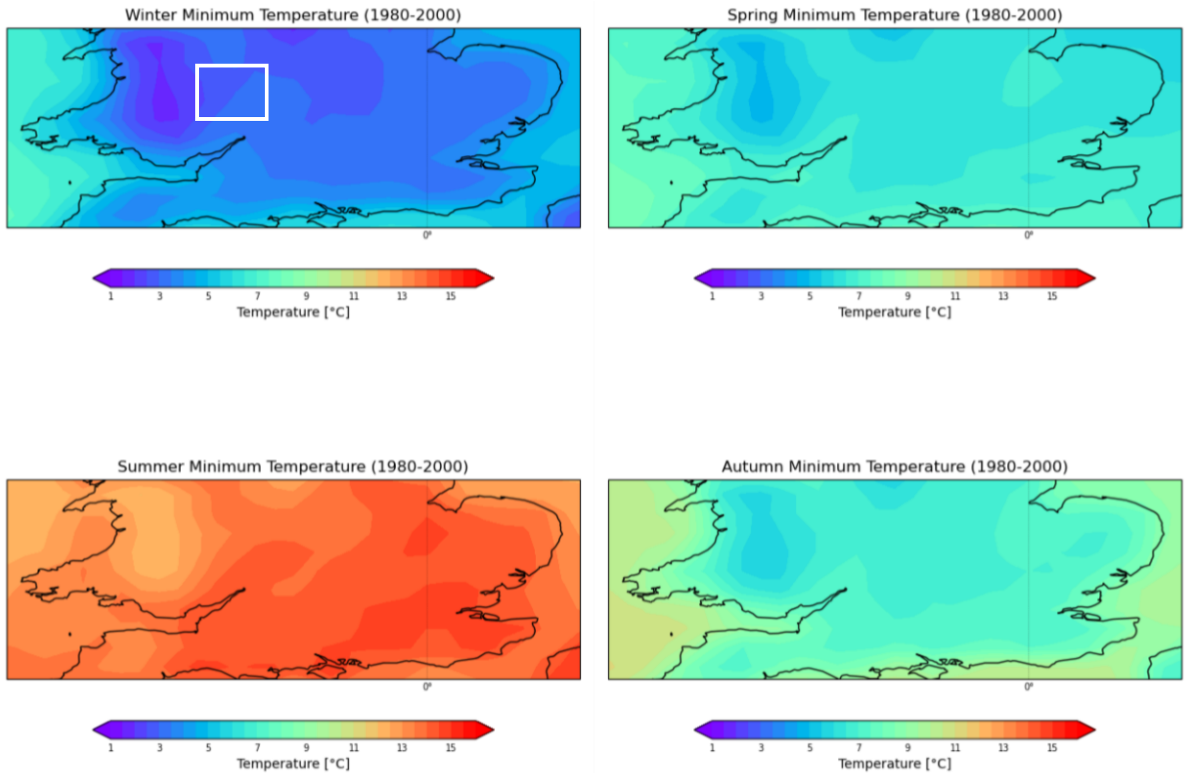

Figure 5 - Seasonal minimum temperature (°C) composites for the period of 1980-2000. The white box indicates the county of Herefordshire.

