DEFRA Project AC0310

Climate Change Impacts and Adaptation - a Risk Based Approach

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Introduction

The consensus of scientific opinion as represented by the International Governmental Panel on Climate Change (IPCC) assessment is that the global climate is warming. This change is taking place in response to changes in the composition of the atmosphere that are likely to include a significant contribution from human activities. As a consequence of global warming, changes for the UK climate are predicted to involve seasonal and regional alterations in temperature and the pattern of rainfall. Thus, in the future, agricultural cropping in the UK is likely to be taking place against a background of changes in environmental factors that have an impact on productivity and the efficiency of land and resource usage.

Generalised predictions of changes in global climate have been produced by the IPCC. More targeted predictions for the UK were previously produced by the UK Climate Impacts Programme (UKCIP) as UKCIP02 and these were superseded by UKCP09 during this project. "Weather generators" that produce synthetic daily time series of weather data with high spatial resolution, facilitate translation of these general predictions into a format that can be applied to specific cropping situations. The outputs from weather generators can be used either to estimate the frequency of a defined set of circumstances known to have an impact on cropping, e.g. dry or waterlogged soil, or as inputs to models of crop scheduling or pest phenology/survival. We used this approach in a previous project (AC0301) to evaluate the risk of several potential impacts on crop growth and development in wheat, sugar beet and some horticultural species. In the previous work the range of crops and situations were limited and the predictions were based on the UKCIP02 scenarios in combination with the Rothamsted weather generator. In this follow-on project, we have used the new UKCP09 probabilistic scenarios and integral weather generator and applied them wider range of agricultural systems and impacts.

The objectives of the study were as follows:

- To construct a series of schedules identifying key stages in annual production systems for target crops or livestock that may be directly or indirectly susceptible to climate variation or weather extremes.
- To identify relevant models (crop, pest and disease, soil, energy) or thresholds for running against climate predictions.
- To run models to identify potential impacts and risks associated with climate change.
- Assemble findings from individual models to determine overall impact and risk associated with the target systems.

Approaches and Methodologies

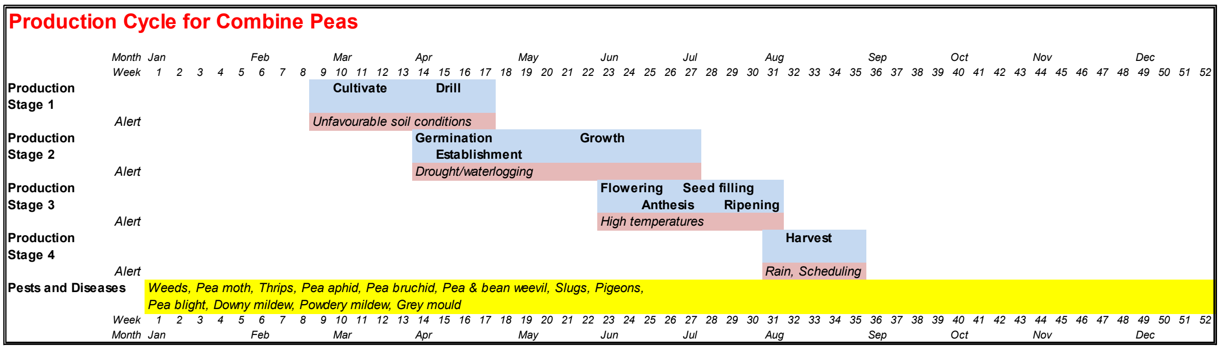
We constructed a series of schedules identifying key stages in annual production systems for target crops or livestock that may be directly or indirectly susceptible (e.g. through pest and disease pressures) to climate variation or weather extremes and assembled findings from individual models to determine overall impact and risk associated with the target systems. The crops were pea, broccoli, cider apple, wheat, potato, oil seed rape and protected tomato. Sheep production was used as an example of a livestock system. To aid in the identification of key stages and in the interpretation of findings we established a consultation group with representatives from the Potato Council (PC), Home Grown Cereals Authority (HGCA), National Farmers Union (NFU), Processors and Growers Research Organisation (PGRO), Horticultural Development Council (HDC) and the organisation for the beef and sheep industry in England (EBLEX) along with academic and industry experts with experience of the relevant crops and sectors. The group was invited to a review meeting after the initial scoping phase and were able to advise on the priority areas for the chosen systems. The experts in the groups also provided and validated information on the descriptions of the crop cycles. Based on these discussions we formulated a scheme of models to run in the project. Each model was run for different locations relevant for the particular system in question using synthetic weather outputs from the UKCP09 weather generator.

The UKCP09 weather generator is based around a stochastic model that simulates future rainfall sequences. Other weather variables are derived from the rainfall states. Statistical measures within the weather generator are then perturbed according to the UKCP09 probabilistic projections to generate time series for future time periods. The UKCP09 weather generator is essentially trained by using the 5km daily-observed baseline of 1961–1995. Change factors, which provide projections for the change between the baseline climate and the future climate, are randomly taken from the sampled data. These change factors are then used to perturb the statistically derived time series to generate statistical expressions of what daily time series of future climate may look like under high medium or low emissions scenarios. It is not statistically robust to use only one set of change factors from the sampled data and we used a minimum of 100 time series in the analyses and used comparisons for 2030s and 2050s time slices using the high emissions scenario. In general we present findings as box plots representing the median values and the calculated probabilities between the 5th and 95th percentile values.

After running the models, a further meeting was held at the end of the project to present the major findings to the consultation group. In addition to crop system-specific analyses we considered the generic issues of soil dryness or wetness, linked to changes in local patterns of rainfall in different locations within the UK and the generic pests, slugs and the peach-potato aphid (*Myzus persicae*).

Section 1 Field Crop Cycle – specific and Generic Analyses.

1 PEA



Production Cycle for Combine Peas

Production Stage 1	Cultivate, Drill	Alert: *Unfavourable soil conditions*
Production Stage 2	Germination, Establishment, Growth	Alert: *Drought/waterlogging*
Production Stage 3	Flowering, Anthesis, Seed filling, Ripening	Alert: *High temperatures*
Production Stage 4	Harvest	Alert: *Rain, Scheduling*
Pests and Diseases	*Weeds, Pea moth, Thrips, Pea aphid, Pea bruchid, Pea & bean weevil, Slugs, Pigeons, Pea blight, Downy mildew, Powdery mildew, Grey mould*	

For pea, we considered the combining crop where the area is increasing because of demand both for human consumption and pet food. The area of combining peas grown doubled from 2008 to 2009. Peas are restricted in the area in which they can be grown. They require the medium to light soils and dry conditions at harvest time found in Lincolnshire and East Anglia. Southerly areas favour latematuring 'marrowfat' pea varieties while northern areas are suitable only for early-maturing varieties. Possible new locations for this crop are in North East Lincolnshire near the Wash, the Northumberland coast, Lothian & Borders coast and Tayside, North of Fife. Vining peas are already grown in these areas.

Pea crops need dry conditions for planting in March and April and harvesting in August. Planting time therefore depends on weather and soil type and the biggest risk is during March. Soil conditions are the key factor for planting, rather than temperature. Planting is possible in February in dry conditions and establishment is negatively affected by waterlogging. Saturation at field capacity for 48 h is enough to cause major losses. The end of April is essentially the cut-off for planting as yields are lower after that. Analyses of the prevalence of wet soil conditions shown in Figure 7.1c indicates that the risk of encountering wet soil during the planting period is not predicted to change greatly in East coast locations by the 2050s.

Flowering takes place in early June. There is no systematic record of the relationship between flowering time and temperature in combining peas, but with vining peas, flowering time would be advanced by warmer temperatures (see AC 0301). Moisture, along with warm weather is required for seed filling but after ripening, further rain has a negative impact on the crop. There is evidence that high temperatures can inhibit flowering. The consultation group reported that two weeks of hot, dry weather in early July resulted in flowering being curtailed and a reduced yield. Production is based on a small number (5-6) of varieties, all of which have similar vulnerabilities.

Pests and Diseases

Relatively few potential pest and disease threats as a consequence of climate change were identified in consultation meetings. The two flagged as being of most concern were Fusarium root rot and Pea aphid.

Case Study 1.1 Fusarium root rot

Fusarium root rot was identified as a significant potential problem with the pea crop. It is known that plants may become infected with Fusarium at any stage of growth. We calculated the predicted daily root rot severity scores that would be accumulated over the whole combining pea season from 15 April to 31 August based on Tu (1994). The resulting accumulated scores over the season are shown below for Wyton in Cambridgeshire and Kirton in Lincolnshire (Figure 1.1).

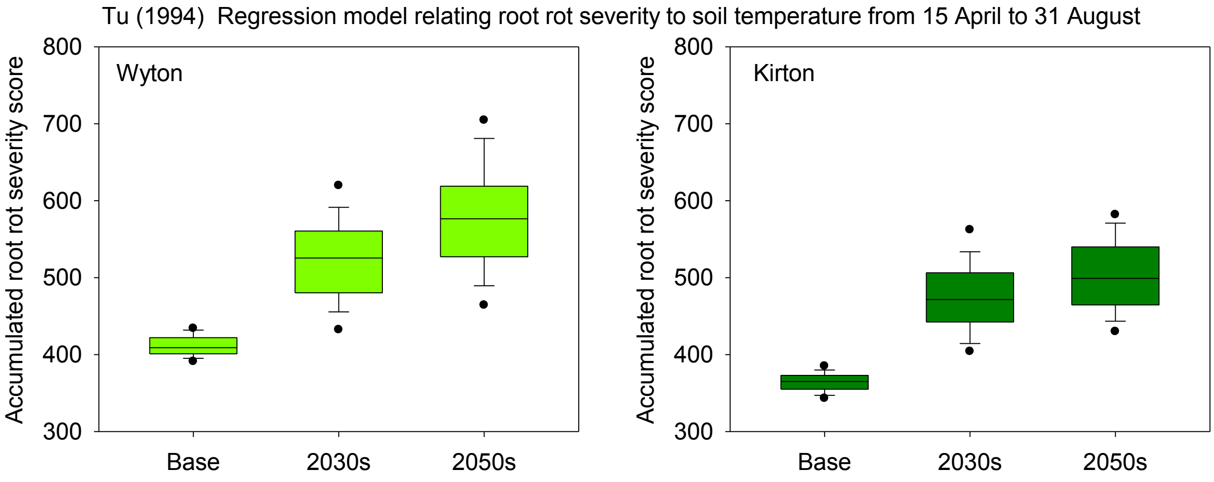


Figure 1:1 Predicted root rot severity scores for Wyton in Cambridgeshire and Kirton in Lincolnshire for Base, 2030s and 2050s time slices.

The models used predict that the likelihood of Fusarium root rot will increase steadily through the 2030s to the 2050s but also indicate that the variability year on year will increase over this period. Adaptation to this increased risk could include selection of varieties with improved resistance to Fusarium root rot or through crop management practices.

<u>Case study 1.2 Pea aphid *Acyrthosiphon pisum*</u>

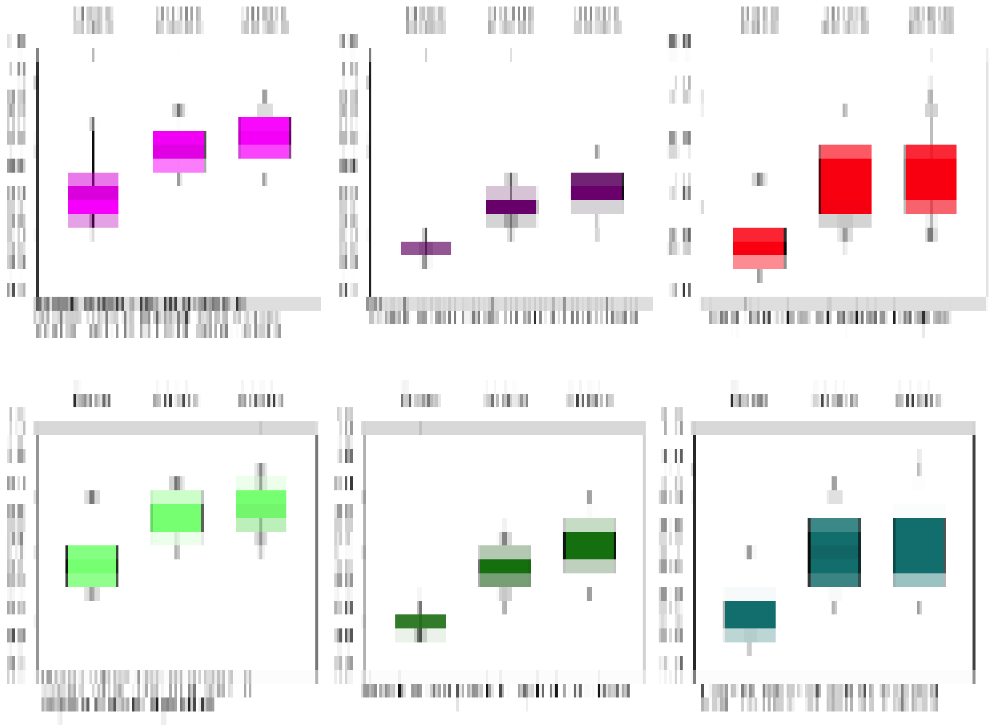
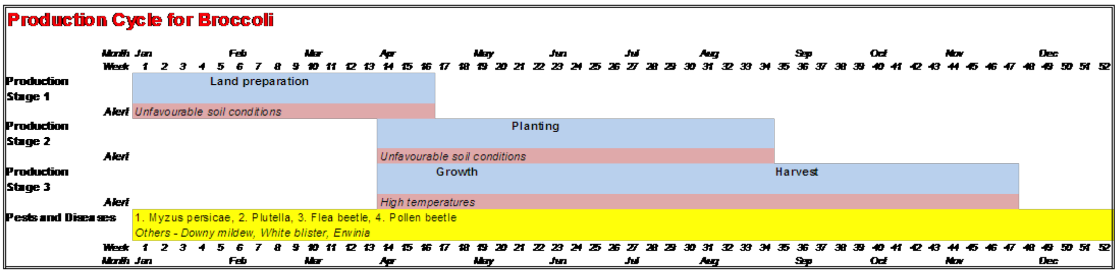


Figure 1:2 Predicted times of first migration, peak numbers and total abundance of pea aphids for Wyton in Cambridgeshire and Kirton in Lincolnshire for Base, 2030s and 2050s time slices.

The consultation group identified pea aphid as a key pest. Empirical regression models relating temperature deviations from average to data from suction trap catches at Broom's Barn in Suffolk (McVean *et al*. 1999) were used to forecast the timings of both the first aphid catch and the peak aphid catch, and the total numbers of pea aphids caught, as a measure of annual abundance (Figure 1.2). Thirty-year climatological averages for 1961 – 1990 for Wyton in Cambridgeshire were used. The Met Office also quotes Wyton as one of the alternative weather stations for Kirton, so it can be assumed that it would be representative of the climate trends for both locations. Therefore, the models were also run using parameter values for the suction trap at Kirton and the temperature data for Wyton.

The models predict that for both locations the overall abundance of pea aphids will decrease for 2030s then be relatively unchanged for the 2050s. This will be combined with an advance in the timing of first migration and peak numbers, again with the biggest change being between the baseline and 2030s. Taken together, these changes do not appear to present an increased long-term risk for the crop.

2 BROCCOLI



Broccoli is a relatively long season crop with planting from April through to August. There are three main areas of production, Cornwall, Lincolnshire and Scotland but also some in Kent and the Midlands. Land preparation can be from any time between February and July and although ploughing is not possible in very wet weather, such conditions can usually be avoided. This is the least vulnerable part of the cycle with Lincolnshire soil, in particular, drying rapidly. Planting usually starts in late March with planting under covers possible in Lincolnshire from early March. Planting schedules in Cornwall may be disrupted by rain and extremes of rainfall have also been seen to impede planting in Scotland. The much higher levels of rainfall in Cornwall in particular can be seen in Figure 7.1a. UKCP09 predictions indicate that there will not be major changes in the amounts and annual distribution of rain in the three areas of production in the 2030s and 2050s compared with baseline levels, although rainfall intensity may increase.

The part of the growing season from April-June is vulnerable because the weather can be volatile. Having geographically dispersed production areas provides insurance against the potential risks of it being very wet or dry in all production areas. The relatively stable rainfall patterns as predicted by UKCP09 indicate that this strategy should not decrease in effectiveness. The industry is dependent on a limited number of varieties and thus continuity of supply depends on sequential planting. If planting is prevented for 5 days, maturity at planned harvest time is affected and a 10-15 day delay can lead to a 3-week hiatus in harvesting. Delays in planting can be caused by dry soil but very wet soil has a greater impact.

Harvesting can take place into the beginning of November but then spear rot and wet rot finish the crop off. Further season extension would require a cold hardy variety and may not be possible in

Scotland because of reduced light levels and integrals and increased susceptibility to rots. Harvesting itself is not greatly affected by weather.

Pests and Diseases

From discussions with experts at the first project workshop, the most important threats from pests and diseases were identified as *Myzus persicae*, the peach-potato aphid, *Plutella xylostella*, the diamond back moth and *Phyllotreta cruciferae*, the crucifer flea beetle. *Myzus persicae* is a generalist pest of crop species in the UK and is considered in section 7 on generic factors.

Case study 2.1: Broccoli   High temperatures during head development

It is known by growers that when the temperature rises above 23-25°C for a period of 3-5 days during head development this can cause problems post-harvest. We calculated the incidence of runs of three days or more when the maximum temperature is 23°C or greater over the entire harvest season from 1 May to 31 October (Figure 2.1).

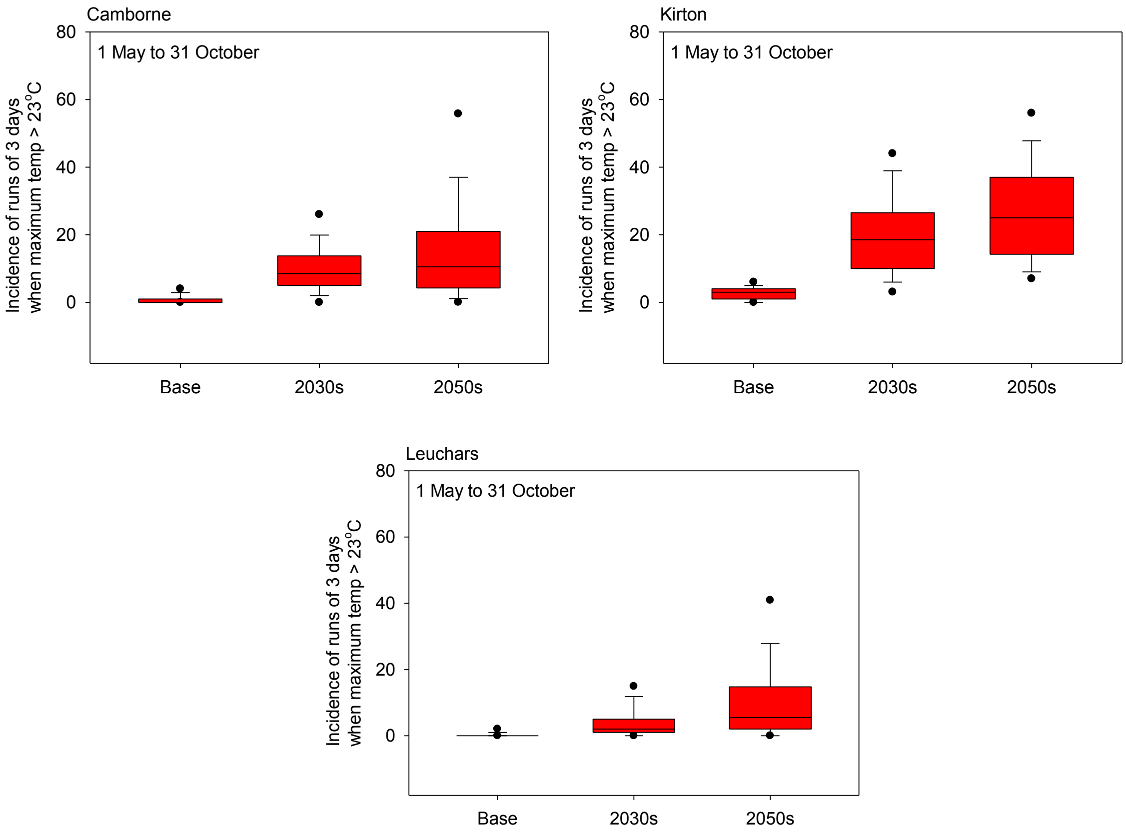


Figure 2:1 Predicted incidence of 3 days at or above 23°C between May and October for Camborne in Cornwall, Kirton in Lincolnshire and Leuchars in Fife, for Base, 2030s and 2050s time slices.

Based on UKCP09 predictions, the risk of runs of temperatures of 23°C or above increases in all three main growing areas in the 2030s and 2050s. The increase is most marked at the Lincolnshire site, less in Cornwall and least at Leuchars, the Scottish location. This indicates that should this factor become critical, moving production areas is a possible adaptation. An alternative would be to develop varieties that are more robust with regards to higher growing temperatures.

Case study 2.2 The Crucifer Flea Beetle. *Phyllotreta cruciferae* and broccoli

Models for the behaviour of the crucifer flea beetle were based on findings that peak emergence occurred as the mean ground temperature reached 15°C in western Canada (Ulmer and Dosdall (2006). Soil temperatures at 10 cm were estimated from the maximum and minimum air temperatures generated by the UKCP09 weather generator as described by Walker and Barnes (1981).

A regression model of flight activity in overwintering adults and newly emerged adults was used to forecast the onset of flight activity. The model was developed in the Czech Republic and used a sum of day-degrees above a base temperature of 10.2°C, the threshold temperature for flight (Kokourek *et al.* 2002). Flight activity in overwintered adults started at 30 day-degrees and that of adults of the summer generation at 280 day-degrees. The resulting forecasts are shown in Figure 2.2 for Camborne in Cornwall, Kirton in Lincolnshire and Leuchars in Fife.