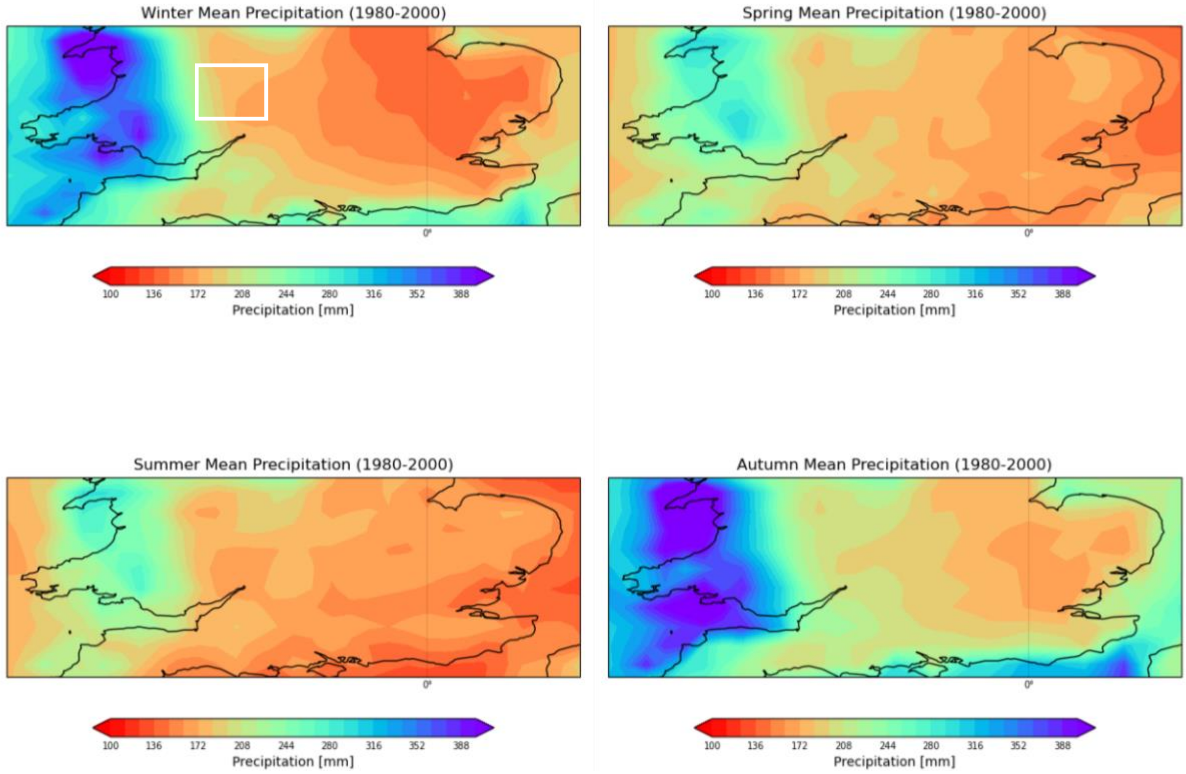

Figure 6 - Seasonal mean total precipitation (mm) composites for the period of 1980-2000. The white box indicates the county of Herefordshire.

3.3 Future projections

To assess the impacts of climate change on apple crop production in Herefordshire, the changes of specific climatic variables need to be examined. This sub-section presents projected temperature and precipitation changes in the short (2021-2040) and long term (2061-2080) for twelve model projection members. Projections are anomalies of the baseline values.

3.3.1 Temperature

In both short- and long-term projections there is evidence of increasing regional mean temperatures (Figure 7). The short-term projections show a limited change in temperature over Herefordshire for all seasons. The models showing the most significant changes present anomaly values of up to 3°C which are seen in summer and autumn, but most models show little change of 0-2°C. However, in the long-term projections more significant temperature changes are seen. In winter six of the members show increases of 4°C. In spring three of the members show this increase, with the rest showing a rise of 3°C. The summer season shows very significant temperature changes. Five members project an increase of 6°C in Herefordshire, while the rest show anomalies of 4-5°C. Significant changes are also seen in autumn, whereby three models show an increase of 6°C, five an increase of 5°C and four an increase of 4°C.

Figure 8, showing projections of maximum temperature anomalies, displays similar patterns to Figure 7. Limited changes are seen in the short-term of 0-3°C, with a maximum increase of 4°C being shown by one member during summer. Long-term projections of winter and spring are very similar to the mean temperature increases, with anomaly values of 3-5°C. The most significant projections are those of the long-term summer and autumn. In summer six of the members show an increase of 7°C and three show an increase of 8°C. In autumn, five members show an increase of 6°C and one an increase of 7°C.

Projections of minimum temperature anomalies, in Figure 9, have similar patterns to the mean and maximum temperatures. In the short-term projections, temperature increases are 1-3°C. In the long-term projections, temperature increases are 2-4°C for winter and spring, and 4- 6°C for summer and autumn. Interestingly, the highest anomaly value is seen in autumn, rather than in summer as is seen in the other projections.

3.3.2 Precipitation

In short- and long-term future projections there are changes to regional mean precipitation rates (Figure 10). The short-term projections show a lot of uncertainty regarding even the sign of change of the precipitation rates. The only exception to this is the summer season, where all of the members except one show a decreased rate of precipitation. Here, three of the members display anomaly values of -10 to -40%, and eight show values of 0 to -20%.