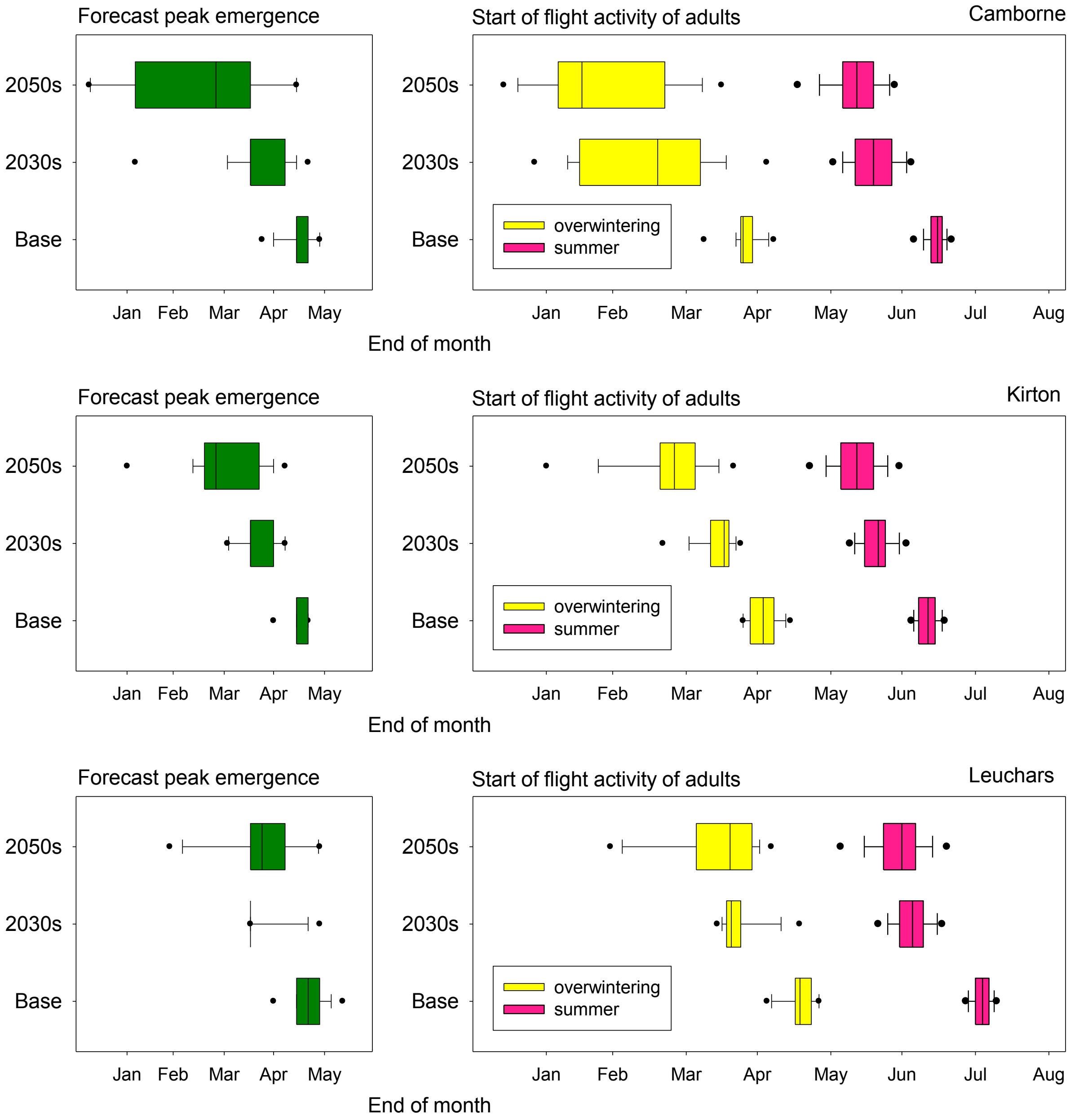


Figure 2:2 Predicted time of peak emergence and start of flight activity for crucifer flea beetles in Camborne in Cornwall, Kirton in Lincolnshire and Leuchars in Fife for Base, 2030s and 2050s time slices.

For all locations there was a trend to earlier emergence and flight over time, although the magnitude of the change differed appreciably with location. The baseline estimation of emergence and flight activity was very similar for Cornwall and Lincolnshire and slightly later for Fife. The degree of advance for early season activity, both for emergence and flight was greater in Cornwall than Lincolnshire. This was accompanied by a large increase in variation associated with the estimates. For summer flight, all locations showed a similar degree of advance, with Cornwall and Lincolnshire being earlier than Fife in each case. The predictions indicate that early season emergence which currently correlates with establishment of the crop may advance by up to two months. This is unlikely to be matched to the same degree by earlier planting of the crop and the asynchrony between the events will reduce the risk of crop damage by this insect. The advance of summer flight would still result in insect attack during the heart of the growing season. However, the summer population may be reduced because of the early season mismatch between insect emergence and crop establishment.

Case study 2.3 The Diamond Back Moth, *Plutella xylostella*

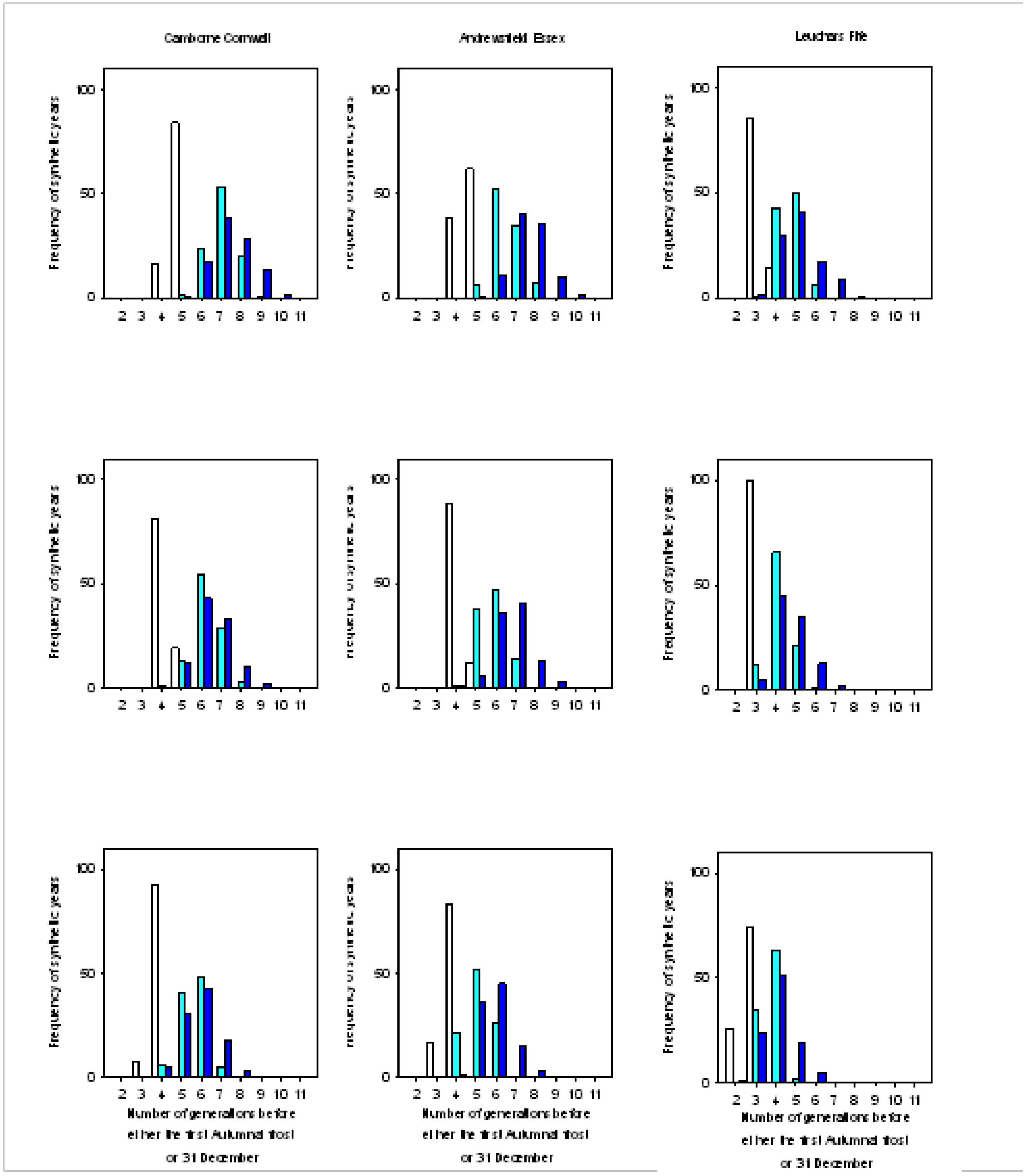


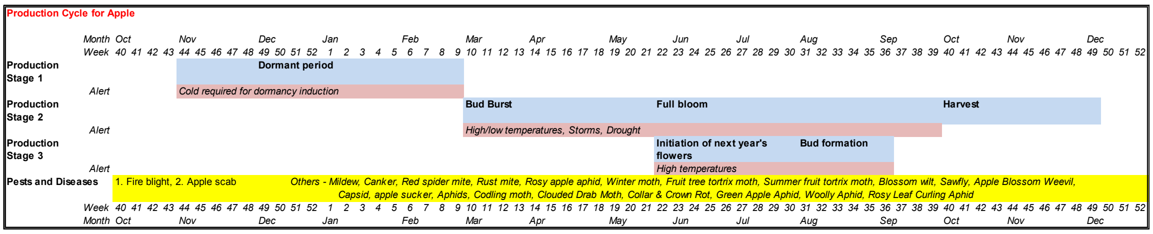
Figure 2.3. Predicted number of generations of Plutella xylostella before 1st Autumnal frost or 31st December assuming A) Successful overwintering and egg-laying from February 1st B)Migration and first egg-laying on May 1st c) Migration and first egg-laying on June 1st for Base, 2030s and 2050s time slices.

The diamond back moth is a pest of brassicaceous species and is particularly prevalent in hot countries. It has limited survival over winter in the UK and infestation is usually the result of migrations from continental Europe. Warmer winters may lead to increased overwintering in the UK and warmer summers will increase the turnover of generations and hence the pest pressure.

Using the model of Harcourt (1954) to predict generation time from egg to adult using a day-degree sum with a base temperature of 7.3°C, predictions were made from three different times of egg-laying. Firstly, the assumption was made that moths would successfully over-winter in UK and start laying eggs from 1 February onwards. The second and third estimates of the start of egg-laying were based on moths migrating into UK from abroad, so eggs were laid on either 1 May or 1 June. For all three prediction model runs, generations were counted until either the first autumnal frost, or if there was none, to end of the calendar year (Figure 2.3).

Running the model with synthetic weather days for sites in Cornwall, Essex and Fife predicts a significant increase in the number of generations in all three locations for the 2030s and 2050s time slices. The more southerly locations show a greater number of generations than Fife, but in all cases the biggest change is anticipated to take place between the Base and 2030s time slice with a further smaller increase to the 2050s. Together the data suggest a step change in the ability of diamond back moth to survive in the UK in the next 20-30 years and this seems to be independent of whether it is able to overwinter in the UK. Adaptations could include plant breeding for resistance or moving production northwards, should the threat become economically significant.

3 CIDER APPLE



Production Cycle for Apple

Month Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Week 40 41 42 43 44 45 46 47 48 49 50 51 52 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52

Production Stage 1 Dormant period
Alert *Cold required for dormancy induction*
Production Stage 2 Bud Burst Full bloom Harvest
Alert *High/low temperatures, Storms, Drought*
Production Stage 3 Initiation of next year's flowers Bud formation
Alert *High temperatures*
Pests and Diseases 1. Fire blight, 2. Apple scab *Others - Mildew, Canker, Red spider mite, Rust mite, Rosy apple aphid, Winter moth, Fruit tree tortrix moth, Summer fruit tortrix moth, Blossom wilt, Sawfly, Apple Blossom Weevil, Capsid, apple sucker, Aphids, Codling moth, Clouded Drab Moth, Collar & Crown Rot, Green Apple Aphid, Woolly Aphid, Rosy Leaf Curling Aphid*

Week 40 41 42 43 44 45 46 47 48 49 50 51 52 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52
Month Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

We considered the cider apple crop, which is based mainly in Herefordshire, Gloucestershire, Avon, North Devon and Somerset, with some production in Suffolk and Sussex. This pattern has developed because of a combination of geology, geography, good light levels, tradition and an established infrastructure. The main area of production is unlikely to change. Apple is a perennial crop and has a continuous annual cycle of dormancy, growth flowering and fruiting. Yield is the main factor determining the value of the cider apple crop with quality being less important than for dessert apples.

Several potentially vulnerable stages were identified in the annual crop cycle. As with other crops, access to the land can be a problem, particularly in the autumn for harvesting and for pruning in February. Projections from UKCP09 indicate no appreciable change in the rainfall in either period. The industry has an aim to move to earlier varieties with earlier leaf fall. Early harvesting would alleviate the current risk and would remain as a benefit in the future climate.

Other weather-related problems identified by the industry include heavy storms which can be devastating if they occur in September and October when the trees are still in leaf and carrying a full crop and warm wet winters where water-logging can lead to rotting off, adversely affecting tree health. A further issue raised was that an early spring could result in earlier emergence of bees when there is not enough food for them, leading to pollination problems at a later stage.

Case study 3.1 Drought in June-Aug

At the workshop and in subsequent discussions it was identified that drought in the June to August period has a negative impact on the crop through the general health and condition of the trees and also through its effect on fruiting.

Using 100 runs of synthetic daily weather from UKCP09 for Shepton Mallet in Somerset and Weobley in Herefordshire, we carried out an assessment of the incidence of days when the SMD was greater than 20mm from 1 June to 31 August. The accumulated rainfall over the same period was also calculated.

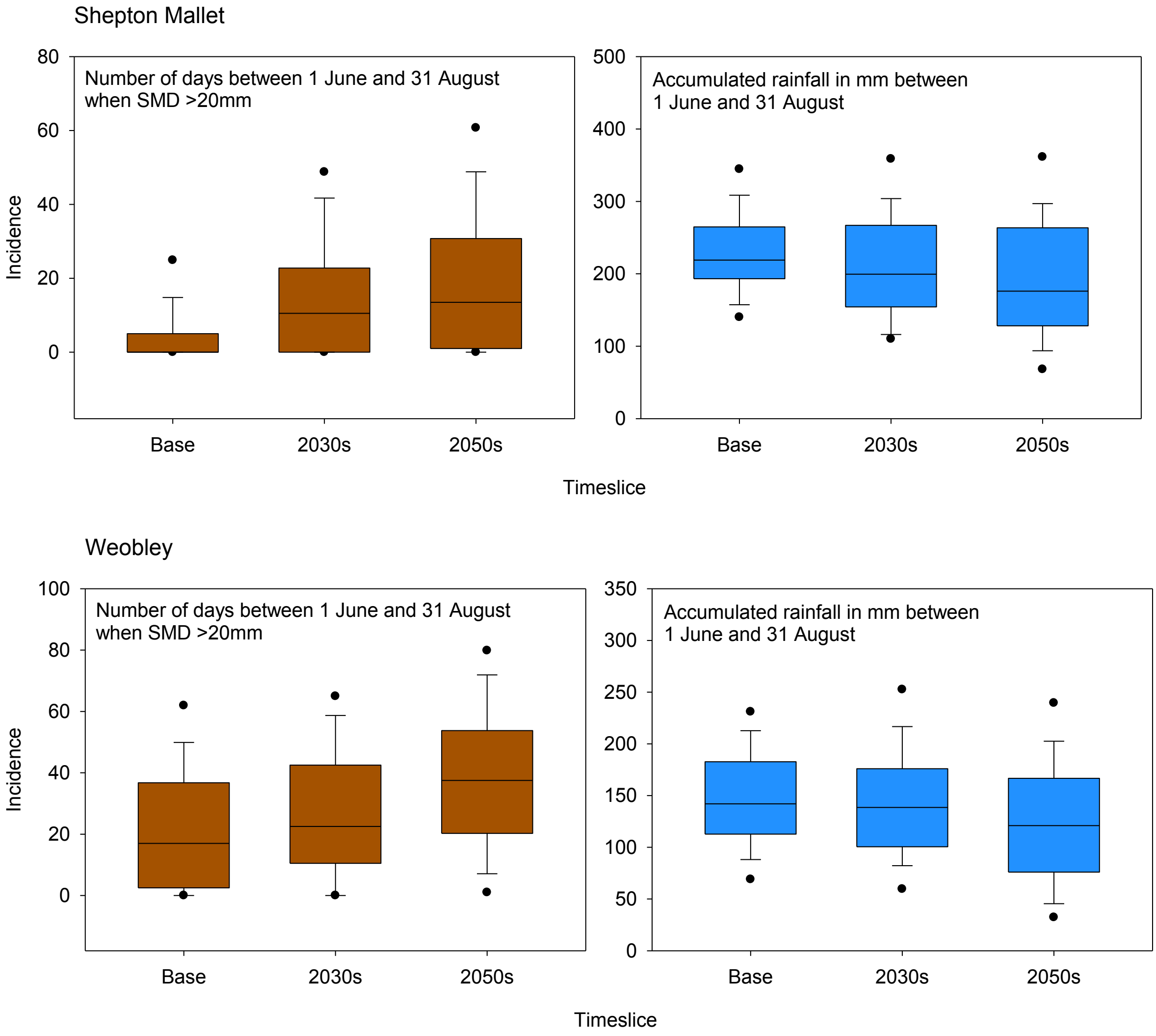


Figure 3.1 Predicted days of dry soil and the predicted accumulated rainfall for Weobley in Herefordshire and Shepton Mallet in Somerset for Base, 2030s and 2050s time slices.

The analyses confirm that the probability of soil dryness will increase in the 2030s and 2050s periods (Figure 3.1). The problem appears to be more pronounced in Herefordshire than Somerset as the rainfall is less and the number of drought days is likely to be higher. The cider apple industry has anticipated this risk and discussed the potential adaptations required. These include improved water management, the use of anti-transpirants and selection of drought tolerant rootstocks.

Case Study 3.2. Winter chill for dormancy release

It is well established that a period of winter chilling is required to overcome dormancy in apple. Industry experts quote a range of target sums of hours below 7°C from 1100 to 1500. We calculated the daily sums of hours below 7°C from 1 November to either the lower (1100 h) or higher (1500 h) end of the range. The results are shown in Figure 3.2.

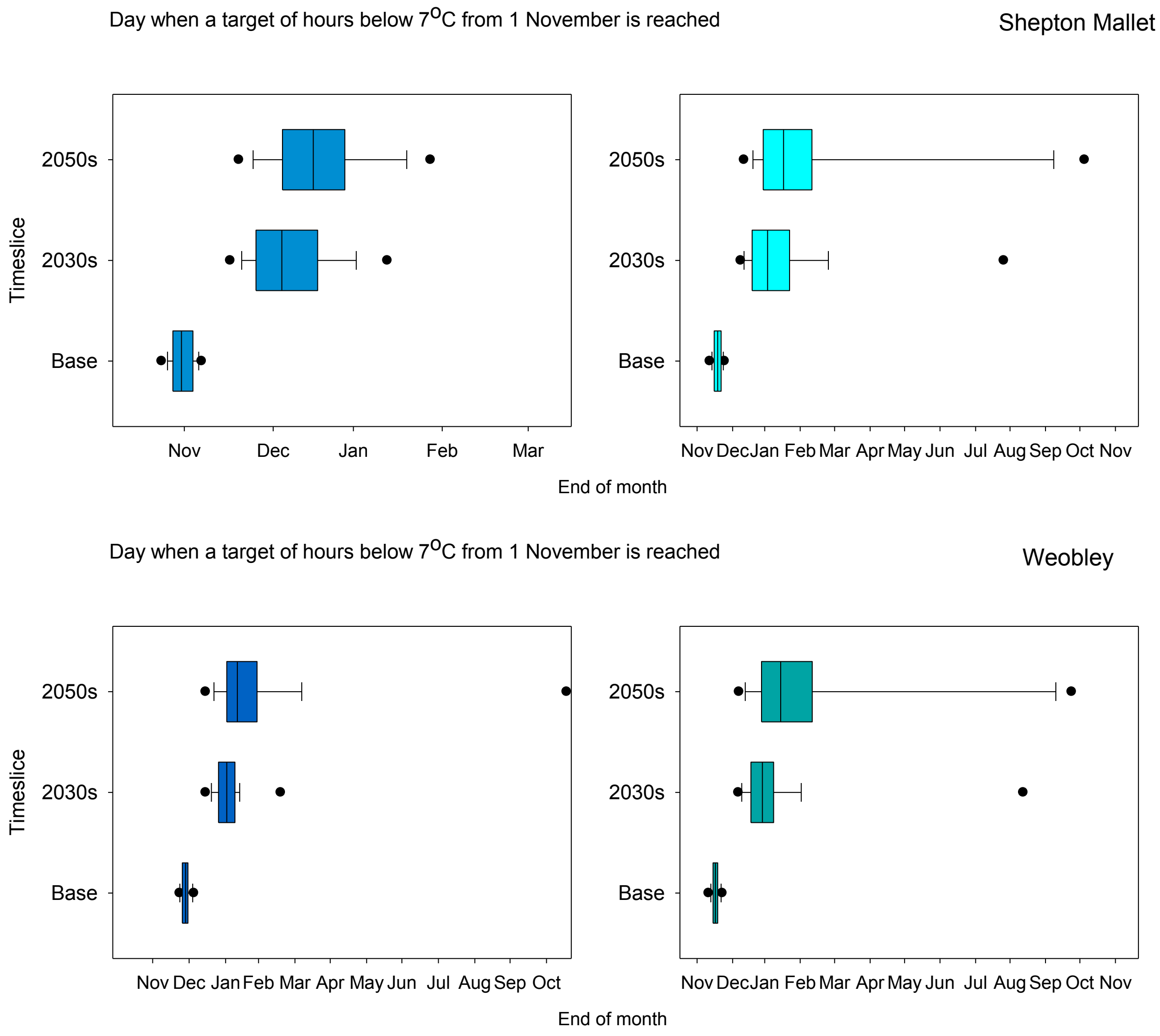


Figure 3.2 Predicted daily sums of hours below 7°C from 1 November to 1100 h (left hand plots) *or 1500 h* (right hand plots) *for Weobley in Herefordshire and Shepton Mallet in Somerset for Base, 2030s and 2050s time slices.*

The results indicate that the winter chill requirement will be satisfied progressively later in the winter at both locations. The variability also increases with time. Thus the risk that there may be years where the chill requirement is not satisfied, or only partially satisfied, will increase for those with a high chilling requirement. For example in the 2050 projection the 1500 hours target was not reached in 2% of the runs at Shepton Mallet and 8% at Weobley. Adaptation will require the use of varieties that require less chilling to replace those with a requirement at the high end of the scale

Case study 3.3. Temperature effects on apple flowering

From discussions with industry representatives at the workshops a number of stages in the flowering process were identified as being potentially vulnerable to temperature and hence may be affected by climate change.

a) Pollination: Pollination is adversely affected by temperatures <10°C or >28°C. Pollination occurs from the last week in April, then all through May. Assuming that pollination may occur earlier in future, the incidence of days when the minimum temperature is below 10°C and of days when the maximum temperature is above 28°C for all April and May was evaluated.

b) Earlier flowering and frost: Blossom opening occurs now between 12 and 19 May. If it occurred earlier then there may be more risk of frost. The incidence of days when the minimum temperature is below 1° C during the period from 1 April to 15 May was therefore evaluated.

c) Initiation of flowers and flower bud formation for the next year : From June to the end of August, the initiation of flowers is sensitive to temperatures >30°C. Once initiated, the formation of the buds for the next year is sensitive to temperatures >26°C. This sensitive time may begin earlier in future, so temperature incidences were evaluated from 15 May onwards.

The predicted impact of temperature changes on flowering is shown in Figure 3.3. The patterns for the two locations are very similar. As might be expected, where low temperatures early in the season have potentially adverse effects, the risk from these conditions reduces with time. However, for flower initiation and flower bud formation, the negative impact of high temperatures in mid to late summer is predicted to become more likely, particularly for the 2050s. The consequences of high temperatures at these times will be manifested in the following season.

Pests and diseases

Apple scab is a major problem for apple and control accounts for a significant proportion of variable costs in apple production. It is believed that microclimate rather than macroclimate is important for this disease. Insects are not considered to be a significant problem

Case study 3.4. Cider Apple and Fire blight *Erwinia amylovora*

The spring blossom period is the time when maximum spread of fire blight is likely. The main variety planted in UK is Dabinett, which generally flowers in mid-season from mid to late May. Blossom opening in an average season in Herefordshire was judged to be from 12-19 May (Tim Epps, personal communication). For a simple approach, thresholds quoted by Billing (1990) to provide broad guidance on risk of fire blight spread were examined, together with Billing's rain score, and a temperature threshold (>15°C) for activity of the bacterium (Table 3.1). Incidence of these conditions was examined for the month of May. Williams (1992) suggested that 'strikes' should occur from June to August. So incidences were also examined over this period (Figure 3.4).

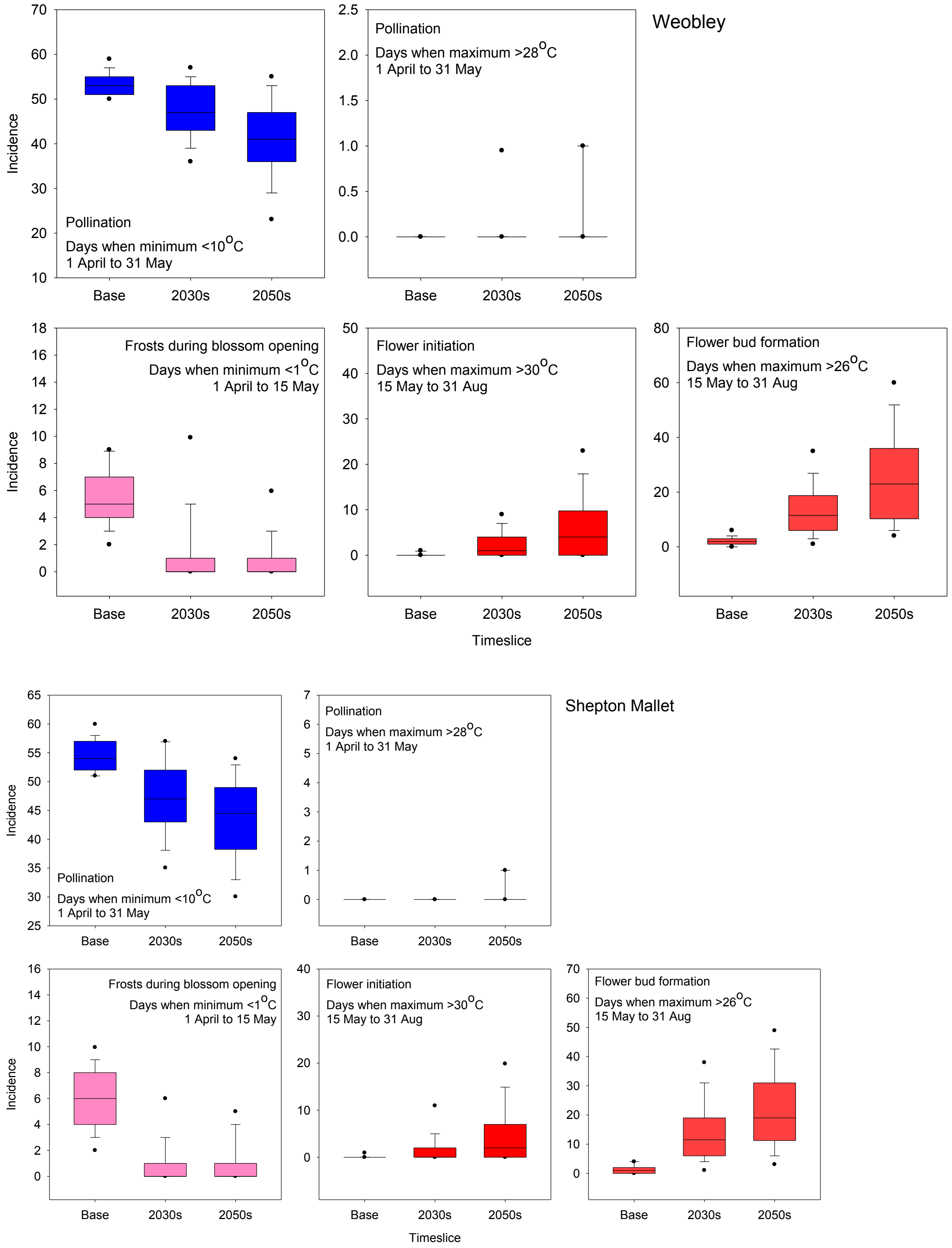
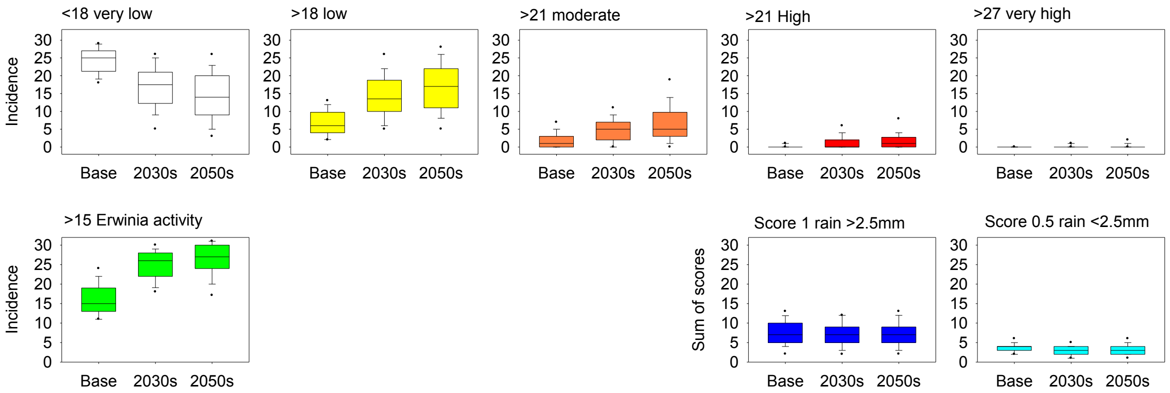
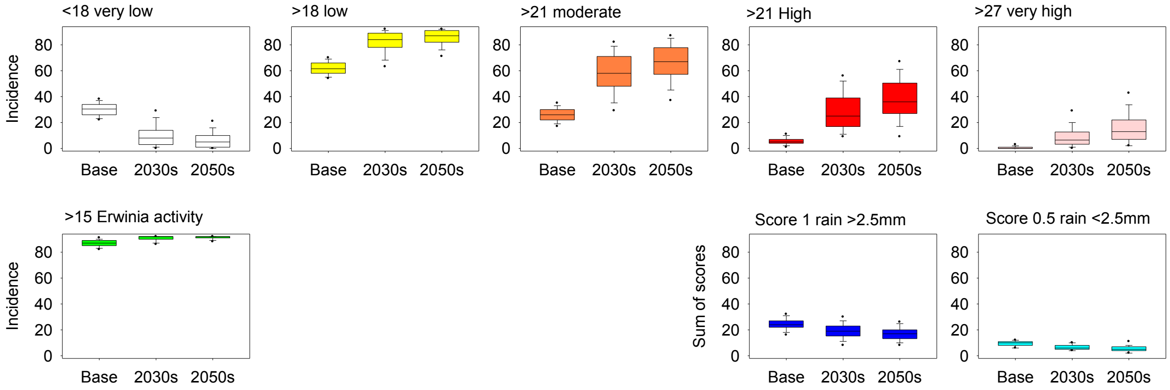


Figure 3.3 Predicted incidences of critical temperature conditions for aspects of flowering for Weobley in Herefordshire and Shepton Mallet in Somerset for Base, 2030s and 2050s time slices.

Shepton Mallet from 1 May to 31 May



Shepton Mallet from 1 June to 31 August



Weobley from 1 June to 31 August

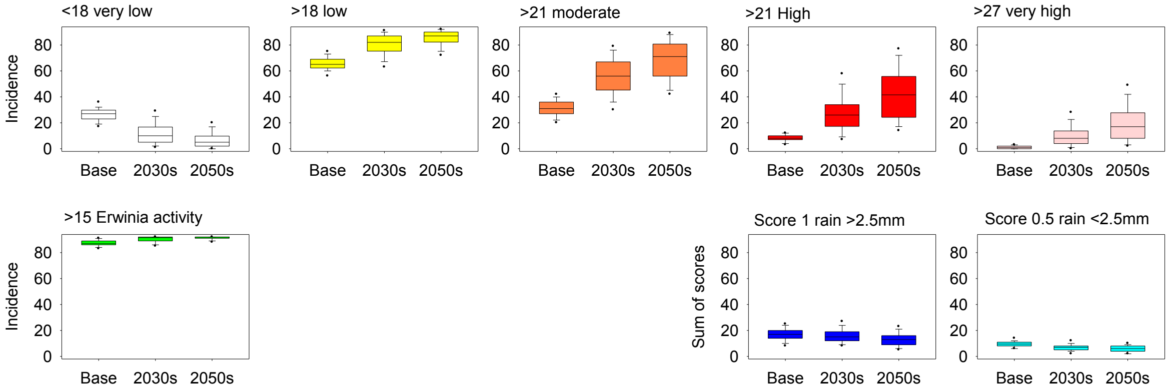


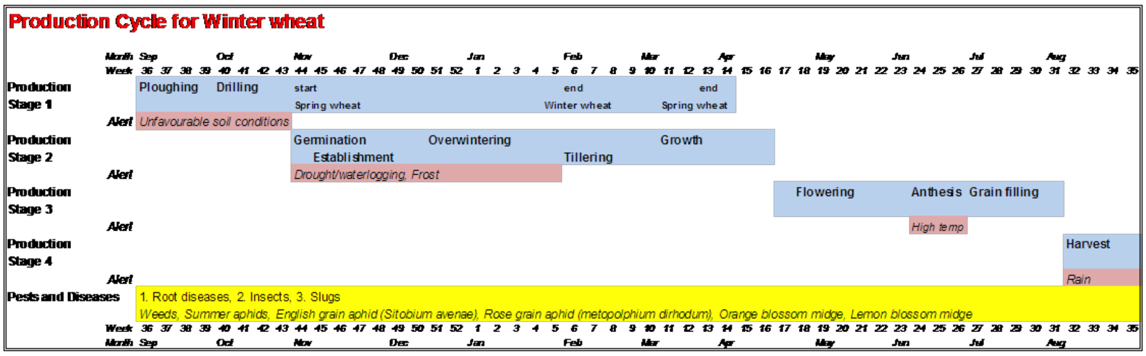
Figure 3.4 Predicted risk of Fire Blight and bacterial prevalence for Weobley in Herefordshire and Shepton Mallet in Somerset for Base, 2030s and 2050s time slices.

Using UKCP09 runs of synthetic weather, the models predict an increasing incidence of fire blight in both Herefordshire and Somerset for 2030s and 2050s time slices compared with the Base series. For the May time period, the incidence rises from very low to low–moderate, but for later in the season, the June - August prediction is that the frequency of high incidence appreciably increases.

Risk or score	Threshold
Risk of spread very low	<18°C
Risk of spread low	>18°C
Risk of spread moderate	>21°C
Risk of spread high	>24°C
Risk of spread very high	27-30 °C
Bacterium activity likely	>15°C
Rain score of 1 for the day	>2.5mm
Rain score of 0.5 for the day	trace to 2.4mm

Table 3.1 Table of critical criteria used to forecast risk of Fire Blight during the spring blossom period based on industry experience and Billing (1990).

4 WHEAT



We focused on winter wheat where there is an extensive amount of genetic material available to draw on from international breeding programmes. Therefore there should not be a problem in adapting to climate change providing that the rate of change is not too rapid. As with many of the crops studied, unfavourable conditions during land preparation or establishment are a potential problem. Predictions for Wyton in Cambridgeshire indicate a decrease in rainfall during the period from September to Mid October when land preparation takes place, but less so in the following three month period when establishment occurs. However, these changes do not appreciably alter the number of days when the soil is predicted to be wet. Other aspects of crop physiology vulnerabilities are covered in the following case studies. In the case of wheat it is possible to take a more holistic view of climate change on the crop because well-developed crop models exist.

Case Study 4.1 Wheat modelling

As part of AC0301, simulations were carried out by Rothamsted Research using the Sirius wheat model. The UKCIP02 scenarios were used and simulations were done for different locations in the UK. The aim of the current work was to assess whether the new UKCP09 scenarios give similar results, and to investigate whether other wheat models (AFRCWHEAT2 and CERES-Wheat as part of DSSAT4) support the conclusions from Sirius.

The models were run with daily UKCP09 data for Rothamsted (lat: 51.80; long: -0.35). Simulations were run for the base, 2030's and 2050's using 100 years of data for each time slice. A sowing date of 20th October was assumed with a Batcombe series soil type. In the case of Sirius and AFRCWHEAT2, the cultivar Avalon was selected, while for DSSAT4 the simulation was more generic for European winter wheat. In all cases the simulations were for entirely rain-fed crops grown with unlimited nitrogen applications.

AFRCWHEAT2 and Sirius use the Penman equation for the calculation of evapotranspiration, therefore, wind speed was required. As wind speed is not included in these synthetic weather data sets a wind run of 200km/d was assumed. The external (ambient) CO_2 concentration was assumed to be 325, 452 and 567ppm for the base, 2030's and 2050's, respectively, based on an average of the values predicted by ISAM and Bern-CC models for the A1F1 climate change scenario (Farquar et al. 2001))

The trends from the Sirius simulations were not too dissimilar to those obtained as part of AC0301, although the absolute yields were slightly higher. This might be because of higher light levels in the UKPCP09 scenarios when compared with the values used in the previous project. The simulations (Table 4.1) showed that if temperatures were to rise without an increase in CO_2 concentration there would be a reduction in the mean yields. This would be due to shorter production times and therefore less light interception. However, when the predicted CO_2 concentrations for the 2030's and 2050's were included, the net effect was an increase in yield due to the positive effect of the CO_2 on canopy photosynthesis.

The year-to-year variation in yield for Sirius is shown in Figure 4.1. AFRCWHEAT2 and DSSAT also predicted that yields would increase as a result of climate change, once the higher CO_2 concentrations are taken into account. Although interestingly, unlike Sirius, these models both showed a greater increase between the base and 2030's than between the 2030's and 2050's. There is also a marked difference in the year-to-year variability predicted by the three models with Sirius showing the least variability and DSSAT having the greatest variability.

Table 4.1. The impact of climate change on the mean wheat yields predicted using Sirius. The simulations were carried out with and without higher ambient CO_2 concentrations.

	Base	**2030s**	**2050s**
Effect of temperature on yield (t/ha) at CO_2 = 325ppm	10.34	9.56	9.40
CO_2 levels (ppm) Average of ISAM and Bern-CC	325	452	567
Yield (t/ha) considering the effects of both temperature and CO_2	10.34	10.62	11.40

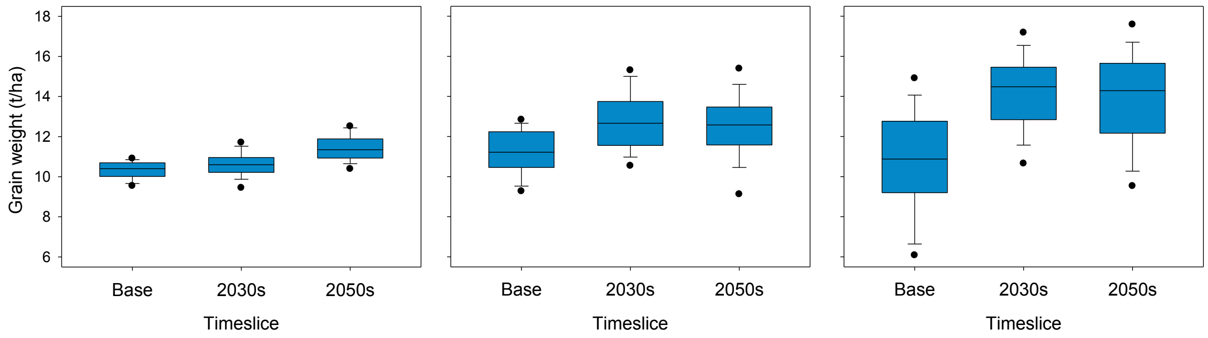


Figure 4.1a. The impact of climate change on wheat yields as predicted by Sirius (left), AFRCWHEAT2 (middle) and DSSAT (right) assuming ambient CO_2 concentrations of 325, 452 and 567ppm for the base, 2030's and 2050's, respectively.

One important implication of warmer weather in wheat is the risk of high temperatures around the time of anthesis. This was discussed as part of AC0301 and the probability of temperatures exceeding 27°C was explored. Therefore, as part of the current study the predicted anthesis dates were also examined and these are shown in Figure 4.1b. The values from the three models are broadly similar due to the fact that in all three models anthesis is predicted based on thermal time. However, the DSSAT model predicts slightly later anthesis, which may be because this is parameterised for generic European Winter wheat, rather than for Avalon, which is an early cultivar.

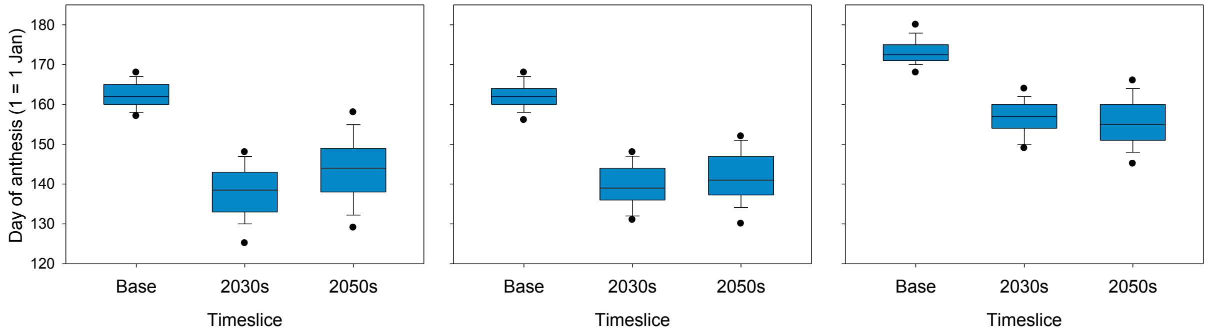


Figure 4.1b. The impact of climate change on anthesis dates for wheat yields as predicted by Sirius (left), AFRCWHEAT2 (middle) and DSSAT (right).

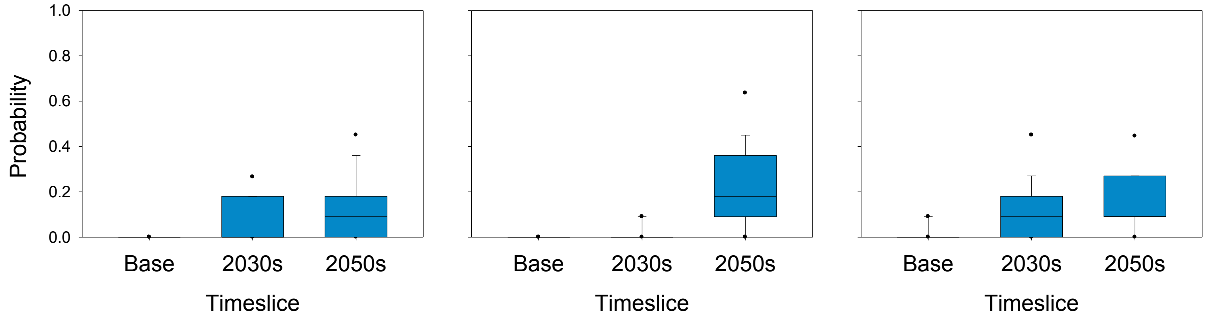


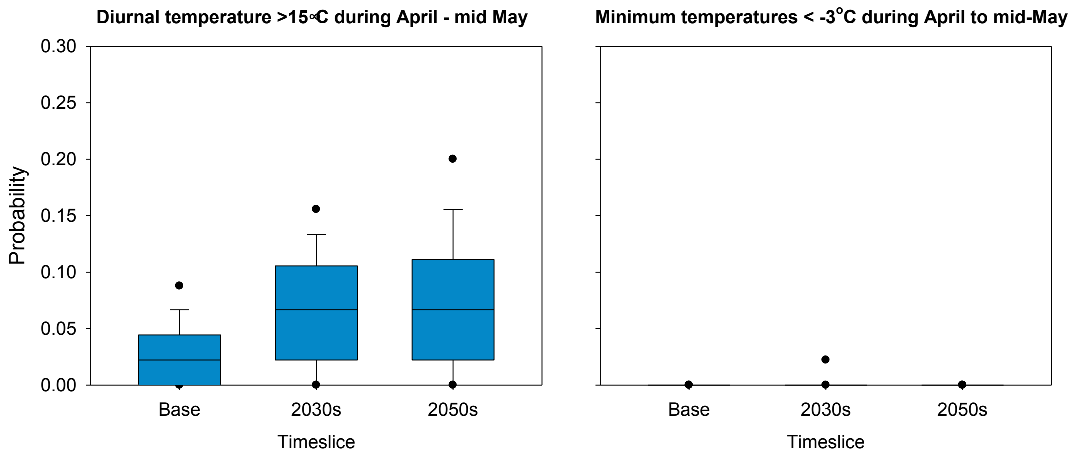
Figure 4.1c. The probability of high temperatures (>27°C) occurring on any given day during the 10 days proceeding anthesis as predicted by Sirius (left), AFRCWHEAT2 (middle) and DSSAT (right).

For each year of synthetic weather data, the anthesis dates predicted by each model were used to investigate the incidence of 27°C occurring in the 10 days following the start of anthesis. The fact that anthesis is predicted to occur earlier in part compensates for increased ambient temperatures. However, the probability of high temperatures causing grain sterility still increases over time (Figure 4.1c).

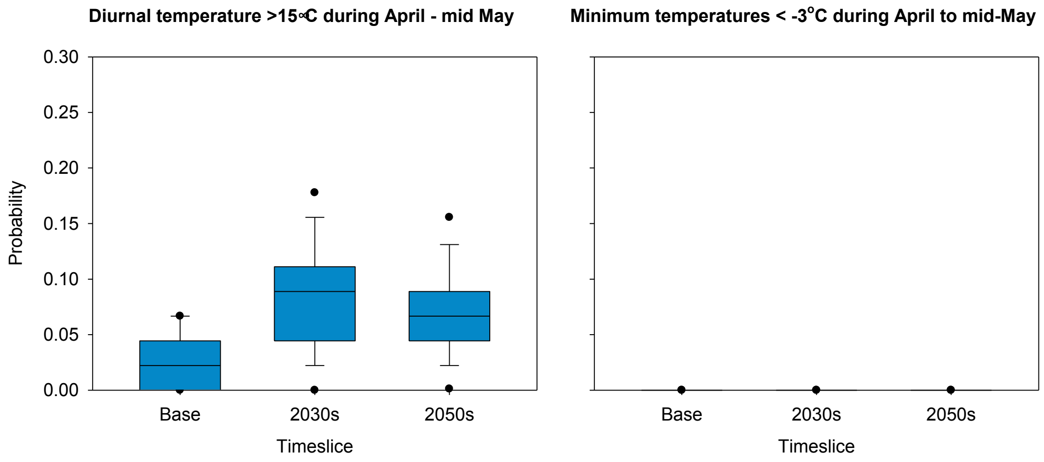
Case study 4.2 Sexual asynchrony

Another issue mentioned at the first workshop (on 19 October 2009) was that of cold weather from 1 April to mid May (pre-meiotic division) resulting in the male and female becoming asynchronised. The feeling was that this might be caused by low absolute temperatures (below -3°C), or large diurnal temperature variations (>15°C). The probability of exceeding these thresholds during the defined period was examined (Figure 4.2) at three sites, Rothamsted, Wyton (Cambridgeshire) and Boulmer (Northumberland). It can be seen that the probability of going below -3°C at this time of year is very small at all three locations. However, there is a much greater chance of achieving a diurnal variation of greater than 15°C, especially in the two more southerly locations. The chances of this occurring also increased with climate change, presumably due to warmer days.