In the long-term, spring and autumn projections remain highly uncertain with members projecting positive and negative anomaly values. However, for winter and summer, the projections are much clearer. In winter, the precipitation rate increases significantly. Nine members show increases of 20-40%, and two members show increases reaching 50-60%. Meanwhile, in summer, the precipitation rate significantly decreases. Four members show anomaly values of -10 to -30%, four members show values of approximately -40 to -50%, and four members show values of -50 to -70%.

Figure 7 – Seasonal mean air temperature (°C) anomalies. Columns correspond to the period of projections (the left column is 2021-2040 and the right column is 2061-2080). Rows correspond to seasons, moving from winter at the top to autumn at the bottom. Individual member maps within a plot are ordered by mean value. The black box indicates the county of Herefordshire.

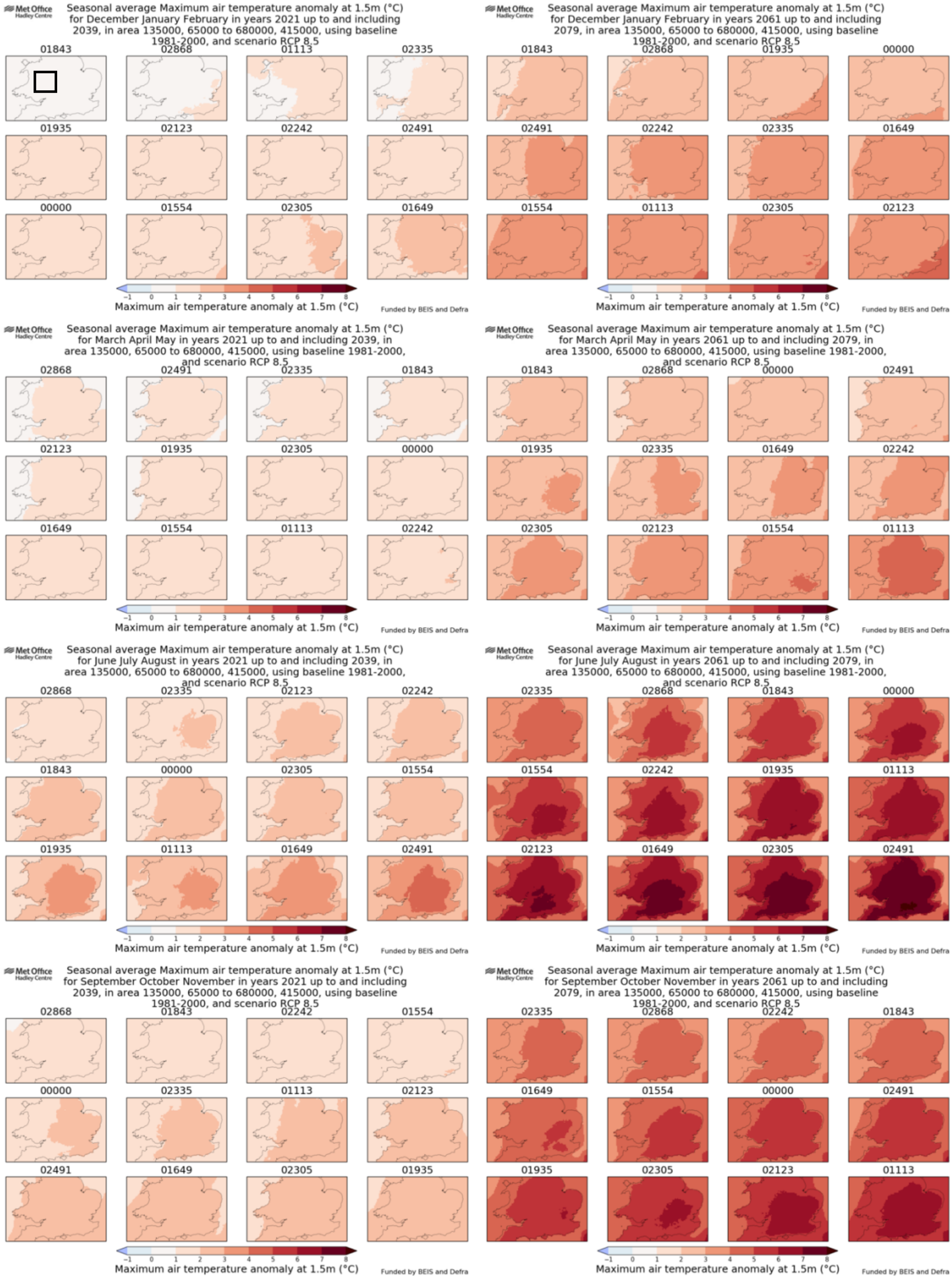

Figure 8 - Seasonal maximum air temperature (°C) anomalies. Columns correspond to the period of projections (the left column is 2021-2040 and the right column is 2061-2080). Rows correspond to seasons, moving from winter at the top to autumn at the bottom. Individual member maps within a plot are ordered by mean value. The black box indicates the county of Herefordshire.