Rothamsted



Wyton, Cambridgeshire



Boulmer, Northumberland

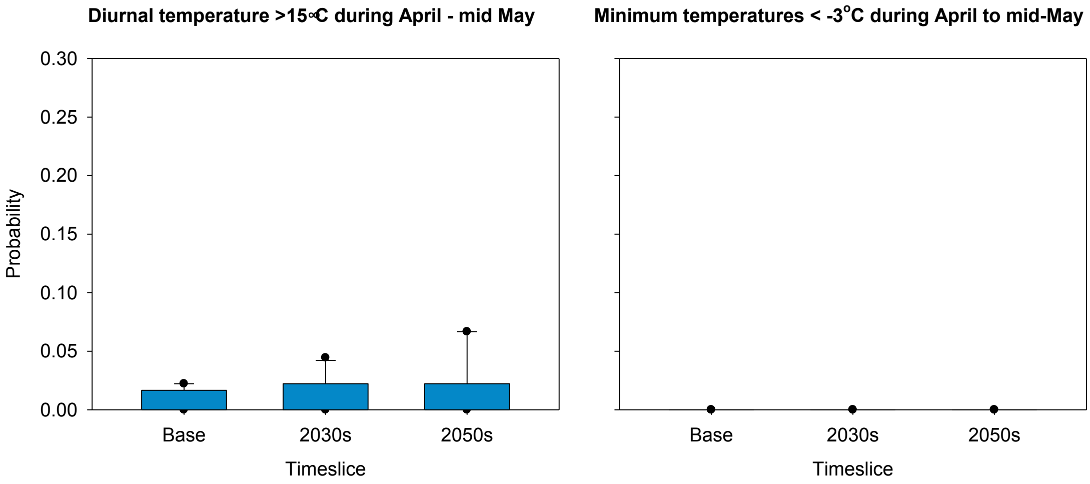


Figure 4.2. The probability of extreme diurnal temperature variations (>15°C) of low temperature (-3°C) occurring during the period 1 April through to mid May.

These results suggest that yields of winter wheat are likely to increase as a result of climate change. However, there is a slight increase in the risk of high temperatures around the time of anthesis causing sterility, and greater diurnal temperatures in April through to mid May, which might be associated with asynchronisity between, male and female.

Pests and diseases

A range of pests and diseases were identified by industry experts as being a problem for wheat. These include yellow cereal fly, gout fly, eyespot, sharp eyespot, powdery mildew, lemon blossom midge. The top three were agreed to be root diseases, of which take-all is a major threat, wheat bulb fly and slugs (see section on generic threats).

Case study 4.3 Winter Wheat Take-all

Gaeumannomyces graminis is a major root-rot pathogen of cereals and grasses. It is most damaging to intensively grown wheat and barley crops, when the same crop is grown year after year at a site. It survives in the infected residues of one crop then invades the roots of the following crop, progressively destroying the root system. In exceptional cases it can kill the whole crop; hence the name "take-all". Take-all is a highly destructive disease for which there are no known resistances.

Associations between winter temperature and rainfall and incidence of disease were used to forecast take-all (Lucas *et al.* 1998). Years with low incidence were associated with <500 DD>0°C from sowing to 60 days afterwards and with <400 DD>0°C from 60 to 150 days after sowing. Rainfall did not appear to be limiting except when >300 mm of rain fell in the period from 60 to 150 days after sowing.

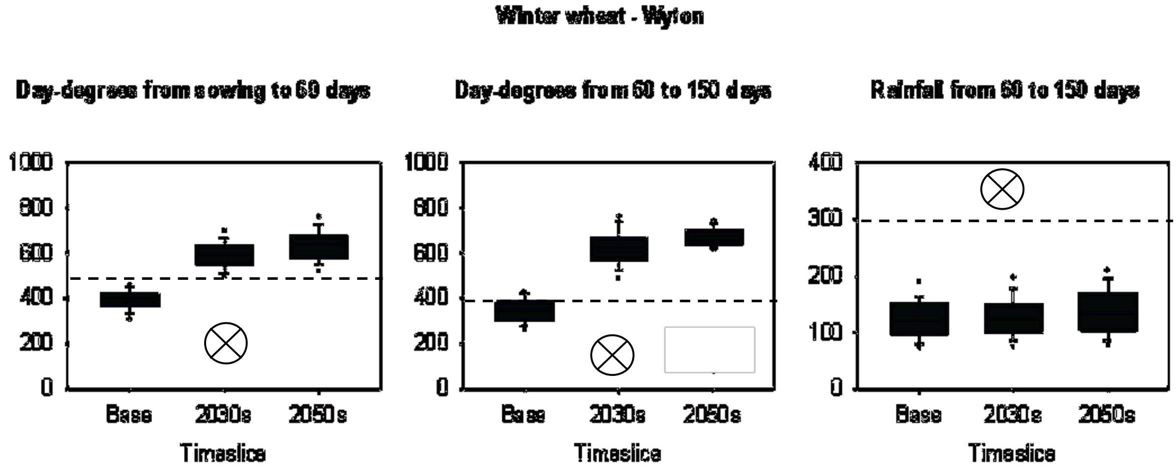


Figure 4.3 Estimated day-degrees and rainfall conditions that affect the incidence and severity of Take-all infections of wheat at Wyton, Cambridgeshire for Base, 2030s and 2050s time slices. Dotted lines indicate the thresholds and ⊗ is the condition relative to the threshold that is unfavourable for disease development

Taken together, conditions favourable for the development of take-all are forecast to become more prevalent in the 2030s and 2050s. The threshold of rainfall days between 60 and 150 required to prevent the disease is rarely achieved in the base calculations and this remains the same in the forecasts. The accumulated day degrees required for disease development, on the other hand, increase from mostly just below the threshold to regularly above the threshold. This suggests that the risk of crop losses to take-all, already an important disease, becomes significantly higher in the future and developing resistant varieties or effective control methods is a high priority.

Case study 4.4 Winter Wheat and Wheat bulb fly

Wheat bulb fly is a serious pest on wheat and other cereal crops. The adult female lays eggs in exposed soil in July-August. Eggs hatch in January-March. Larvae bore into the base of cereal plants feeding on the central shoot, a condition known as “deadheart”. An egg count of 2.5 million eggs per hectare is used as the threshold at which damage is likely in the following spring. We used the forecasting model of Young and Cochrane (1993), derived empirically from field sampling in East Anglia 1952 – 1990, to predict the proportion of fields at or above the threshold for damage (Figure 4.4).

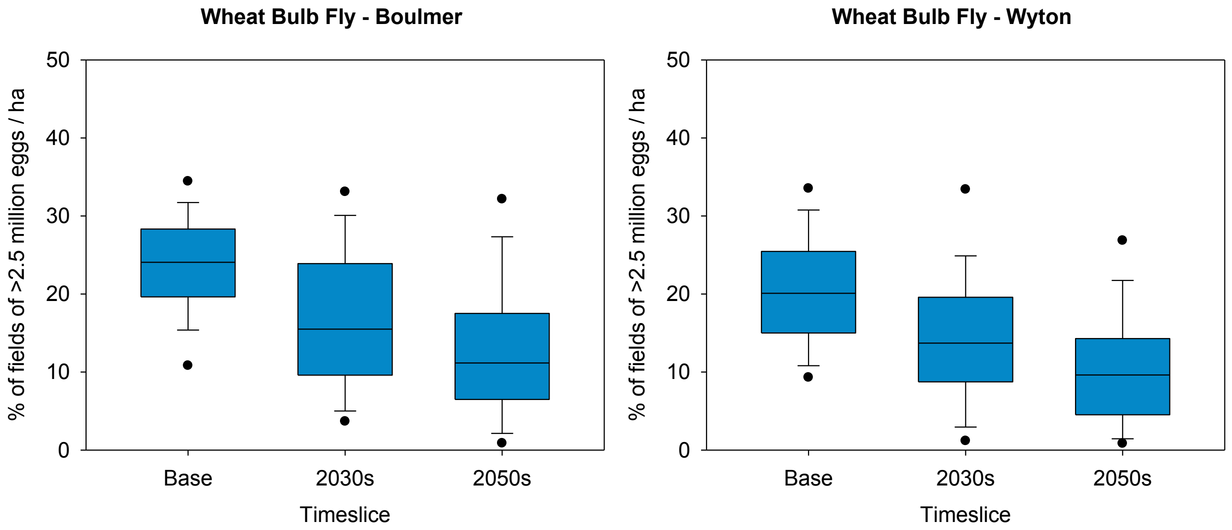
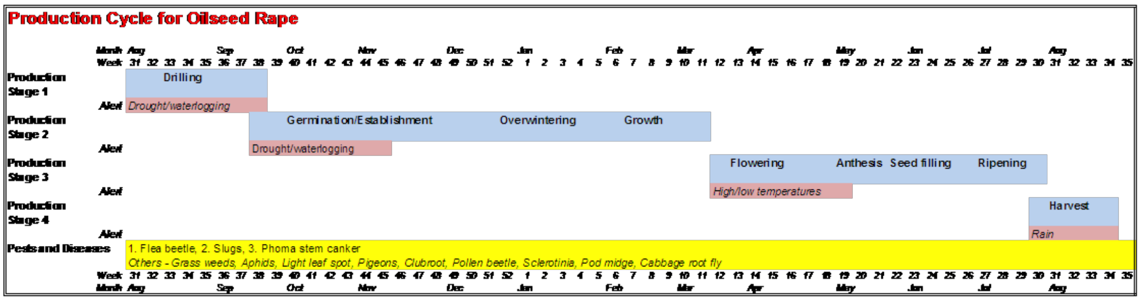


Figure 4.4 Calculated % of fields with more than 2.5 million wheat bulb fly eggs per hectare for Boulmer in Northumberland and Wyton in Cambridgeshire for Base, 2030s and 2050s time slices.

Using synthetic weather data from UKCP09, the model predicts that the likelihood of wheat bulb fly damage decreases steadily through to the 2050s, implying that no specific adaptation measures beyond current practice will be required.

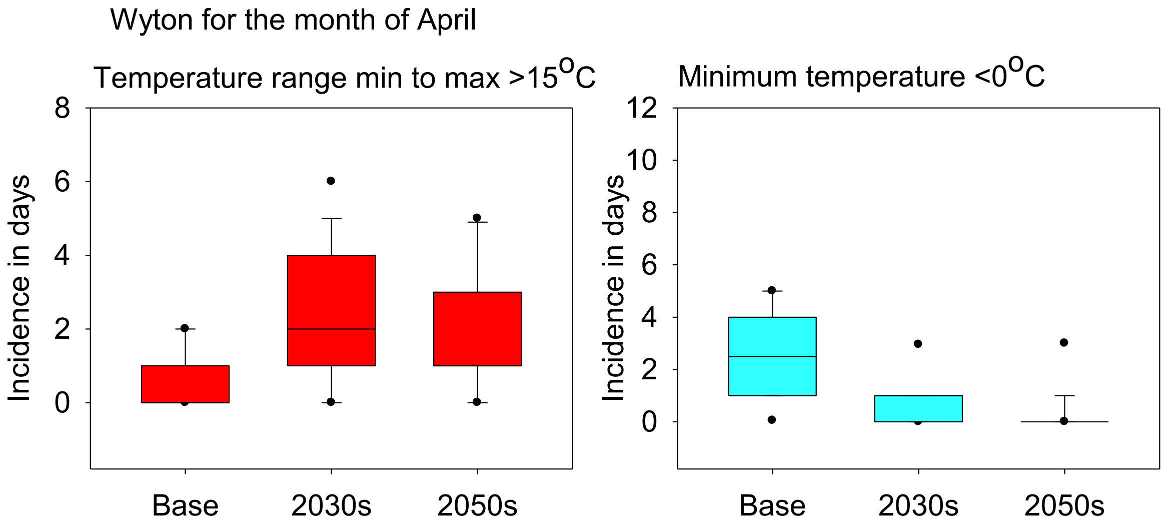
5 OIL SEED RAPE



Oil seed rape is grown as either a winter or spring crop in the UK. In this study we chose to consider winter oil seed rape, which represents more than 95% of the area grown in the UK. Winter rapes are sown at the end of August and the beginning of September and harvested the following July. The most important stage is getting to 3-4 leaves, after which the crop is very sturdy. The aim is to have the crop growing by mid-October or it will not survive the winter. Sowing takes place from mid August to the end of September. If the soil is wet it can become anaerobic and impair germination. However, UKCP09 synthetic weather outputs indicate that rainfall is not likely to increase in the late summer period and dry, rather than wet, soil may be more of a problem. Experiments carried out in controlled environments have identified anthesis as being sensitive to high temperatures e.g. 35 – 40 ^{o}C. However as anthesis occurs in May in the UK, this is unlikely to be a problem except in rare circumstances.

Case study 5.1 Oil seed rape and temperatures in April

From the workshop discussions, it emerged that as with wheat, late frost or large diurnal fluctuation in temperature can be a problem. For oil seed rape the critical period is during April when the crop is flowering. Thresholds where problems may occur were defined as the range between the daily minimum and maximum temperature being greater than 15^{o}C. The absolute minimum was less than -3^{o}C. As this is rarely seen in April, we took 0^{o}C as the threshold for this response.



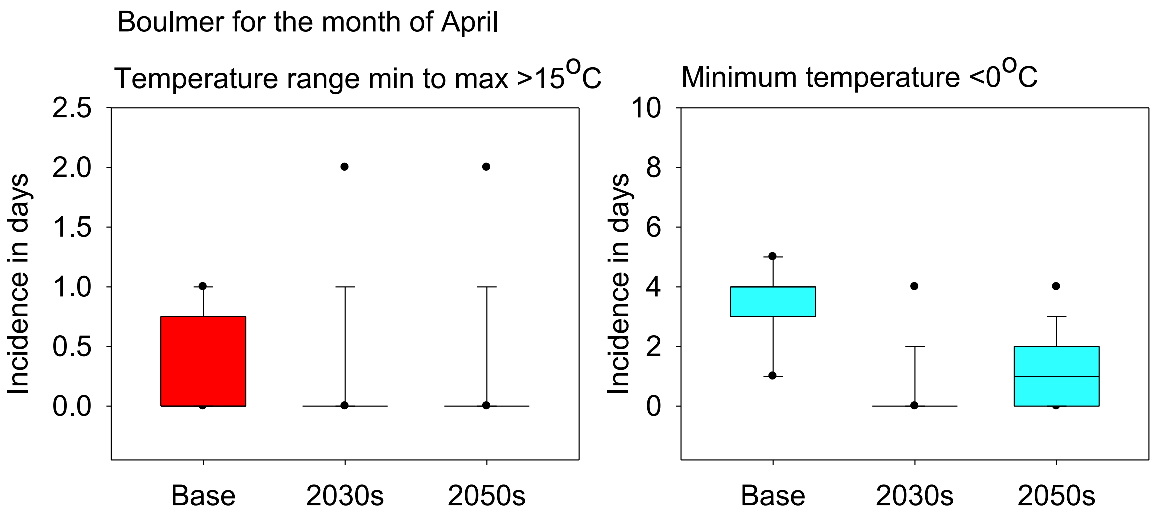


Figure 5.1 Incidence of days with a temperature range of more than 15°C or a minimum temperature of less than 0°C Wyton in Cambridgeshire and Boulmer in Northumberland for Base, 2030s and 2050s time slices.

The predictions based on UKCP09 synthetic weather data indicate a decrease in the number of days with temperatures of less than 3°C in April for both Cambridgeshire and further North in Northumberland (Figure 5.1). The pattern for temperature range however, was related to location. In Cambridgeshire there is predicted to be a small increase, while in Northumberland average risk decreases but this accompanied by a large increase in variability. For both these indicators the number of days per month and the change was very small and so these are unlikely to be significant issues for the industry in the foreseeable future.

Pests and diseases

From discussions with the consultation group, the top three pest and disease threats were identified as cabbage stem flea beetle, slugs and phoma stem canker.

Case study 5.2. Cabbage stem flea beetle *Psylliodes chrysocephala L.*

Cabbage stem flea beetle (*Psylliodes chrysocephala*) is widespread and is a significant pest in winter oil seed rape where the adult beetles cause “shot-holing” damage to cotyledons and early leaves. Adult numbers are at their peak in late September to early October and, in addition to damaging the crop, lay eggs in the soil. The larvae hatch in the period from October to April and cause holing and purple discoloration of the leaves. The larvae also can cause extensive damage by burrowing into leaf stalks and the main stem.

Using the relationship between temperature and egg laying (Bonnemaison, L. & Jourdheuil, P. (1954), the number of eggs laid over a 31 day period in October was estimated (for Wyton in Cambridgeshire and for Boulmer in Northumberland Figure 5.2).

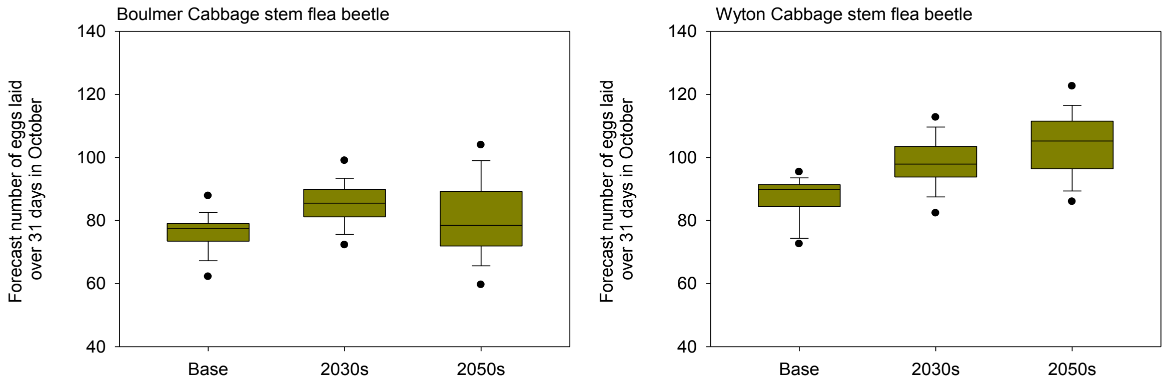


Figure 5.2a Forecast of the total number of eggs laid in October for Boulmer and Wyton for Base, 2030s and 2050s time slices.

Using base temperatures and sums of thermal time, the developmental stages of cabbage stem flea beetle can be forecasted (Derron, 1979). Starting from 1 October, when the eggs would be laid in the stem of the plant, we predicted the hatch of eggs, the stage when the larvae pupate in the soil and the emergence of the adults. Again, forecasts were made for Wyton in Cambridgeshire and for Boulmer in Northumberland.

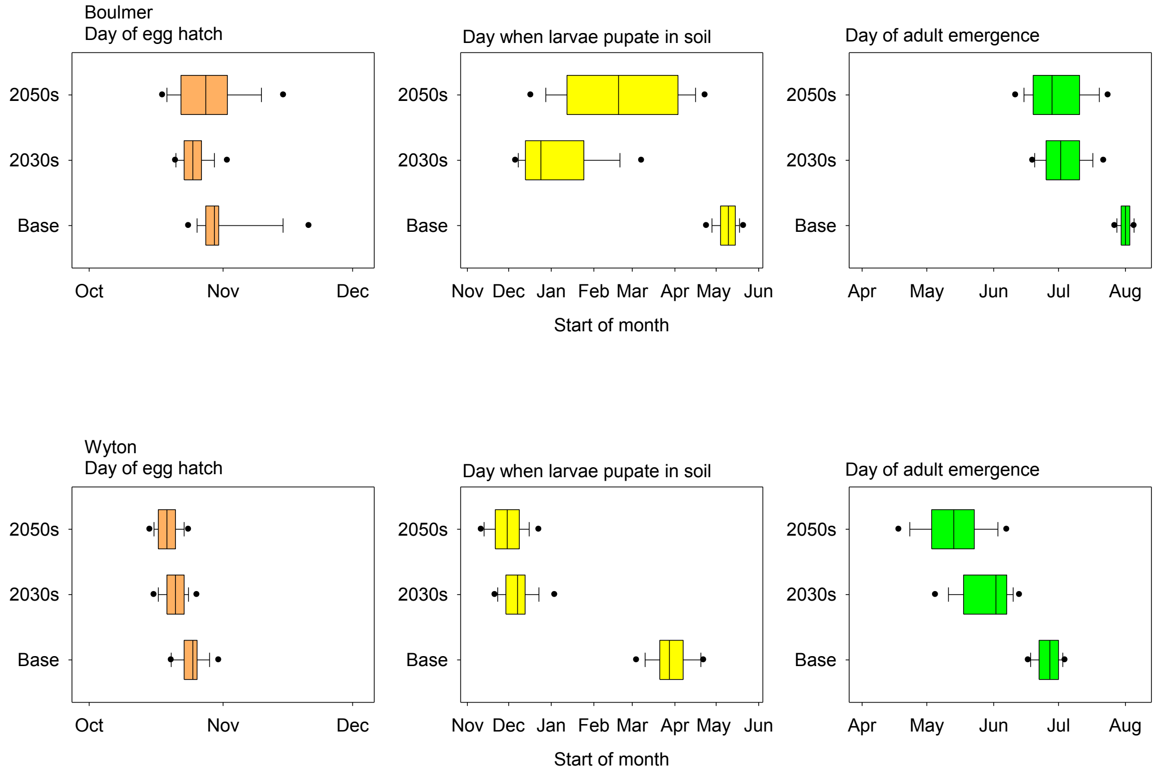


Figure 5.2b Forecast of the day of egg hatch, larval pupation and adult emergence for Boulmer and Wyton for Base, 2030s and 2050s time slices.

Overall, the models predict a pattern of change over time starting with earlier adult emergence, particularly in Cambridgeshire. Egg hatch is also predicted to be earlier in Cambridgeshire and the model also predicts that pupation will take place much earlier, especially for Cambridgeshire. Thus the period of damage is shorter, but the implication is that the larvae will be more active during their growth period. The model also predicts increased egg numbers in the more southerly location. The changes predicted indicate a complex interaction with the insect life cycle, making it difficult to assess the total impact. It is apparent that the changes will be more significant for the southerly location, with relatively small changes predicted for the Northumberland location.

Case study 5.3 Phoma stem canker

Phoma stem canker or blackleg is caused by *Leptosphaeria maculans*, and is an important disease on oil seed rape. It results in seedling death, lodging or early senescence. It is widespread, being found in Australia, Canada and Europe.

We used a weather-based disease-forecasting model (Evans *et al.* 2008) to forecast the severity of phoma stem canker epidemics on oil seed rape. The forecast is made using a combination of three models. The first model forecasts the start of the leaf spotting epidemic using mean maximum temperature and total rainfall between 15 July and 26 September. From the forecast start of the epidemic, the second model forecasts the start of phoma stem canker in spring using a target of accumulated thermal time either for susceptible cultivars with resistance rating 1-5 (www.hgca.com), or for resistant cultivars with resistance rating 6-9. The third model then forecasts the severity of stem canker at harvest on 15 July on a 0-4 scale as proposed by Zhou *et al.* (1999), for both the susceptible and the resistant cultivars, using a function of thermal time. Forecasts were made for Wyton in Cambridgeshire and for Boulmer in Northumberland (Figure 5.3).

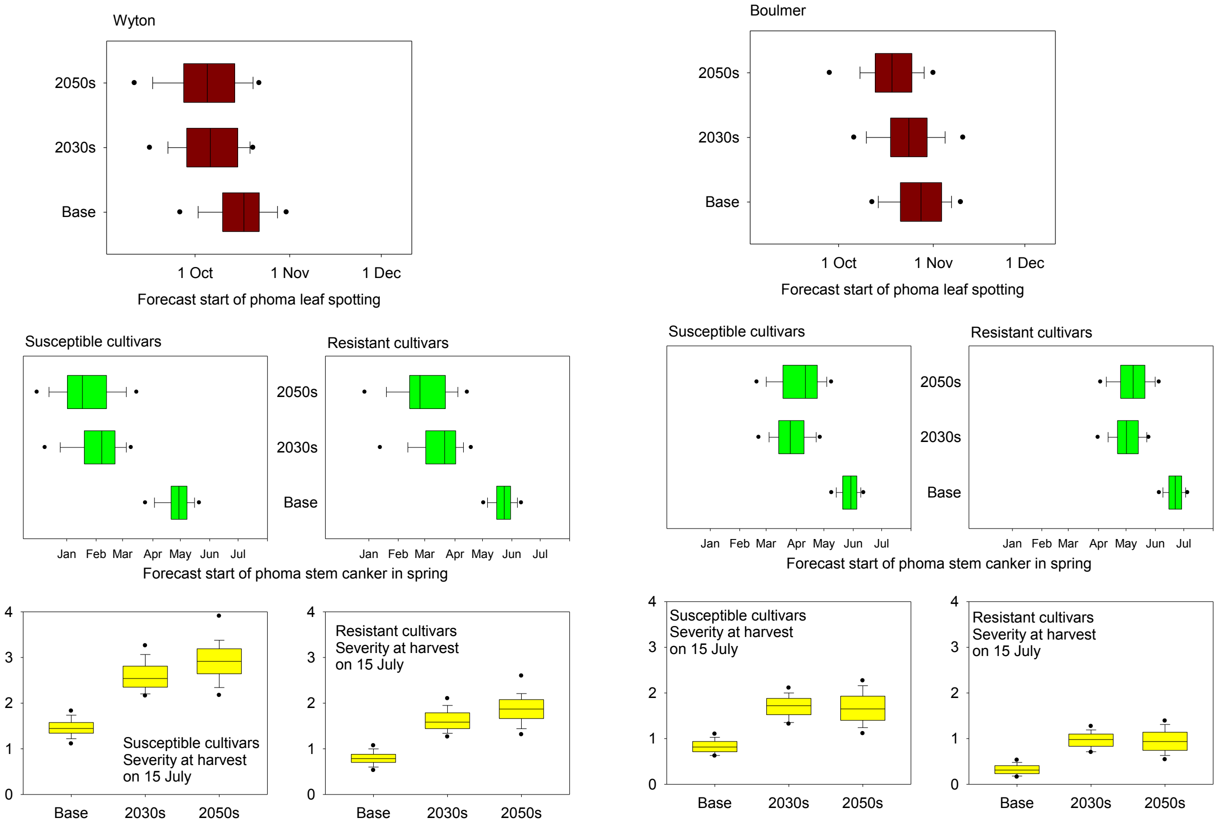
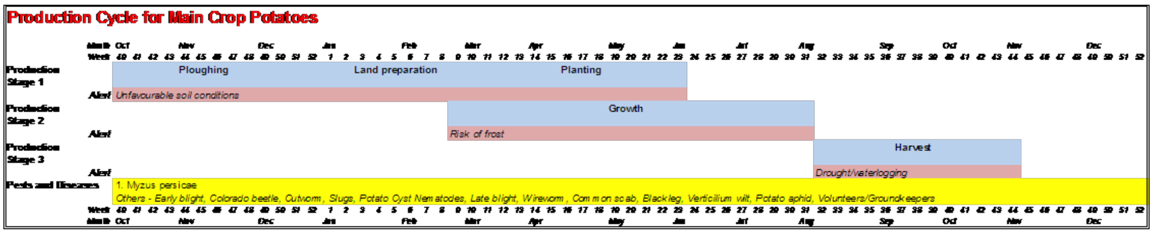


Figure 5.3 Forecast of the date of leaf spotting, start of stem canker in the spring and severity of symptoms for Phoma stem canker in susceptible and resistant varieties of oil seed rape for Wyton and Boulmer for Base, 2030s and 2050s time slices.

According to the forecast, leaf spotting is likely to be observed slightly earlier in Cambridgeshire than Northumberland under base conditions. In both cases, spotting is observed progressively earlier in both locations in the 2030s and 2050s time slices. The start of stem canker in the spring is likely to be much earlier in the future, advancing from May to February in Wyton and from June to April in the more northerly location for susceptible varieties and a similar shift, but slightly later for resistant varieties. There was a significant increase in the severity of symptoms forecast for both sites but particularly at Wyton in the susceptible varieties. Breeding for resistance to Phoma will be increasingly important for oil seed rape production in the future, particularly in the more southern locations, and is a priority target for adaptation.

6 MAINCROP POTATOES



UK potato production is highly complex with different cultural practices relating to the market for which the crop is produced. In this study we concentrated on maincrop potatoes, which are grown in widespread locations across the UK. In a previous study we reviewed the general threats to potato production and in this report we concentrate on case studies of particular vulnerabilities identified by the consultation group and in discussion with industry experts. We chose three locations, Camborne in Cornwall, Kirton in Lincolnshire and Fowlis in Angus to cover the geographical range of the crop.

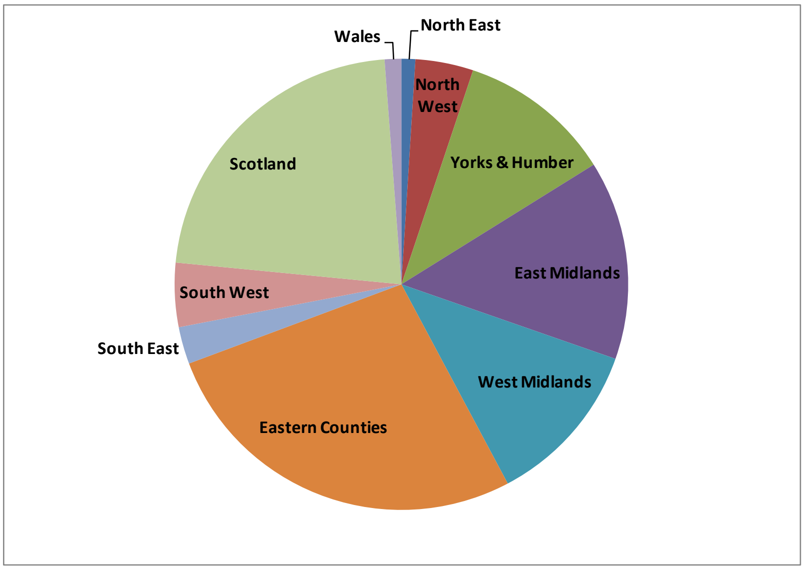


Figure 6. Distribution of maincrop potato production in the UK in 2009 (taken from Defra statistics)

Case study 6.1 Potato planting and temperatures in March

Following the workshop, it was suggested that planting may take place earlier, in either mid-March or even 1 March, if the risk of frosts were to diminish. To explore this, incidence in March of a minimum temperature ≤0°C was evaluated for Camborne, Kirton and Fowlis (Figure 6.1). The analyses show that the baseline prevalence of frost days in March is lower in Cornwall than in other parts of the country, with the Eastern part of England being the highest and Scotland sitting between the two. The risk from late frosts in March is predicted to decrease in all regions and by the 2050s appears to have a low probability of occurring in the Cornwall region. A general decrease in the predicted mean for the other regions is partially offset by an increase in variability. Overall these data suggest that earlier planting will become increasingly feasible in the South West but will be a risky strategy in more northerly locations.

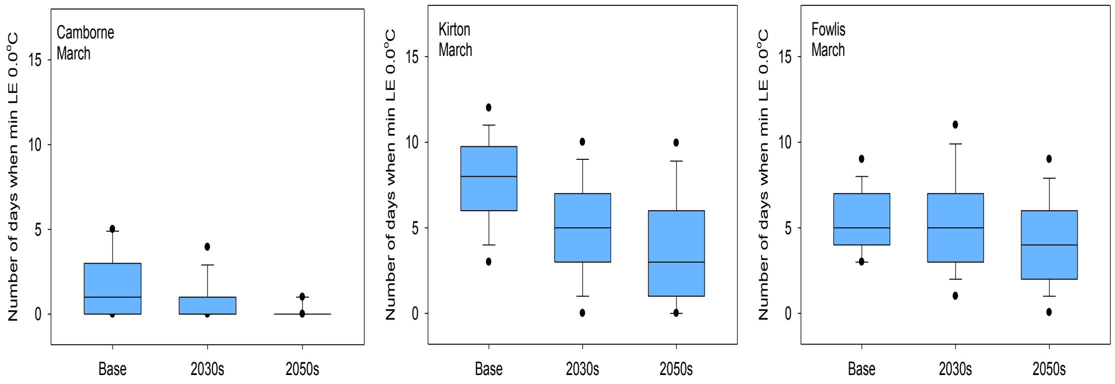


Figure 6.1 Forecast prevalence of days in March where the temperature is 0^{o}C or below in Camborne, Kirton and Fowlis for Base, 2030s and 2050s time slices.

Case study 6.2 Lifting of main crop potatoes in the autumn.

During 2000, heavy rainfall late season caused widespread problems for potato lifting (Potato Council, pers. comm.). By Christmas 2000, 20% of the crop (25,000 ha) was still in the ground. In a year where lifting goes to plan, by mid-September 70% of the UK crop is defoliated and ready to lift and go into storage. In order to identify threshold values of cumulative rainfall, data for Kirton in Lincolnshire for 2000, the problem season and 2003, a season where lifting went to plan, were compared. Examination of the rainfall data suggested that accumulations of 10mm or greater rainfall would be likely to cause problems with lifting. The analyses calculate the incidence of runs of 7 days with an accumulated rainfall total of 10 mm or greater between 1 August and 31 October.

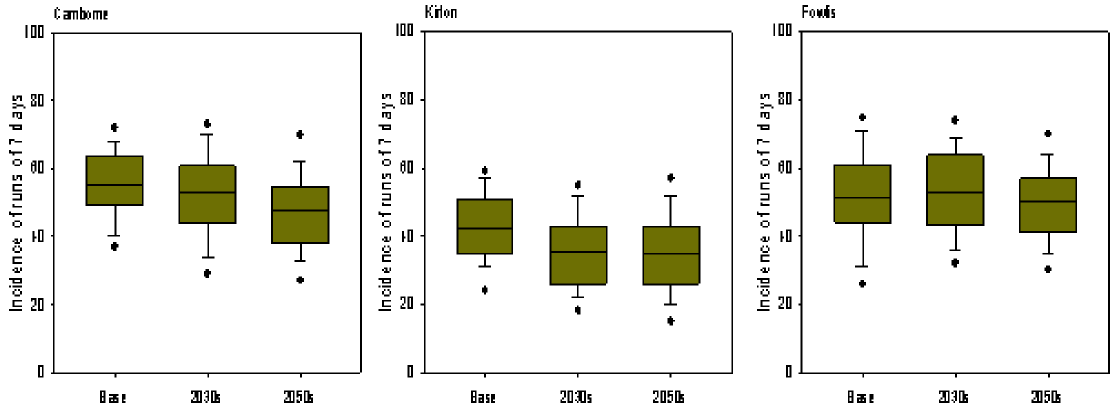


Figure 6.2 Forecast runs of 7 days between 1st August and 31st October with an accumulated rainfall total of 10mm or more in Camborne, Kirton and Fowlis for Base, 2030s and 2050s time slices.

The analyses indicate that for the base period, levels of rainfall that might affect potato lifting are more likely in Cornwall and Angus than in Lincolnshire. In the 2030s and 2050s time slices, the forecast prevalence of wet spells decreases in Cornwall and Lincolnshire but remains fairly constant in Angus. At present, wet spells cause problems in lifting, but the extreme situation faced in 2000 is still a rare event. The adaptations currently used by the industry are therefore likely to remain adequate and the overall problem is predicted to ease, particularly in the South West

Pests and Diseases

A range of pests and diseases can affect the potato crop. The main threats are shown in the crop cycle diagram. Discussions at the workshops identified the three most important pest and disease threats as being the aphid *Myzus persicae*, Late Blight and Slugs. Predictions of the likelihood of *Myzus* and slug attacks are presented in Section 7, (Generic Issues).

Case study 6.3 Late Blight (*Phythophthora infestans*)

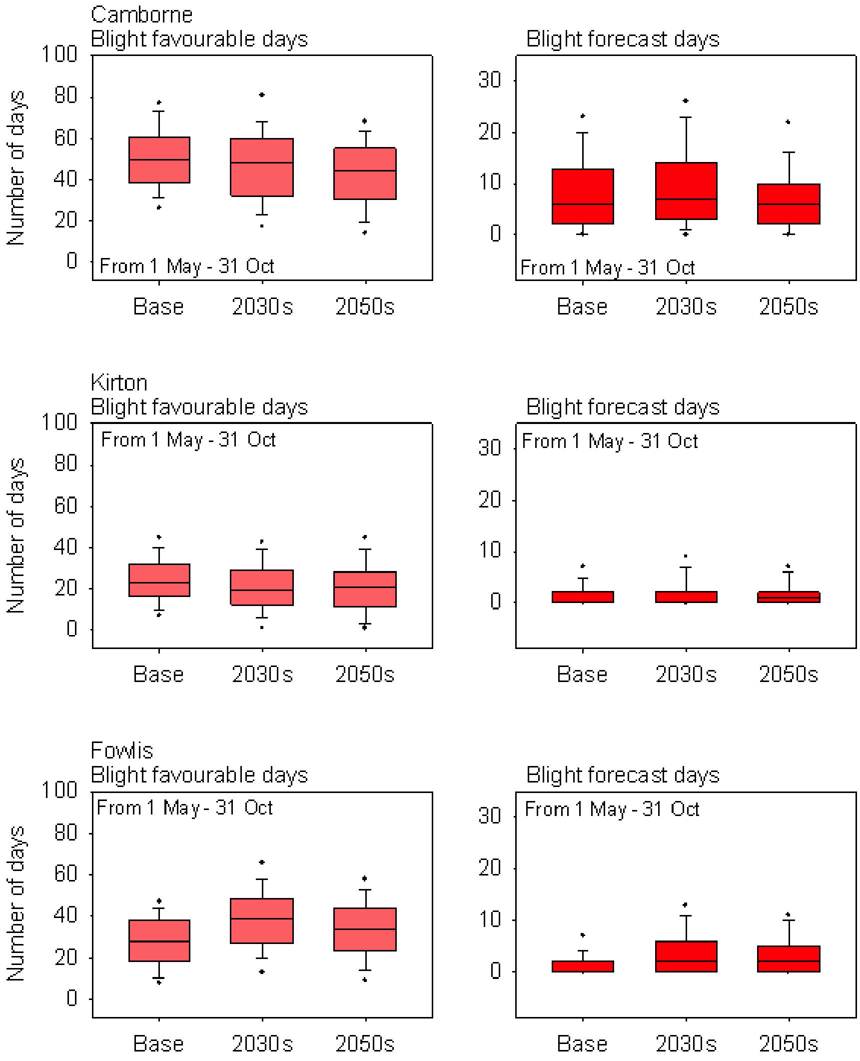


Figure 6.3 Predicted number of Blight favourable days and Blight forecast days at Camborne in Cornwall, Kirton in Lincolnshire and Fowlis in Fife for Base, 2030s and 2050s time slices.

A model (Hyre, 1954) was run to estimate the number of blight favourable days and the number of days when blight was forecast within a window from 1 May to 31 October for 100 samples at each location and for each timeslice. From baseline data, Camborne in the South West was predicted to be the most susceptible of the three areas for late blight followed by Fowlis in Scotland,with Kirton in Lincolnshire being the least at risk. In the future predictions, this ranking remained the same but the overall risk was predicted to decrease with time at all three locations. This predicted decrease was least at Camborne indicating that by the 2050s time slice there would be significantly more risk of Blight in the South West than elsewhere in the country. However, the risk would still be less than at present, and one can anticipate that more blight-resistant varieties will become available over this time period.

7 GENERIC ISSUES FOR FIELD CROPS

Case study 7.1 Wet and dry conditions.

Very wet or dry soil conditions will have an impact across a range of crop production systems. Wet conditions can prevent machinery from getting onto the land to prepare the ground or harvest crops. Conversely, very dry ground can cause problems with growth and prevent seed planting. We used the UKCP09 outputs to look at predicted rainfall patterns (Figure 7.1a) and resulting periods of very dry (Soil Moisture Deficit (SMD) <20 mm) (Figure 7.1b) or very wet (SMD zero) conditions (Figure 7.1c).

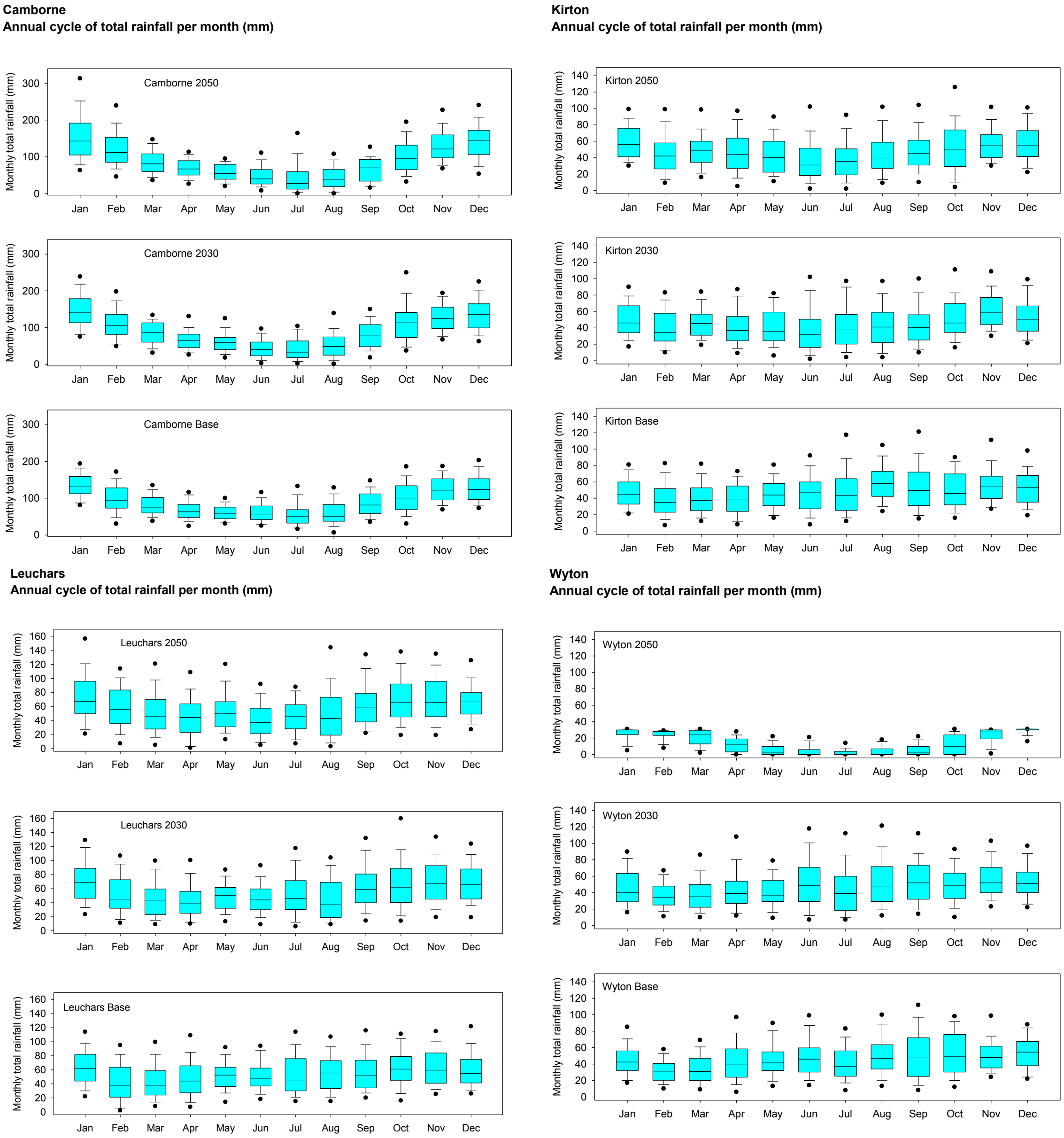
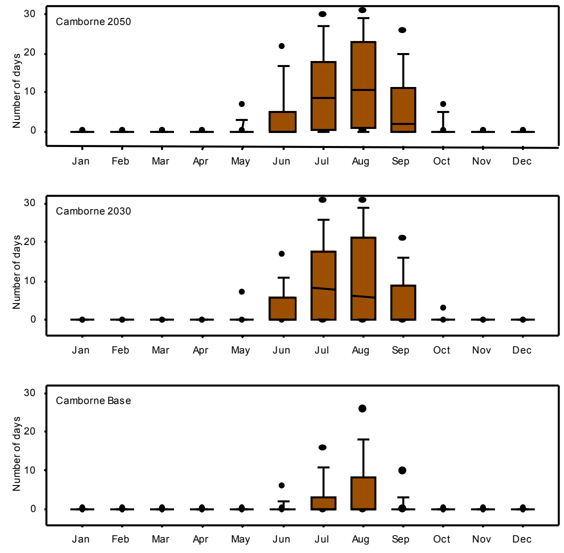


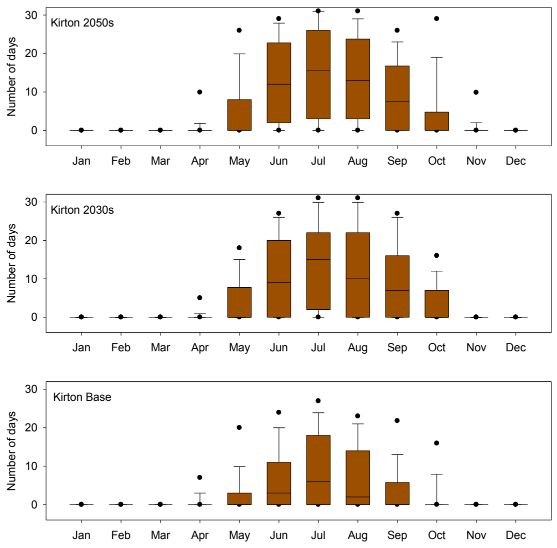
Figure 7.1a. Annual cycles of monthly rainfall for Camborne (Cornwall), Kirton (Linclolnshire), Leuchars (Fife) and Wyton (Cambridgeshire) for Base, 2030s and 2050s time slices.