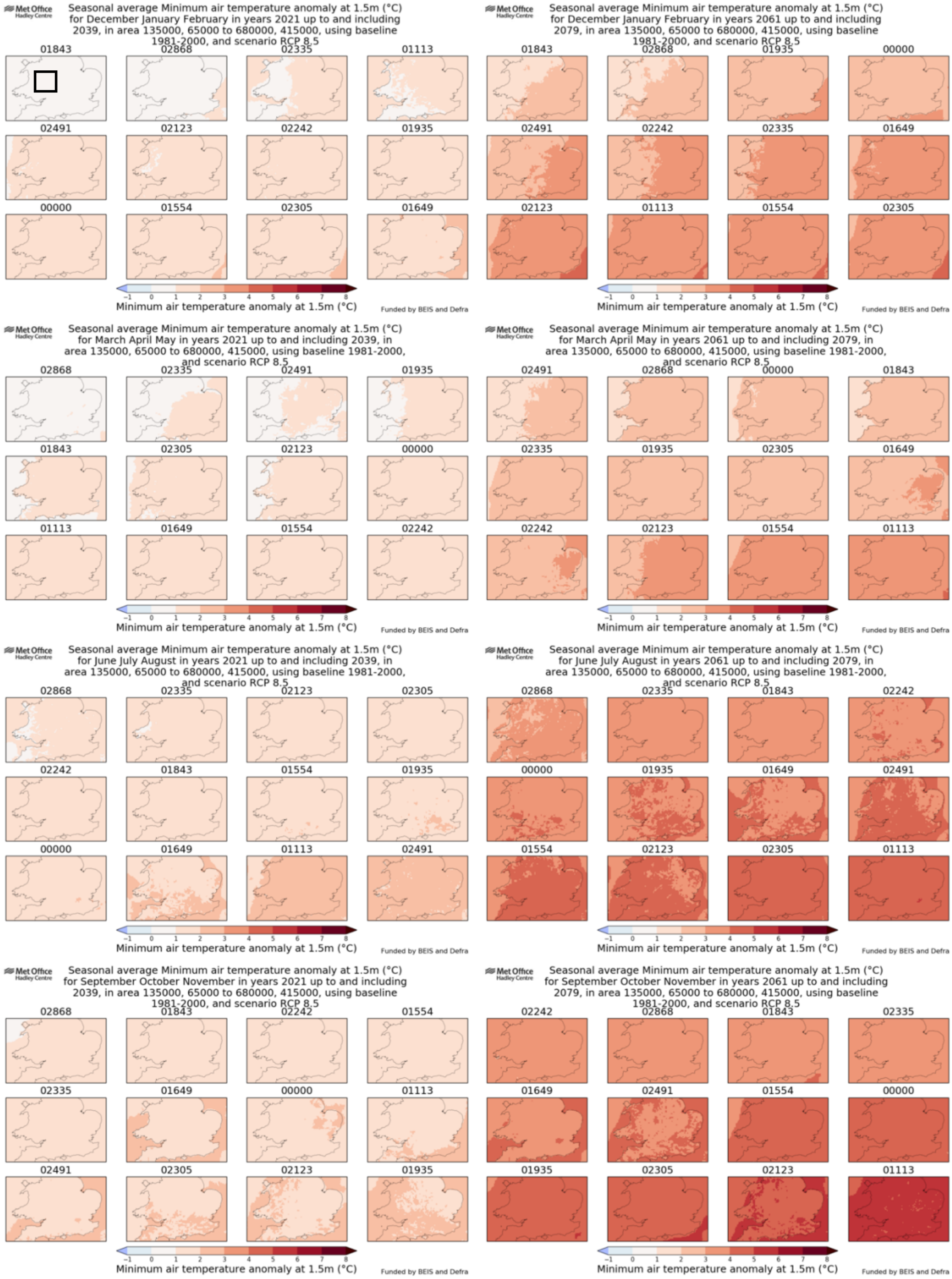

Figure 9 - Seasonal minimum air temperature (°C) anomalies. Columns correspond to the period of projections (the left column is 2021-2040 and the right column is 2061-2080). Rows correspond to seasons, moving from winter at the top to autumn at the bottom. Individual member maps within a plot are ordered by mean value. The black box indicates the county of Herefordshire.