The data show interesting differences for different parts of the UK. In Cornwall, which overall has the highest rainfall, a distinct pattern of winters having greater rainfall than the summer is maintained although the summer rainfall is predicted to decrease, giving a greater seasonal differential. Also, winter rainfall is predicted to become more variable. For the Eastern locations of Lincolnshire and Cambridgeshire, the annual distribution is more even, but for Cambridgeshire a significant overall decrease in rainfall at all points in the annual cycle is predicted to take place between the 2030s and 2050s time slices. For the Northerly location the distribution is relatively even with a slight increase in winter rainfall giving a more seasonal pattern into the 2050s

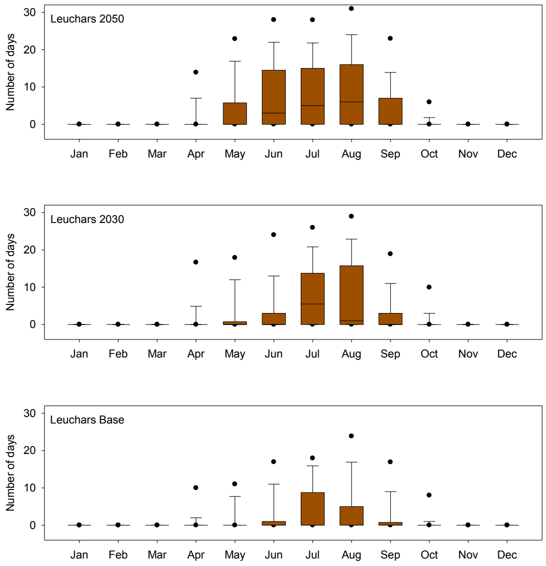
Camborne
Annual cycle of number of days per month when the soils dry defined as SMD >20mm



Kirton
Annual cycle of number of days per month when the soil is dry defined as SMD >20mm



Leuchars
Annual cycle of number of days per month when the soil is dry defined as SMD >20mm



Wyton
Annual cycle of number of days per month when the soil is dry defined as SMD >20mm

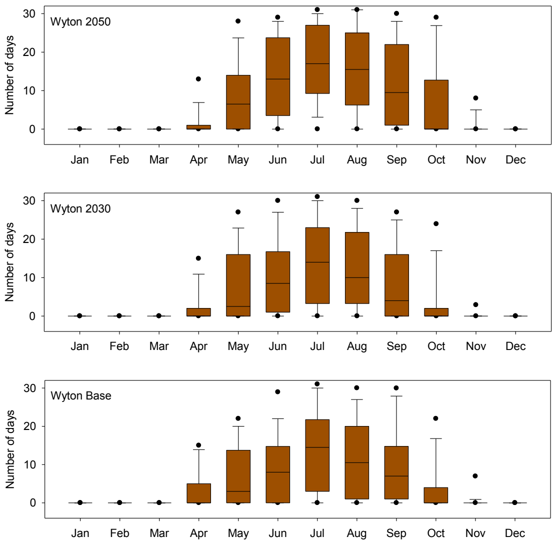


Figure 7.1b. Annual cycles of dry soil for Camborne (Cornwall), Kirton (Linclolnshire), Leuchars (Fife) and Wyton (Cambridgeshire) for Base, 2030s and 2050s time slices.

All four locations show an annual pattern where periods of dry soil are predicted to occur in the summer. For the base data, the incidence is very low in Cornwall but for the 2030s and 2050s time slices, the risk increases, with the vulnerable period being from June to September. The easterly

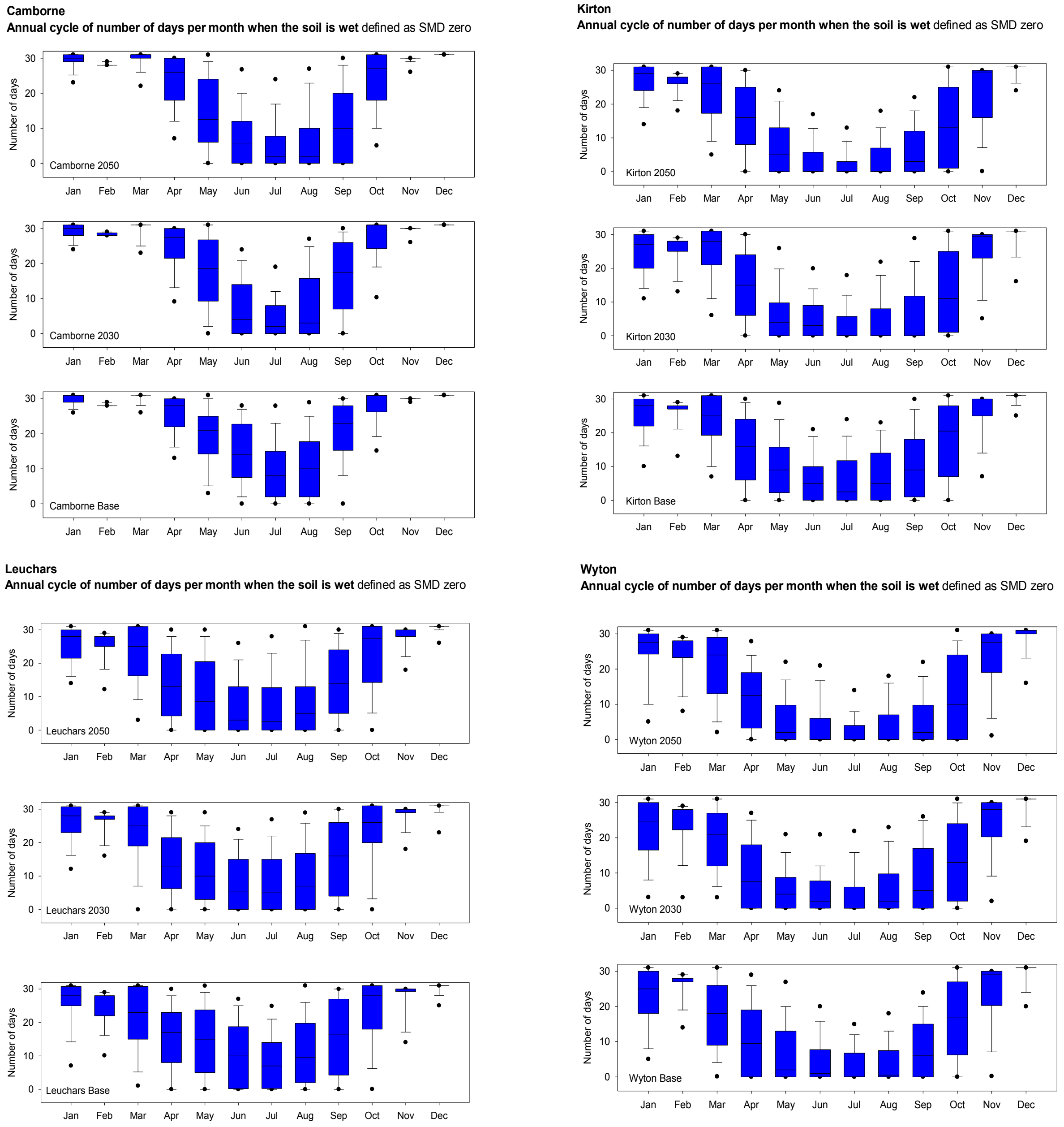


Figure 7.1c. Annual cycles of wet soil for Camborne (Cornwall), Kirton (Linclolnshire), Leuchars (Fife) and Wyton (Cambridgeshire) for Base, 2030s and 2050s time slices.

locations have a much higher risk for the base period, particularly in Cambridgeshire, and this is accompanied by a further increase in the prevalence of dry soil in the 2030s and 2050s time slices (Figure 7.1b).

For wet soil, the most vulnerable region is Cornwall in the South-West and this remains the case for the 2030s and 2050s time slices. For all regions the prevalence of days with wet soil decreases in the summer period with the difference being most apparent in Cornwall and Lincolnshire. Overall, the UKCP09 predictions do not suggest there will be significant increases in the prevalence of days with wet soil (Figure 7.1c). Rainfall increases are generally predicted for the winter in regions where the combination of rain and low temperatures already leads to a high incidence of wet soil.

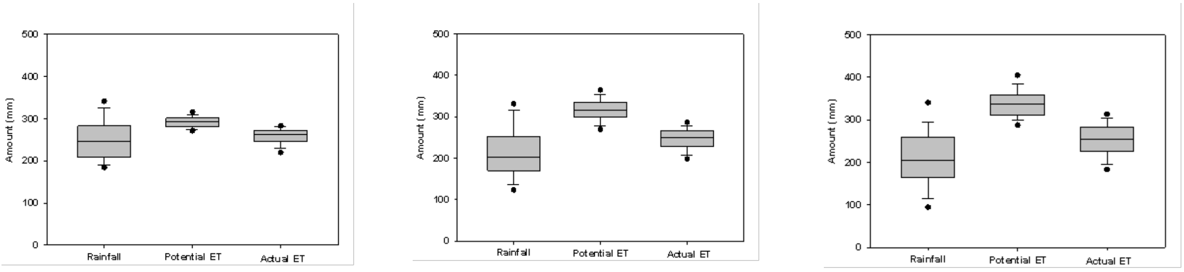
Case study 7.2: Crop yield and irrigation requirement

In this study we looked in more detail at the potential effects of climate change on the interaction between crop yield and irrigation requirements. We modeled the potential impact on the yield of potato, a crop that is usually irrigated, and the irrigation requirement for growing broccoli, currently a rain-fed crop. The model used in this simulation practice was developed by Yang *et al.* (2009) and validated over a number of crops (Yang *et al.*, 2009; Zhang *et al.*, 2011). The model, mechanistically devised, is able to simulate water dynamics in the soil-crop system, and estimate water requirement in crop production as described in the project FAO56 (Allen *et al.*, 1999).

The following assumptions and parameter values were adopted in this study:

- Kirton was selected as the production location, and the generated weather data for 'Base', 2030s and 2050s (each for 100 yrs) is used. Soil texture was assumed to be a sandy loam and the soil hydraulic property values are from Wösten *et al.* (1999).
- Potato was planted on 15 April and harvested on 15 September, while broccoli was planted on 1 June and harvested on 15 August.
- Durations of various growth stages and their corresponding crop coefficient for potential transpiration of both crops are according to the FAO56. Rooting depth was proportional to the above-ground dry weight and the maximum rooting depth was 50cm for both crops. Root length distribution was exponential from the soil surface, see Yang *et al.* (2009).
- Simulations are carried out from the first day of the year to the harvest date, and the soil water content in the profile at the beginning of simulations was at field capacity.
- The ratio of the actual yield Y_{act} to the potential yield Y_{pot} equals that of the cumulative actual envapotranspiration ET_{act} to the potential envapotranspiration ET_{pot} during growth (Wild, 1988), i.e. $Y_{act}/Y_{pot}=ET_{act}/ET_{pot}$
- The irrigation amount was the difference between the cumulative potential evapotranspiration ET_{pot} and rainfall during growth.

Figure 7.2a shows the graphical summary of predicted cumulative rainfall, potential and actual envapotranspiration from 'Base', 2030s and 2050s weather data during growth for potato crop. The average cumulative rainfall during the growing season would be about 250mm from the 'Base' weather data, whilst the corresponding value would drop to 215mm in 2030s and 210mm in 2050s. Meanwhile, the average potential ET_{pot} would increase from 293mm (Base) to 316mm in 2030s and 339mm in 2050s. The predicted actual ET_{act} would be about 258mm, 247mm and 252mm for 'Base', 2030s and 2050s, respectively.



(a) Base (b) 2030s (c) 2050s

Figure 7.2a: Predicted cumulative rainfall, potential ET_{pot} and actual ET_{act} during growth

Based on the above assumptions on yield ratios, the proportion of potential yield that could be achieved without irrigation would be about 0.88 for ‘Base’, 0.78 in 2030s and 0.75 in 2050s (Figure 7.2b), suggesting that climate change could significantly reduce the yield of potato grown in the selected location without irrigation. In addition, the variability in potential yield increases markedly with time suggesting that in some years the loss of yield would be very damaging. Clearly the requirement for irrigation in the potato crop will become more critical under future climate scenarios.

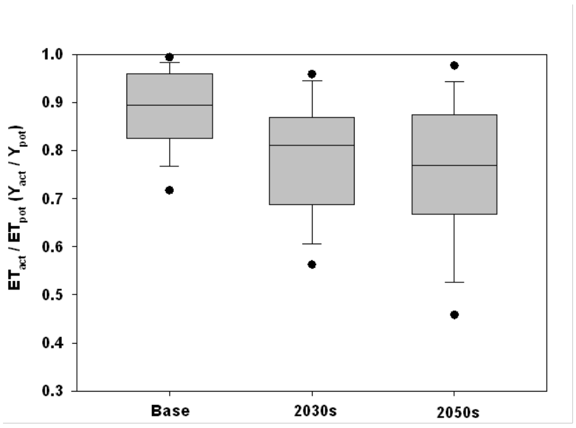
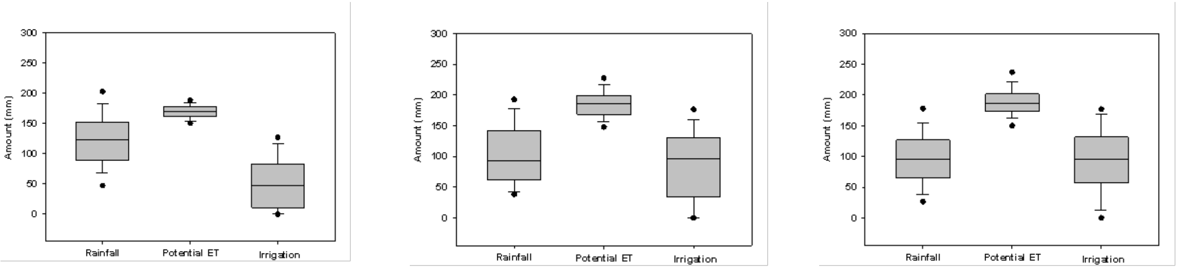


Figure 7.2b: Predicted ratio of actual yield Y_{act} to potential yield Y_{pot} for potato crop

Similar simulations were also carried out for growing broccoli in the identical location (Figure 7.2c). The average cumulative rainfall during the growing season would be about 123mm, 104mm and 97mm for ‘Base’, 2030s and 2050s, respectively. However, the average cumulative potential envapotranspiration ET_{pot} would increase from 170mm (Base) to 186mm (2030s) and 189mm (2050s). This indicates that there would be a big drop in rainfall and a noticeable increase in ET_{pot} from ‘Base’ to 2030s, but these changes would be flattening out from 2030s to 2050s. Irrigation requirement was simply calculated as the difference between the potential ET_{pot} and rainfall. The predicted irrigation requirement for growing broccoli in the selected location would be about 48mm for ‘Base’ and 96mm for 2030s and 2050s. Broccoli is resilient to moderate water deficits (Gutezeit, 2006) and the predicted changes between 2030s and 2050s are relatively small. The impact of future changes in soil water availability on brassica production may therefore be limited.



(a) Base (b) 2030s (c) 2050s

Figure 7.2c: Predicted cumulative rainfall, potential ET_{pot} and irrigation requirement during growth

Pests and diseases

The two pest threats identified as being relevant to several crops were slugs and *Myzus persicae*, the peach-potato aphid. We analysed the potential impact of changing climate on the prevalence of these threats.

Case study 7.2 Slugs.

We forecasted the number of days when slugs may be active using a threshold of ≥ 2mm of water remaining after potential evapotranspiration was subtracted from daily rainfall total, and a minimum temperature ≥ 5°C

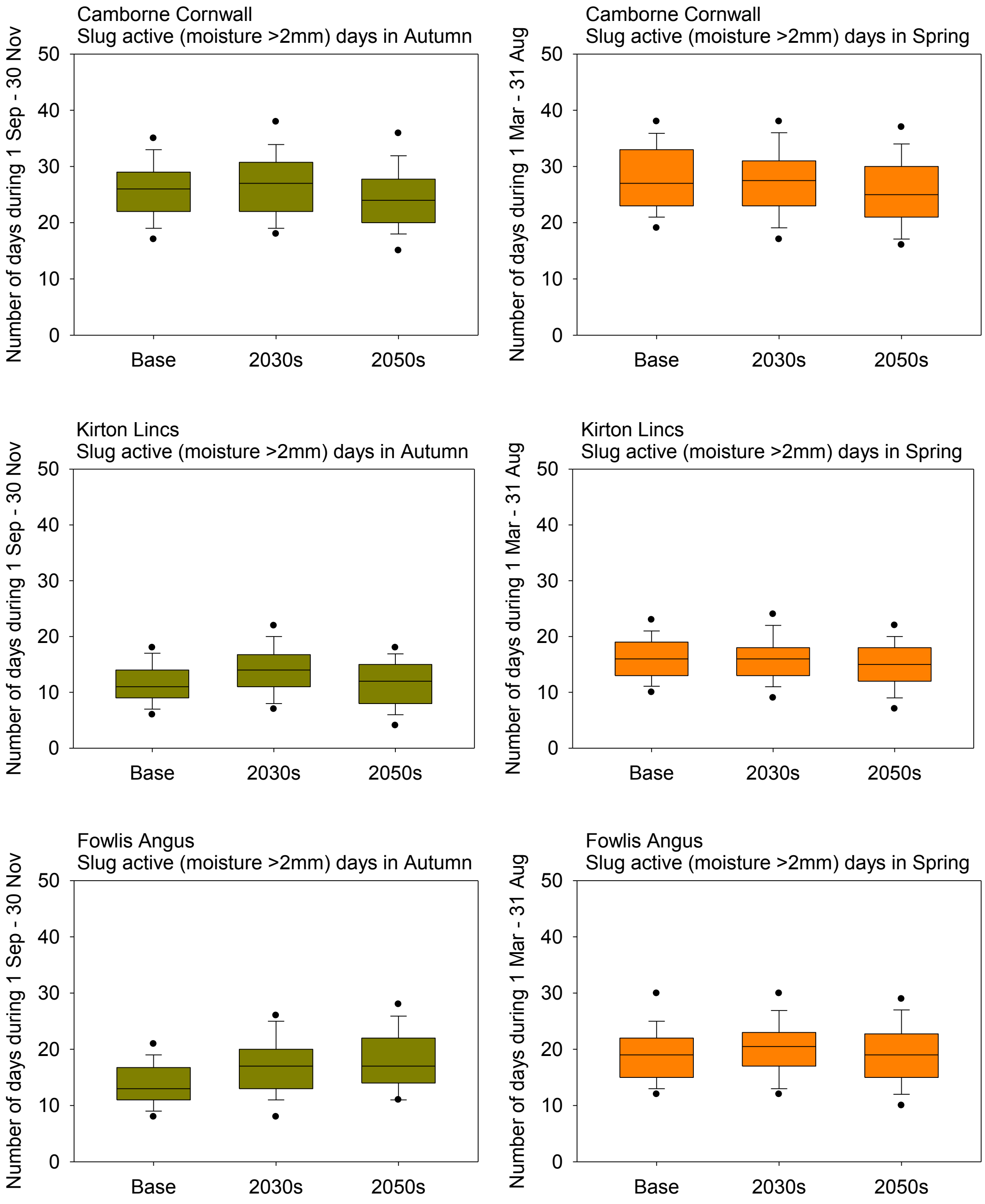


Figure 7.2. Days favourable for slug activity in Autumn and Spring for Camborne, Kirton and Angus for Base, 2030s and 2050s time slices.

The model for slug activity indicates that the higher spring and autumn rainfall in Cornwall (see Figure 7.1a) provides more favourable days for slug activity than in the other locations studied. There is no indication that this number of days varies appreciably between the 2030s and 2050s time slices with the possible exception of a slight increase for Angus in the period to the 2050s. Thus it is predicted that no additional adaptation responses to the changing climate are predicted to be required beyond control measures required under current conditions.

Case study 7.3 Peach-potato aphid *Myzus persicae*

Myzus persicae is highly polyphagous, being able to feed on hundreds of summer host species from over 40 families. The models predict the first sighting of the aphid based on historical trap data and the number of generations based on day degree models (Collier and Harrington, 2001).

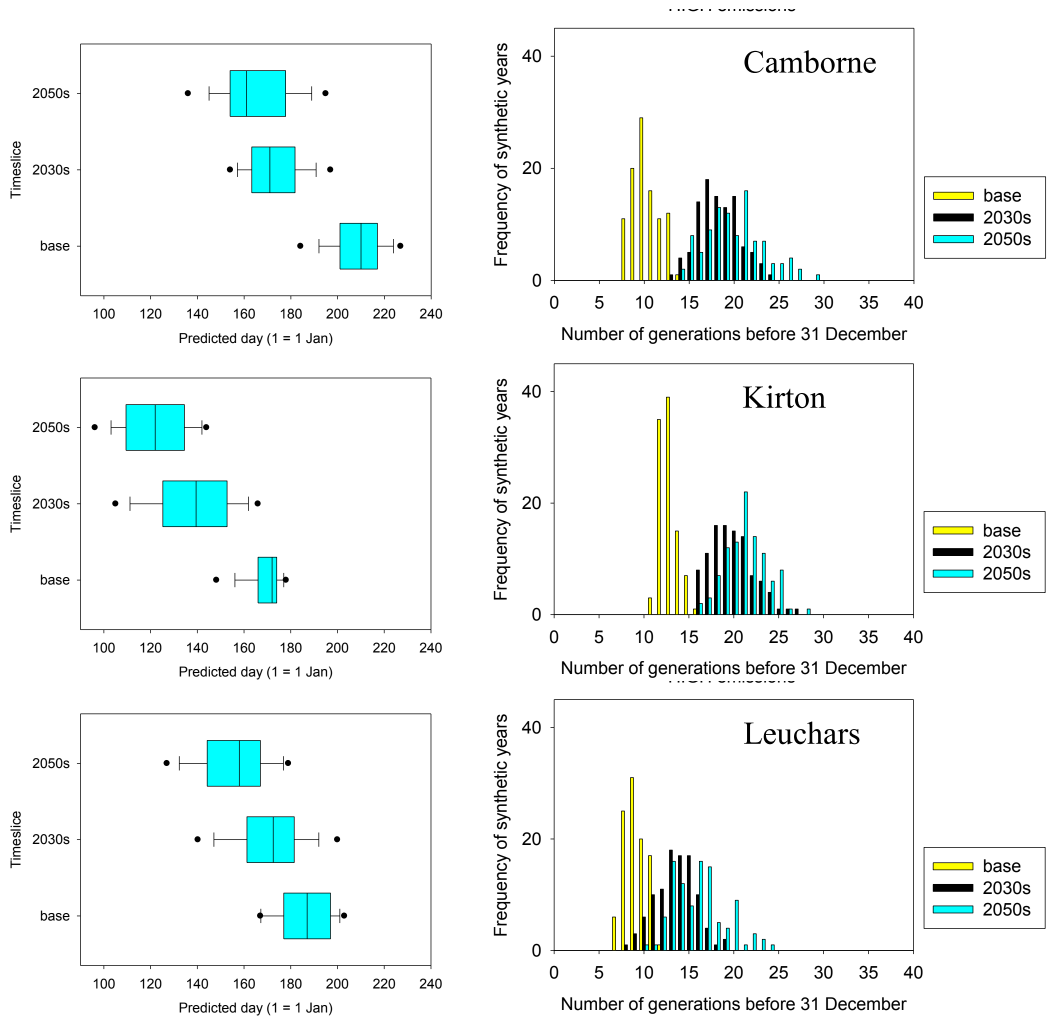


Figure 7.3. Predicted first sighting and number of generations of Myzus persicae for Camborne, Kirton and Leuchars for Base, 2030s and 2050s time slices.

The models predict that for base data aphid sightings are earliest at the Lincolnshire site, followed by Fife, with Cornwall being the latest to see the aphids. This pattern is maintained for the 2030s and 2050s time slices. For all three locations, the predicted number of generations increases with time to the 2050s, but with the biggest shift being between the base and 2030s time slices. This is very similar to the pattern seen with the Diamond back moth in case study 2.3.

8 PROTECTED CROPS - TOMATOES

In order to predict the effect of climate change on the internal environment and energy use of a glasshouse growing tomatoes, an energy balance model developed as part of Defra project AC0407 was used. The model includes all of the main heat flows within a glasshouse such as the heat losses via convection, radiation, leakage and ventilation, and evaporative cooling due to transpiration. The heat gains include solar radiation, heat from piped hot water and condensation on the cladding. The model also incorporates a layered soil model, which absorbs and returns heat to the glasshouse depending on the solar radiation and differences in soil and air temperatures.

The model was run assuming a 1 ha block of Venlo glasshouse growing tomatoes, heated with a 2MW gas fired boiler. During the day, the CO_2 from the boiler was used to enrich the glasshouse CO_2 concentration (up to 1000ppm) in order to increase photosynthesis and hence yields. Following commercial practice, we incorporated a 200m^3 hot water storage tank into the model so that gas could be burnt during the day and hot water stored for use at night. In this way there is more CO_2 during the day for enrichment and hence higher yields. During the day the boiler was set to burn at a rate that would fill the heat store by the end of the day and fulfil the heating requirement of the glasshouse. The heating system was set to achieve a minimum day temperature of 18°C. During the night the heating set-point was 17°C, and the heat was primarily taken from the heat store. However, if there was insufficient capacity in the heat store the boiler was also used at night to maintain the desired glasshouse temperature. Cooling was via ventilators in the glasshouse roof, and these began to open at 20°C (day and night). Some ventilation was also used when the glasshouse relative humidity exceeded 90%. Net canopy photosynthesis was predicted based on the model presented by Chalabi *et al*. (2002) and this was converted to a fruit yield based on 70% of assimilates being partitioned to fruits, a 5.5% dry matter content, and a 39% carbon content.

The model was run with hourly UKCP09 data for a site just south of Chichester (lat: 50.84; long: -0.78). Simulations were run for the base, 2030's and 2050's using 100 years of data for each time slice. As wind speed is not included in these synthetic weather data sets, a value of 4m/s was assumed. The external (ambient) CO_2 concentration was assumed to be 325, 452 and 567ppm for the base, 2030's and 2050's, respectively, based on average of the values predicted by ISAM and Bern-CC (reference) models for the A1F1 climate change scenario.

In the base year the average annual gas use was predicted to be 451kWh/m^2, of which 338kWh/m^2 was assumed to be delivered to the glasshouse as heat in the form of hot water (75% boiler and distribution efficiency). However, due to higher ambient conditions, the annual energy use is predicted to decline in the 2030's and 2050's when compared with the base period (Figure 8.1). The average gas use was predicted to be 341kWh/m^2 in the 2030's and 310kWh/m^2 in the 2050's. These values assume no heat is destroyed for CO_2 enrichment and a 'vent then reheat' humidity control strategy. If minimum pipe temperatures were used, the energy use would be higher and higher ambient temperatures would have less of an effect on the energy use.

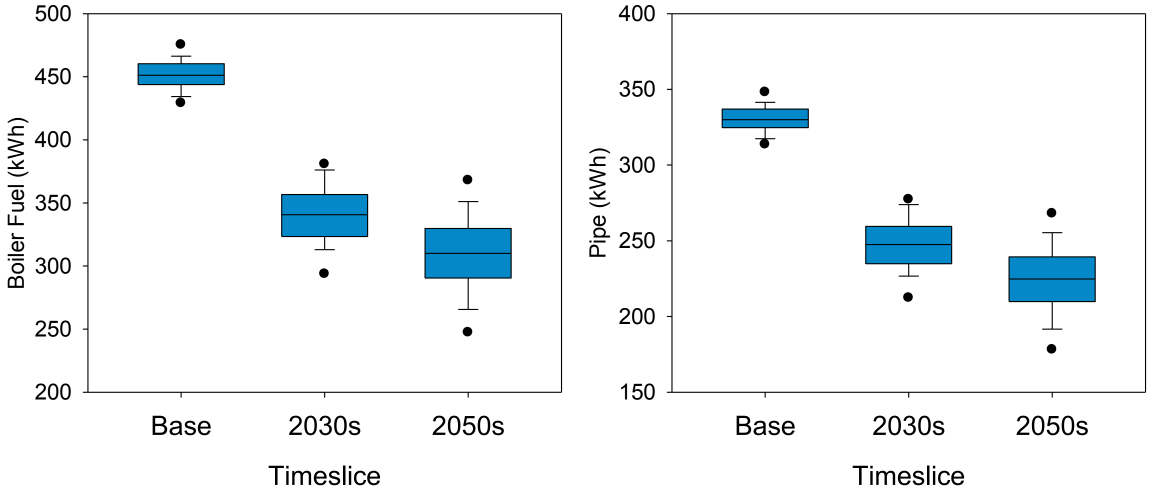


Figure 8.1. The impact of climate change on the predicted amount of gas burnt (kWh/m^2/annum) via a boiler and the amount of heat delivered to the glasshouse in the form of pipe hot water (kWh/m^2/annum).

In the winter months, higher ambient temperatures will tend to reduce energy use, but will have little effect on the internal glasshouse temperatures, due to the fact that there is heating to 17°C at night and 18°C during the day (providing that the boiler and pipes can provide sufficient heat). Whereas in the summer, higher ambient temperatures may increase the glasshouse temperature, even though there is ventilation at 20°C. The simulations suggest that this will be the case as average glasshouse temperatures are predicted to increase by 0.4°C by the 2030's and by 0.7°C in the 2050's (Figure 8.2). This is due to higher summer temperatures; the minimum temperature remains largely unchanged. This may prove detrimental in terms of summer fruit quality and more erratic yields.

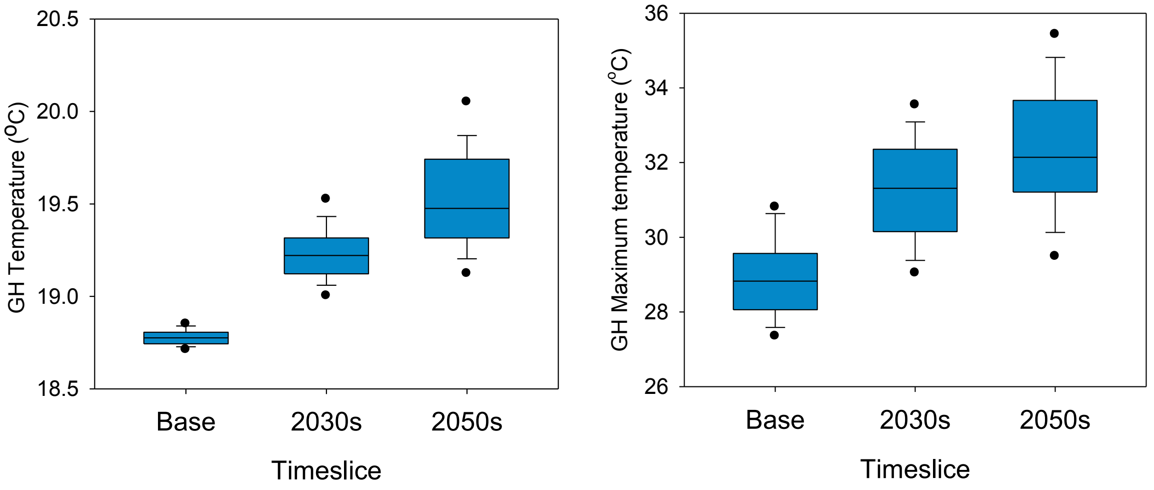


Figure 8.2. The impact of climate change on the predicted mean diurnal glasshouse temperature and the maximum temperature recorded in the glasshouse over the course of the year.

The RH/HD in a glasshouse is very important because of disease; high humidity will tend to encourage diseases such a botrytis. High RH can also reduce transpiration, and if transpiration is too low, yields can be affected as a result of poor calcium uptake and leaf damage. The predicted increase in the average RH is minimal (around 1%) and, therefore, the impact on crops is likely to be small and could be controlled through modification of the humidity control strategy.

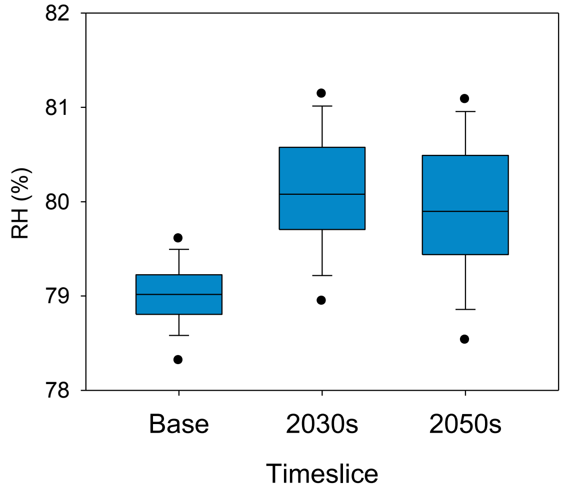


Figure 8.3. The effect of climate change on the mean diurnal relative humidity of the air.

The desired concentration of 1000ppm is unlikely to be achieved when there are high ventilation rates, or when the heat demand is low and little CO_2 is produced. The model was initially run for each time slice with the ambient CO_2 concentration at the 325ppm base level. Lower internal CO_2 concentrations, and hence yields, were predicted (Figure 8.4). This was because of higher ambient temperatures reducing the heating demand and therefore CO_2 availability, and increasing the amount of ventilation which increased the CO_2 loses.

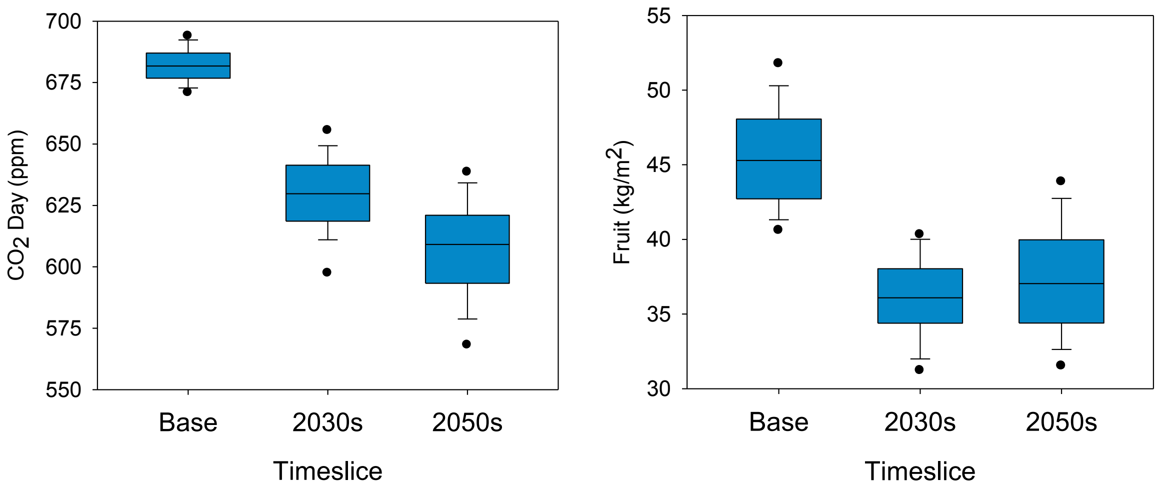


Figure 8.4. Predicted internal average CO_2 concentrations and associated fruit yields assuming an ambient CO_2 concentration of 325ppm.

When higher ambient CO_2 concentrations were factored in (Figure 8.5), higher internal concentrations could be achieved and yields were predicted to increase as a result. However, this assumes no heat destruction for CO_2 and different results may be obtained where there is a different relationship between CO_2 availability and heat use. For example, with combined heat and power (CHP) more CO_2 is available for a given heat output (due to the production of electricity). As a result the set-point concentration of 1000ppm will be achieved more frequently than with a boiler, and higher ambient concentrations will presumably have less of an impact.

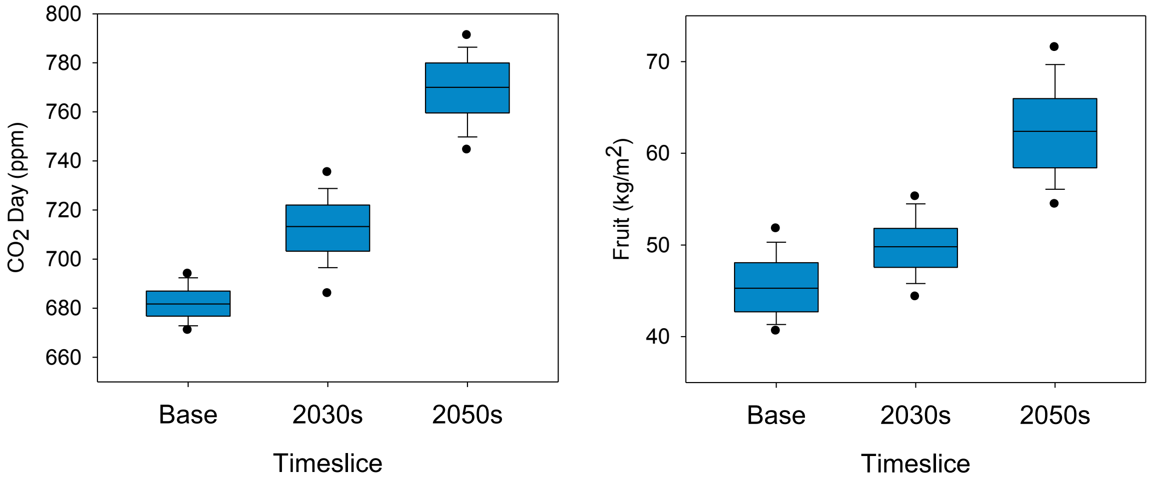
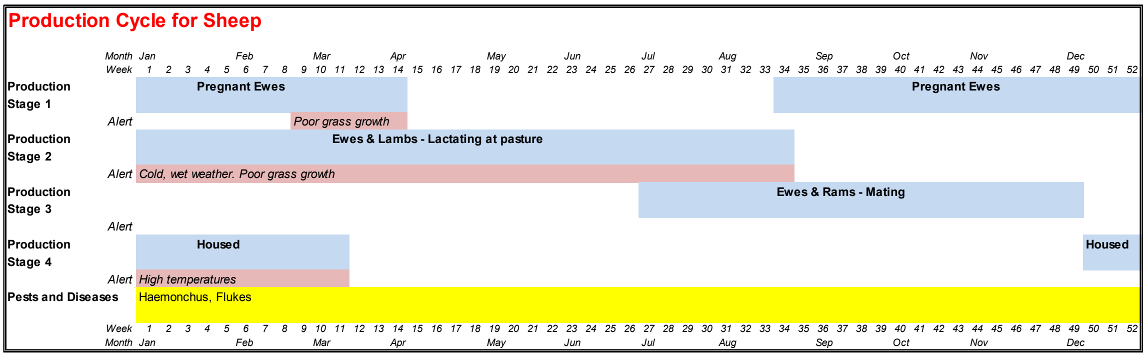


Figure 8.5. Predicted internal average CO_2 *concentrations and associated fruit yields assuming ambient* CO_2 *concentrations of 325, 452 and 567ppm for the base, 2030's and 2050's, respectively.*

This work has shown that despite the fact that a glasshouse environment is controlled via sophisticated heating and ventilation control systems, climate change will still have an effect on protected cropping systems. Energy use will tend to decrease, while yields might well increase due to higher ambient CO_2 concentrations. The main detrimental effect is likely to be the impact of higher summer temperatures on fruit quality and scheduling.

9 LIVESTOCK - SHEEP.


Production Cycle for Sheep

There are approximately 13 million breeding ewes in GB and around two thirds of these sheep are grazing upland areas where other land use options are limited. Upland hill breeds tend to be small hardy animals that survive well on low quality extensive grazing. Lambing commonly takes place outdoors and is timed to be sufficiently late in spring that the weather is not unfavourable. In many areas of England, lowland sheep production takes place. Sheep are larger cross-bred animals with greater prolificacy. Lambing takes place earlier, and indoor lambing is often used.

We looked at a number of different locations across the UK to reflect these different management practices associated with different locations.

There is potential for increased concentrations of atmospheric CO_2 and climate change in the future to impact on sheep production in a range of ways. Direct effects of changes in the weather may impact the housing of sheep, particularly during lambing and could result in adaption of the timing of the reproductive cycle. Forage is the primary source of nutrition for sheep therefore the potential changes in grass growth could be significant. Research to date suggests there will be a general trend for an increased growing season and yield. This will be at least partially offset by drought and water logging reducing grazing availability. It is also probable there might be a move towards reduced feed quality and digestibility. A short review of the current science on climate change and grassland is given in Annex 1. Changes in our climate may allow exotic diseases to become established. Climate might also impact on the transmission of endemic diseases linked to the environment e.g. footrot, fly strike and internal parasites increasing or reducing incidence of disease.

We asked for help from a number of sheep industry experts to identify key areas in the sheep production cycle that are sensitive to the impact of changes in climate. Starting at the onset of the reproductive cycle, it was highlighted that summer droughts leading to forage shortage and an impact on sheep fecundity the following year would be problematic. Increased rainfall during autumn would be detrimental to the effectiveness of working rams, again affecting reproduction. However, the key area where the sheep industry is vulnerable to the impact of the weather is during lambing, both outdoor lambing and the prevailing weather when young lambs are turned out to pasture. In 2008 there was a move towards outdoor lambing to improve returns in the sheep industry. Warmer dry weather during lambing would be greatly beneficial for this and earlier outdoor lambing would allow more lambs to be finished straight off grass. Conversely, an increased risk of rain and cold weather would be detrimental. For these reasons, the period of greatest risk for the sheep industry was considered to be spring and consequently we modelled synthetic UKCP09 weather during spring.

Wet and cold weather during lambing is a problem because lambs are susceptible to hypothermia: it is the most common cause of death in young lambs. Hypothermia, that is body temperature dropping below 37°C, occurs when there is excessive heat loss, and inadequate heat production. Lambs are born with a store of brown fat, which provides an energy source for a short period after birth to help keep them warm. It is well accepted that cold temperatures in conjunction with wet weather increase the rate of heat loss from the lamb, as does wind small body size and limited wool cover. There are no clear environmental critical temperature and rainfall thresholds in published literature. There are several mentions of < 5 °C being 'cold' for a lamb, so we used this for temperature, and for rainfall we used >0.2mm of rain as a cut off. This is a commonly used figure when handling rainfall data.

Case study 9.1 Impact of rain and cold, wet days on lambing.

In consultation with sheep farmers we learned that cold and wet weather during spring 2008 caused a number of problems. Ewes did not milk well as lambs were malnourished and at weaning ewes struggled to regain body condition before the following mating season. Weather recordings of the reported event were compared with typical weather for the time and location but we were not able to identify what made this problem weather period distinct. There are complex interactions with the body condition of ewes and grass growth making the impact of weather variable.

The approach we took was therefore to count the number of cold and wet days during the lambing season, February to April and determine whether there was a trend revealed by UKCP09 synthetic weather runs. As examples we present data for a lowland location, Benson in Oxfordshire and a hill location, Pwllpeiran in Mid Wales (Figure 9.1a).

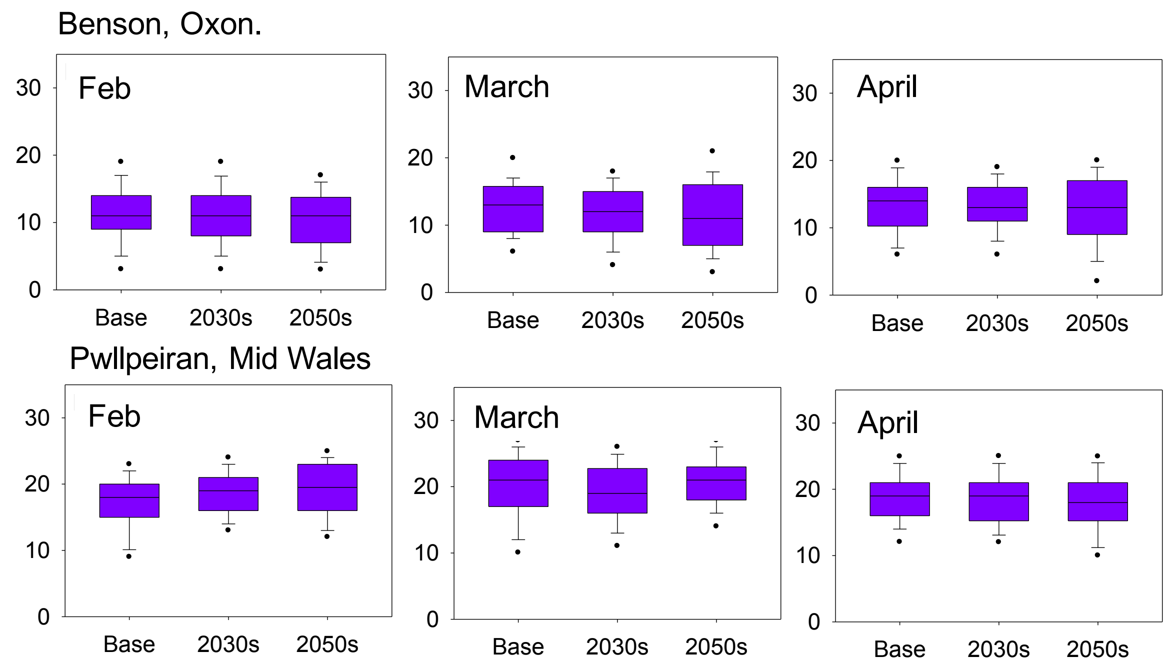


Figure 9.1a. Predicted number of rain days for February, March and April in Benson, Oxfordshire and Pwllpeiran, Mid Wales for Base, 2030s and2050s time slices.

For Benson, the UKCP09 projected weather indicates similar numbers of rain days in February, March and April in the 2030s and 2050s as the base level. And although it is wetter in Pwllpeiran than in Benson, the pattern is the similar. Rainfall is predicted to stay about the same.

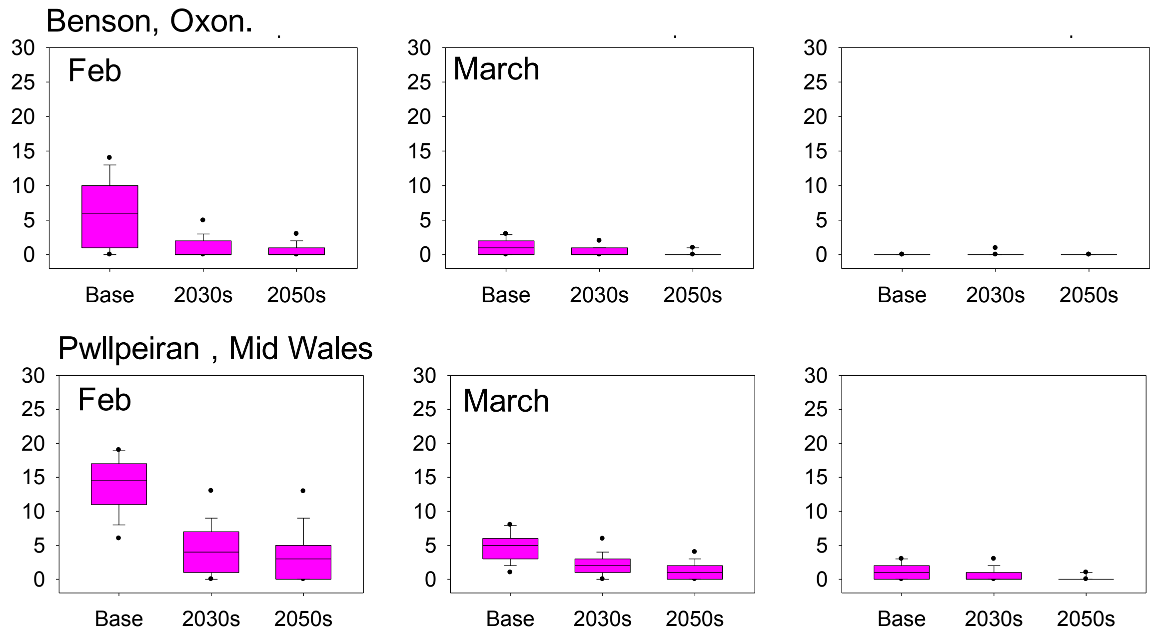


Figure 9.1b. Predicted number of cold (<5□C) and wet days by month for February, March and April in Benson, Oxfordshire and Pwllpeiran, Mid Wales for Base, 2030s and2050s time slices.