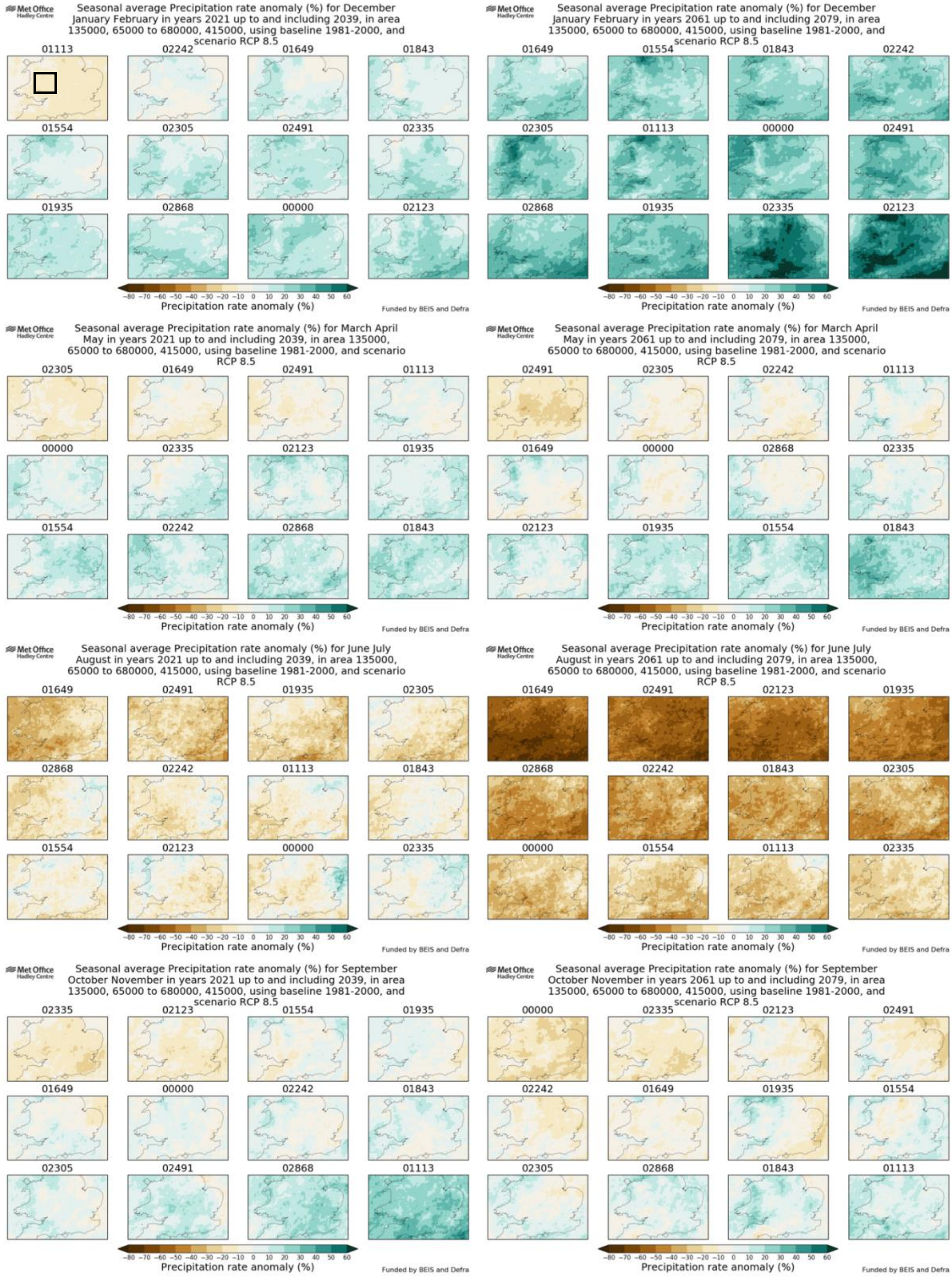

Figure 10 - Seasonal precipitation rate (%) anomalies. Columns correspond to the period of projections (the left column is 2021-2040 and the right column is 2061-2080). Rows correspond to seasons, moving from winter at the top to autumn at the bottom. Individual member maps within a plot are ordered by mean value. The black box indicates the county of Herefordshire.

4. Impacts of climate change on apple crop production in Herefordshire

After assessing how the climate is projected to change in Herefordshire in Section 3, this section will assess the impacts of climate change on apple crop production in the region based upon the themes identified in Section 2. This section will also briefly cover other potential impacts of climate change.

4.1 Pheno-phase changes

Pheno-phase changes in apple crops are primarily determined by temperature. In the short-term projections, seasonal temperature increases are not significant, and thus in the next 20 years, the pheno-phases are unlikely to change. However, in the long-term trends mean temperature shows substantial increases, especially in summer and autumn. Higher mean temperatures in summer and autumn, with increases of 4-6°C, are likely to enable a longer growing season which will increase crop yield. Temperature increases are also seen in winter and spring, although of smaller magnitude, which could result in earlier springs and again a longer growing season.

4.2 Winter chill

As a result of warmer winters, apple crops in Herefordshire may suffer from less winter chill in the future. In the winter long-term projections, mean and minimum temperatures are seen to increase by up to 4°C. The baseline period temperatures shown in ERA5 for winter are 4-5.5°C and 1.5-3.5°C for mean and minimum temperatures respectively. Therefore, an increase of 5°C is likely to prevent apple crops from frequently reaching the necessary chilling temperatures required to break full dormancy.

4.3 Spring frost

The potential for Herefordshire to experience earlier springs due to increased temperatures in the long-term future could put apple crops at risk from damage by spring frost. Mean temperatures in spring are predicted to increase by 1- 2°C in 2061-2080. This is not substantial warming, and so is unlikely to have a large impact on the pheno-phase of apple crops. Therefore, a significant advance in the date of flowering is unlikely, and thus the likelihood of increased risk from late spring frost in the future is low.

4.4 Other potential impacts

In the summer season, especially in the long-term projections, drought is likely to become a problem as a result of significantly reduced precipitation rates (reductions of up to 70%). Although apple crops can withstand short dry periods, prolonged drought conditions may result in water stress on the crops which can reduce productivity, cause root stress and accelerate fruit ripening (Henson, 2008; Moretti, 2010; Dey et al., 2016; Thomas et al., 2016).

Conversely, the long-term projections show that in the winter months there is likely to be much higher levels of precipitation, with rates increasing by up to 60%. Warmer, wetter weather could increase the risk of diseases such as apple scab (*Venturia inaequalis*) and fire blight (*Erwinia amylovora*) (Thomas et al., 2016). Increased precipitation could also increase the risk of flooding. This can affect apple crop production positively and negatively, through flood-inducing rains benefiting the following season's crops (Khan, 2011; IPCC, 2012) but flooding causing waterlogging (Vermeulen et al., 2012).

4.5 Concluding remarks

Overall, results point towards a number of changes in the future climate, which will affect the growth of apple crops. However, there are clear uncertainties in these projected changes, and projections show a range of results between the members. This means that although the impacts of climate change on apple crop production in Herefordshire can be approximated, no quantitative values can be provided. Moreover, the key factors addressed (pheno-phase changes, winter chill and spring frost) are based on literature from other regions and therefore the same impacts might not apply in Herefordshire.

5. Adaptation options

Sections 3 and 4 have provided evidence that in the coming decades implementing adaptation strategies is crucial to make the agricultural sector in Herefordshire more resilient to climate variability and to reduce risks or take benefits from the potential long-term climate changes. Unterberger et al. (2018) identify three areas of adaptation for apple farmers: physical, cultivar and economic adaptation. This section will use these areas to identify several potential adaptation options for apple crops in the region.

Physical adaptation protects the crop yield by directly safeguarding the crop. For instance, to adapt to dry summers the industry should improve water management by investing money to develop more sustainable irrigation systems (Else and Atkinson, 2010). Meanwhile, to adapt to frost risk highly efficient frost protection techniques are advised (Eccel et al., 2009). These include over-canopy irrigation, forced air circulation and artificial heating (Unterberger et al., 2018). However, these methods are extremely water and energy-intensive and so do not provide the most sustainable adaptation options. Winter chill impacts on apple crops are more complex to adapt to, and research into the effects of adaptation options is necessary. For example, some chemicals have been successful in breaking dormancy even if chilling requirements are not met, but many of these chemicals can be phytotoxic if used incorrectly (Erez et al., 2008). Physical adaptations will increasingly rely on technological innovations, with farmers who employ these earlier putting themselves in a better position to reduce the risks of climate change (Calleja, 2011).

Cultivar adaptation involves choosing cultivated varieties more favourable to the future climate. This is an important adaptation strategy because orchard establishments are expensive and remain in production for decades (Luedeling, 2012). Thus, selecting tree cultivars that will be able to survive and produce a high crop yield is important, and farmers should start growing them now if they would like to see the benefits by the time climate change impacts become significant. Favourable cultivar includes tree varieties that are more frost resistant to reduce the risk of frost damage (Unterberger et al., 2018); that require less chilling and so can still break full dormancy even in warmer winters (Thomas et al., 2016); or that have drought-tolerant rootstocks for when the crops experience dry summers (Thomas et al., 2016).

Economic adaptation safeguards the incomes of farmers. This is usually done through insurance or diversification (Unterberger et al., 2018). Encouraging farmers to have insurance in case of crop failure reduces the immediate financial strain of reduced crop yield. However, in the long-term, this strategy can be precarious and ultimately detrimental to the farmer and their business if farmers do not also choose to implement adaptation measures. Meanwhile, diversification encourages farmers to look for income elsewhere by expanding their business (NFU Mutual, 2020). This is already a common technique in Herefordshire, with many farms now offering services such as luxury camping.

Overall, is it important for decision-makers to understand that because of high uncertainty, there is not just one future that is being adapted to and that adaptation needs to be sensitive to potential changes. Therefore, this study must highlight the significance of ‘no regrets’ and ‘win-win’ adaptation strategies, so that an adaptation lock-in is avoided. ‘No regrets’ strategies provide benefits regardless of the future climate change, and ‘win-win’ strategies reduce climate change-related risks whilst also providing social, environmental or economic benefits (Cimato and Mullan, 2010). Compounding this, effective adaptation frameworks should be implemented that incite increased understanding of the impacts and clear communication between policymakers and farmers of the potential adaptation strategies, so the production of apple crops is most successfully protected.

6. Conclusions

This study has investigated how climate change is going to impact apple production in Herefordshire, and what adaptation options are necessary to prepare for these changes. To assess the impacts and therefore determine appropriate adaptation measures, key factors for the success of apple crop production were identified from the literature and climate change projections of the region were simulated for short (2021-2040) and long term (2061-2080) periods.

The projections showed the climate is not projected to change significantly in the short-term, but that in the long-term several important changes are likely. By 2061-2080 mean temperatures in summer and autumn are expected to increase by up to 6 °C in Herefordshire, while winter and spring show increases of 3-4 °C. Similar patterns are also projected for long-term maximum and minimum temperatures. Summer and autumn maximum temperatures show increases of 6-8 °C, but winter and spring have little difference to the mean temperature projections. Summer and autumn minimum temperatures increase by 4-6 °C, and winter and spring increase by 2-4 °C. For precipitation, the key results again are seen in the long-term projections and show increases in the precipitation rate of 20-60% in winter and decreases in the rate by 40-70% in summer. These results provide this study with guidance on future climate changes in Herefordshire, but it is clear there are high levels of uncertainty in projections of each climatic variable, especially precipitation rates.

The main conclusions that can be drawn from these results are that in the coming decades Herefordshire is likely to experience several climatic changes, however, the extent of these changes cannot be conclusively stated due to the uncertainty of the climate projections. Based on the climate projections available and the understanding of general factors affecting the success of apple crop production, this study has suggested the regional impacts to apple production are likely to include extended growing seasons due to warmer autumn temperatures, winter chill requirements not being reached because of increased mean temperatures in winter, and water stress from dry, hot summers.

Therefore, this study has suggested several potential adaptation options based upon the three areas identified by Unterberger et al. (2018). These options include investing money to develop more sustainable irrigation systems, researching winter chill adaptation mechanisms, choosing cultivated varieties that require less chilling or have drought-tolerant rootstocks, and safeguarding the incomes of farmers. Importantly, climate changes and subsequent impacts cannot be determined conclusively, and therefore the adaptation planners in Herefordshire are going to need ‘no regrets’ or ‘win-win’ adaptation policies in which they appreciate the uncertainty in the future climate.

7. References

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