However, when we look at cold wet days (Figure 9.1b) the incidence decreases in the 2030s and 2050s in both the upland and lowland location. Therefore, although the rainfall is likely to stay about the same in the future, the incidence of days where the temperature is below 5^{o}C is predicted to reduce as we get into the 2030 and 2050s. Although it may be warmer, it is likely to be as wet, so the picture of the future climate is not one that is overwhelmingly more inviting for outdoor lambing, or earlier lambing outdoors. Whether increased temperature will significantly reduce the incidence of hypothermia depends on the relative contribution of cold and wet, along with other factors such as wind, that are not projected in the UKCP09 synthetic weather. However, increased temperature is likely to result in earlier grass growth. This will be an important factor that might allow earlier lambing outdoors or indoors to take advantage of being able to turn out on to grass.

Pests and Diseases

Three diseases featured highly among the top priorities for the sheep industry in our consultations with industry experts. These were blow fly strike, liver fluke and foot rot. All are affected by environmental conditions but there is insufficient understanding of the impact of weather conditions on transmission of *Dichelobacter nodosus* the bacterium that causes foot rot, the most common cause of lameness in sheep to be able to forecast future trends.

Case study 9.2 Liver Fluke

Liver fluke involves a snail as an intermediate host. The incidence of *Fasciola* infection can be predicted by the prevalence of environmental temperature greater than 10 ^{o}C and moist conditions, calculated from total rainfall, number of rain days and rate of transpiration. A disease threshold value was calculated to estimate the risk of disease. A value of less than 300 is associated with a low incidence of disease, 300 – 400 is associated with mid range risk of disease and values greater that 400 associated with presence of the disease. The infection cycle divides into two parts, infection that over winters in the snail and infection that multiplies in the sheep during the summer.

When the two locations are compared it is evident that the risk of disease is predicted to be low in Benson but higher in Pwllpeiran (Figure 9.2). In Benson it is below the threshold where there is likely to be little disease, and is projected to reduce in the 2030s and 2050s both summer and winter infection. In Pwllpeiran the prevalence of infection is high, particularly the summer infection. However, prevalence is projected to decrease in the 2030s and 2050s.

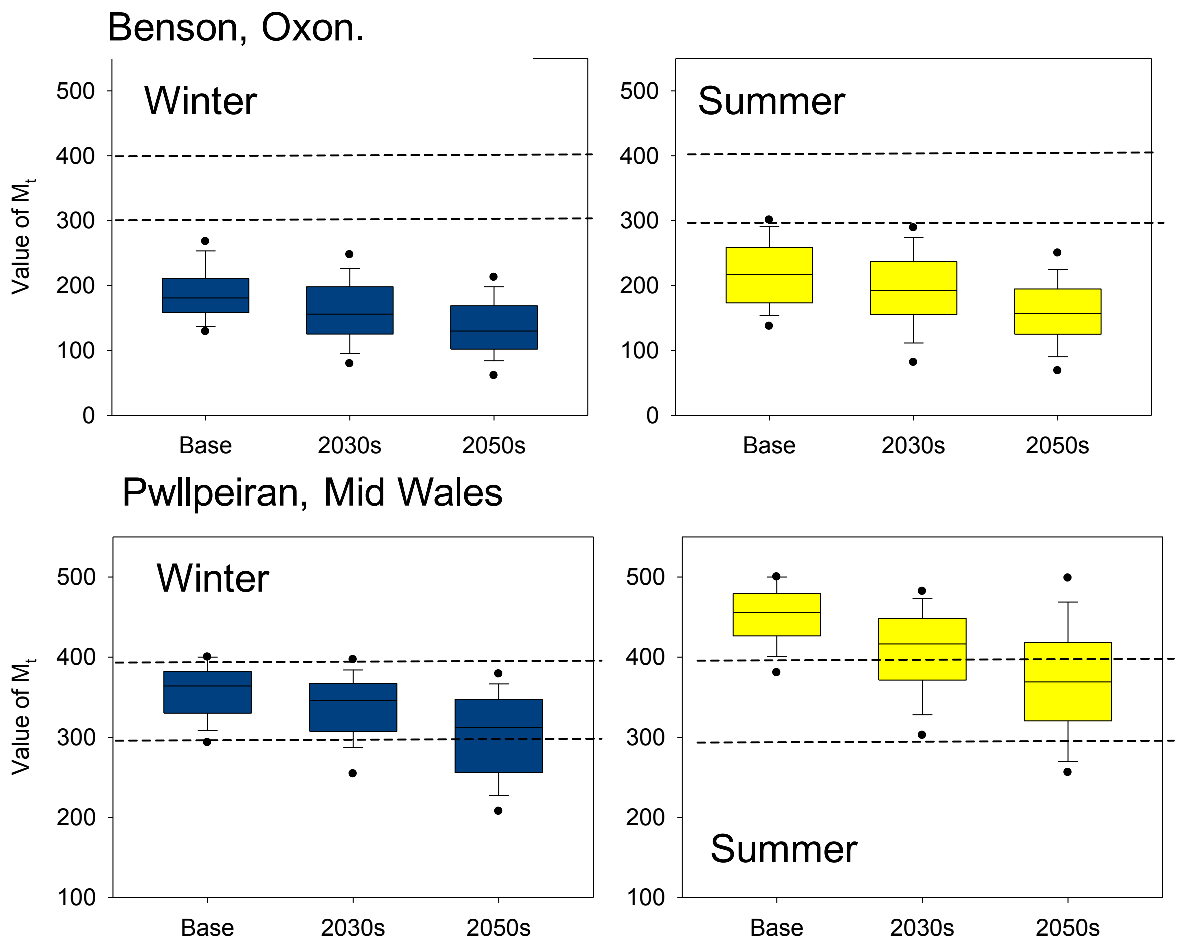


Figure 9.2. Predicted Incident of liver fluke infection winter and summer in Benson, Oxfordshire and Pwllpeiran, Mid Wales for Base, 2030s and2050s time slices. Dotted lines indicate the threshold: below 3300 is low risk, 300-400 medium risk and above 400 disease presence.

This reduced prevalence is attributable to the projected reduction in rainfall over the summer months. These predictions are contrary to the disease pattern we are currently experiencing, where wet summers and flooding have resulted in high incidence in recent years. The risk of transmission of the disease caused with flooding is not included in this simple model. This might affect the predictions for future incidence.

Case study 9.3 Blow Fly Strike

Blow fly strike occurs when green bottle flies (*Lucilia serricata*) lay their eggs on sheep and the maggots invade and feed off the sheep's body tissues. Some of the life cycle occurs off the sheep and is affected by environmental temperature and moisture. Flies emerge from the ground and start laying eggs on sheep (oviposition) at temperatures > 8.5 ^{o}C and lambs > 9.5 ^{o}C (Broughan and Wall (2007). We summed the day degrees over the environmental cut offs during April and May. For Oxfordshire there are predicted to be more days when ovipositon can occur during April and May in the weather projected for the 2030s and 2050s compared to the baseline. The rainfall is likely to remain about the same in future as current levels (Figure 9.3). Overall the reproductive cycle is likely to start earlier in the projected future climate leading a greater number of generations of blow fly per year and larger epidemics. A full analysis taking into account the dryer conditions during later summer and possible earlier shearing would be required to determine how the likely earlier onset of strike would play out across the season.

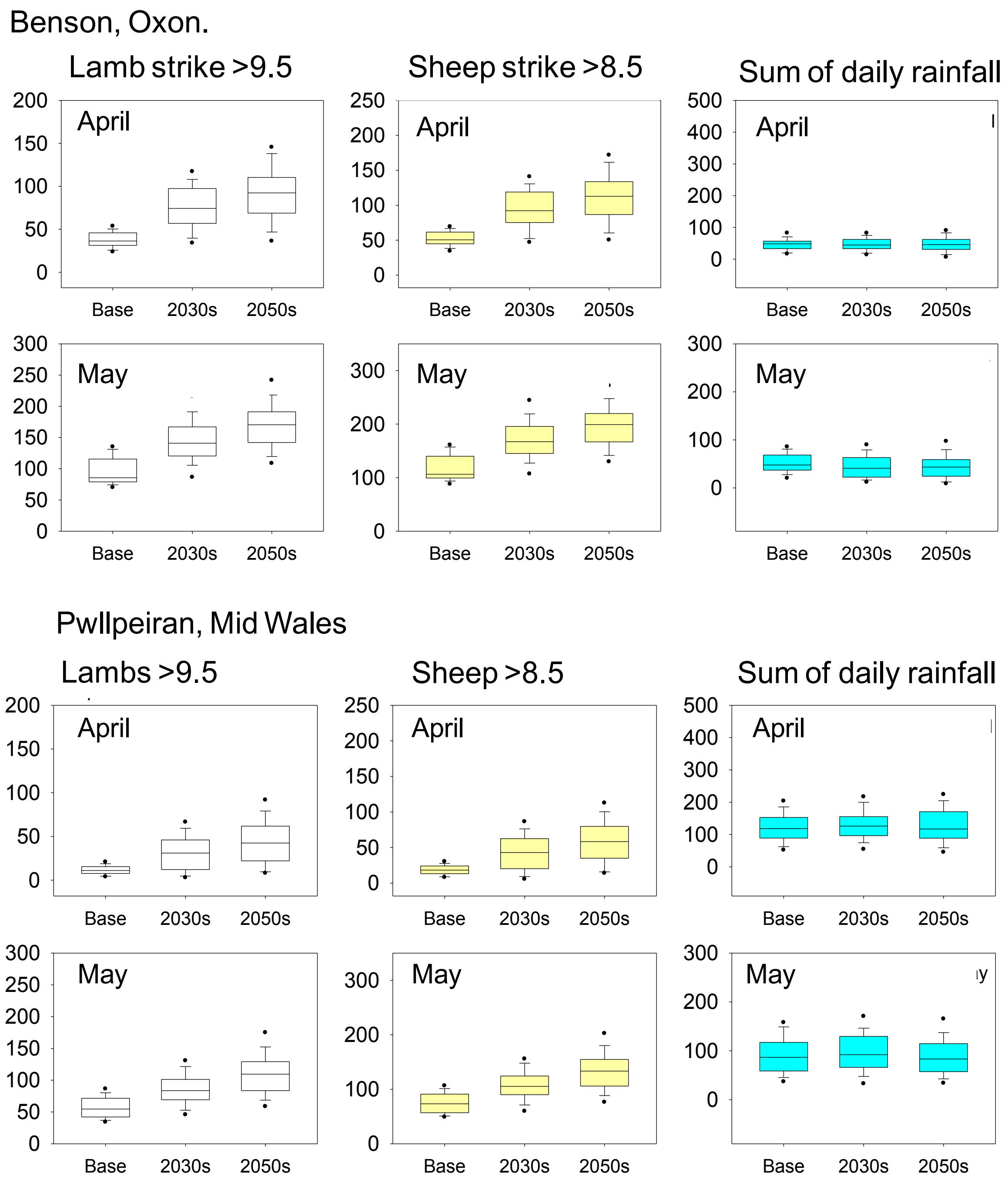


Figure 9.3. Predicted sum of day degrees in April and May at Benson, Oxfordshire and Pwllpeiran, Mid Wales for Base, 2030s and2050s time slices.

10 DISCUSSION AND CONCLUSIONS

Approach and limitations

The aim of this project was to develop a broad picture of the potential impacts of climate change on a range of agricultural systems, including Arable, Horticultural and Livestock farming. This is potentially a very wide subject and it was necessary to be selective for the systems to be studied and to prioritise aspects of production for each system. The systems we selected for study included the following field crops: peas (protein seed), broccoli (vegetable), cider apple (fruit), wheat (arable cereal), potato (irrigated vegetable) and oil seed rape (arable oil seed). We also included tomato as crop grown fully under protection. As an example of livestock farming we looked at sheep production.

In order to decide which specific aspects of production to look at in detail we constructed a series of production calendars for our target crops or livestock that identified times at which production could be directly (e.g. high temperatures) or indirectly (e.g. through pest and disease pressures) susceptible to climate variation or weather extremes, we established a consultation group with representatives from the Potato Council (PC), Home Grown Cereals Authority (HGCA), National Farmers Union (NFU), Processors and Growers Research Organisation (PGRO), Horticultural Development Council (HDC) and the organisation for the beef and sheep industry in England (EBLEX) along with academic and industry experts with experience of the relevant crops and sectors. Experts were invited to a review meeting after the initial scoping phase and were able to advise on the priority areas for further study in the chosen systems. In particular, these groups were able to advise on the most important pest and disease threats and to identify combinations of environmental conditions known to have had adverse impacts in crops grown in particular locations.

Based on discussions at the review meeting, we formulated a scheme of models that encompassed environmental sensitivities for crop development and quality or conditions linked to pest and disease threats. Each model was run for different locations, relevant for the particular production system in question, using synthetic weather outputs in the form of daily temperature and rainfall from the UKCP09 weather generator. In addition to production system-specific analyses we considered issues that were not deemed to be limited to a specific crop. These "generic issues" included predicted seasonal changes soil dryness or wetness, linked to changes in local patterns of rainfall in different locations within the UK and how this could affect the requirement for irrigation. Also, slugs and the Peach-potato aphid pests were deemed to be threats to a range of crops and were included as generic issues.

In evaluating the results of these studies, some inherent limits of the study should be recognised. The first of these relates to the predictions of future climate and weather. Predictions of future climate depend on a combination of atmospheric circulation models, economic scenarios and biogeochemical predictions to arrive at general predictions for the future. Each of these models has uncertainties and the collective uncertainty is recognised in UKCP09 outputs, which give probabilistic predictions i.e. a range of projections associated with differing levels of probabilities between 10 and 90%. In order to relate the general predictions from UKCP09 to the probability of daily weather patterns, which are the relevant inputs to the biologically based models, we used the UKCP09 weather generator. This feature relies on applying past patterns of annual, daily and geographical variability to future climate scenarios, which adds in another level of uncertainty. We run the models with at least 100 years of synthetic weather and present our results as plots that give the median values and the 25th/75th, 10th/90th and 5th/95th percentile values. These allow the uncertainty and potential variability to be shown for the individual analyses. Thus what we present and attempt to interpret is a range of probabilities and not simple predictions.

Results compare predictions for the 2030s and 2050s with baseline data for 1961 to 1995. We chose these time windows to cover a period during which is sufficiently far in the future for predicted trends to develop, while still being of relevance to current decisions and policy options. Later time windows would, in our opinion, be subject to much greater uncertainty, not only in terms of the climate scenarios but also the nature and production practices of the industry. It is worth noting that in 2010/2011, when this study was conducted, we lie in an intermediate point between the baseline and 2030s and results should be interpreted in that context. Climate change is gradual and industry adapts to changes over time. It is also faced with great year on year variability and has built in resilience to such variations e.g. diversifying location of production either within a region or across regions provides a level of security against localised extremes such as flooding or droughts. These adaptations to annual variability will, in many cases, provide an important contribution to adaptation to climatic shifts.

A second limitation is the availability of biologically based models that are suitable for making future projections. Ideally, such models should be compatible with weather generator outputs with regard to their inputs and, for pest and disease predictions, relate to relevant aspects of their life cycles. For many of the analyses we needed to use quite old descriptive models of pest behaviour or occurrence and in some cases we were not able to find any suitable information in the literature. We suggest that for potentially serious pests and diseases, developing robust models that can be used in a predictive way should be a priority for future research. For some crops e.g. wheat, we were able to use comprehensive crop models that include response to the environment. For other crops, e.g. cider apple, some relevant information could be found in the literature but for other aspects, we were reliant on the knowledge and experience of the industry itself. Thus in selecting the specific models to run, we used a combination of industry view of the most important threats and the availability of relevant biological models or criteria (e.g. thresholds) for the analysis.

Rainfall and water availability:

Rainfall patterns show interesting variations for both seasonal and geographic differences of the UK. In Cornwall, which has the highest overall rainfall, a distinct annual pattern can be seen, with winters having more rainfall than the summer. This continues in the future and the summer rainfall is predicted to decrease giving an even greater seasonal differential. For the Eastern locations of Lincolnshire and Cambridgeshire the differential between winter and summer is much less. In Cambridgeshire a significant overall decrease in rainfall at all points in the annual cycle is predicted to take place between the 2030s and 2050s time slices. The critical issue for crops is not simply the rainfall, but the availability of water in the soil. This affected not only by rainfall but also by evaporative losses (evapotranspiration), which will increase with projected increases in temperatures. Calculations predict increasing soil dryness through the summer months in both Cambridgeshire and Lincolnshire. This is manifested as not only an increased number of days with dry soil in the summer months but also an extension of the period for potential dry soil to September and even October in these locations. There is little change in the spring, which together with the modelling study in section 4 indicates that the impact of water availability on winter wheat will be small compared to the impact of temperature and elevated CO_2, despite the drier summers. However, the impact on long season crops such as vegetables and salads grown in eastern locations of England could be significant.

We looked at two examples of the potential impact of climate change on the requirement for irrigation of specific crops. Firstly, for potatoes grown in Lincolnshire, soil water and crop models indicate that the yield penalty for not irrigating the crop increases from 12% in the baseline period to 22% for the 2030s and 25% for the 2050s. This would lead to an increasing pressure to irrigate the potato crop in this area. According to Defra Project WU0101 (Thompson, 2007) potato is the most irrigated crop in the UK with about 50% of the crop being irrigated in 2001. Much of this is to control scab. Irrigation requirement for potato is predicted to rise from 43mm in baseline to 100 mm in 2030s and 129mm in the 2050s. Typically, a farmer will give on average about 118mm to a potato crop with about 30 – 50% of this given over a four week scab control period. If properly managed, this may be sufficient to safeguard yield under current conditions. However, this becomes marginal in an average year and with annual variations predicted to increase over this period is likely to be insufficient in many years. Potential adaptations are discussed in WU0101 and include breeding potatoes that are more efficient in using available water, increasing yield per unit area, moving production to areas such as the North East and South West in which water availability will be less of a problem or more sophisticated control of the use of available water for irrigation.

The second example was broccoli where we calculated the irrigation requirement for the crop to maintain yield. The predicted irrigation requirement for growing broccoli in Lincolnshire is about 48mm for the baseline and 96mm for 2030s and 2050s. It interesting to note that for both calculations, the majority of the change takes place by the 2030s. Also, as mentioned previously, we are currently about mid way between baseline and the 2030s time bands. Broccoli is resilient to moderate water deficits (Gutezeit, 2006) but these calculations imply that broccoli production could be increasingly impacted by water availability in the next 20 years. Adaptation would, again involve either breeding for water deficit tolerant crops or moving the centres of production.

While the general conclusions on irrigation requirements outlined here are well known and understood, what is new is the predicted timing of the changes, with most of the required increases in water requirement between now and the 2050s occurring over the next 20 years rather than being evenly spread. Thus the timescale for response by the industry may be more pressing than previously thought.

For the more Northerly locations the monthly rainfall is relatively even through the year but over the period to the 2050s, a slight increase in winter rainfall results in a more seasonal pattern. The UKCP09 predictions do not suggest there will be significant increases in the prevalence of days with wet soil. Rainfall increases are generally predicted for the winter in regions where the combination of rain and low temperatures already result in a high incidence of wet soil and where any increased rainfall may be offset by increased evapotranspiration with higher temperatures.

Crop and livestock summary

Combining Peas

Combining peas grown mainly for animal protein are grown mostly in Lincolnshire and East Anglia. Production areas are increasing and they could in future be grown in more northerly locations such as Northumberland and Tayside. They require dry conditions for planting and harvest and these factors are not predicted to change greatly in East coast locations by the 2050s. Flowering is anecdotally described as being adversely impacted by high temperatures but there was insufficient knowledge of what are the critical temperatures to model the future impact. The two crop and disease pressures highlighted by the industry were pea aphid and Fusarium root rot. The overall abundance of pea aphids is predicted to decrease for 2030s then be relatively unchanged for the 2050s. This will be combined with an advance in the timing of first migration and peak numbers. In contrast the models predict that the prevalence of Fusarium root rot disease prevalence is likely to increase steadily through the 2030s to the 2050s. This disease threat from Fusarium appears to be the main potential impact of climate change on combining pea production. Adaptation to this increased risk could include selection of varieties with improved resistance to Fusarium root rot or through crop management practices. As the main driver for the changes in Fusarium prevalence is an increase in soil temperature, migration of production areas to more northerly locations could be considered.

Broccoli

Broccoli is an example of a leafy vegetable crop grown over a relatively long season crop grown in three main areas of production, Cornwall, Lincolnshire and Scotland. Having geographically dispersed production areas provides insurance against the potential risks of it being very wet or dry in all production areas. This will remain an important strategy for the industry although, as described above, the irrigation requirement for broccoli and similar leafy crops will increase significantly in Lincolnshire, with most of the increase by the 2030s. This might suggest that the balance of distribution may gradually move to the South West and Scotland. The effect of warm temperatures during head development on post harvest quality and dry soil on crop establishment and development (see AC0301) appear to be more of a threat to broccoli production by mid century, particularly in Lincolnshire. Should this factor become critical, moving production areas is a possible adaptation. An alternative would be to develop varieties that are more robust with regards to higher growing temperatures. From discussions with experts, the most important threats from pests and diseases were identified as *Myzus persicae*, the peach-potato aphid, *Plutella xylostella*, the diamond back moth and *Phyllotreta cruciferae*, the crucifer flea beetle. The pest pressure from all three species is predicted to increase, with most of the increase by the 2030s time band. For the peach-potato aphid and diamond-backed moth, the impact is predicted to be less in the Scottish region than in Lincolnshire and Cornwall. Crops with a degree of resistance to these pests would be a valuable aid to adaptation.

Cider Apple

We considered cider apple as an example of a tree fruit crop. Production is based mainly in Herefordshire, Gloucestershire, Avon, North Devon and Somerset, with some production in Suffolk and Sussex. Apple is a perennial crop and has a continuous annual cycle of dormancy, growth flowering and fruiting. Yield is the main factor determining the value of the cider apple crop with quality being less important than for dessert apples. As with other crops, access to the land can be a problem, particularly in the autumn for harvesting and for pruning in February. Projections from UKCP09 indicate no appreciable change in the rainfall in either period. The industry has an aim to move to earlier varieties with earlier leaf fall, which would alleviate the current risk and be a benefit in the future climate. The main issues for the cider apple industry appear to be decreased winter chill, hot dry summers and increased Fire Blight activity. Because of its long-term nature, the industry is actively considering the potential impact of climate change on these aspects and preparing adaptation measures. The main area of production is unlikely to change.

Wheat

Wheat can be grown as an autumn-sown (winter wheat) or spring-sown (spring wheat) crop, with winter wheat being the dominant version. At the present time, wheat is grown on about 2,000,000 hectares with a value of about £1.2 billion. There are major international breeding programmes for wheat and an extensive amount of genetic material available to draw on. Finding varieties for the UK that can be adapted to the direct effects of climate change should be feasible, providing that the rate of change is not too rapid. As with many of the crops studied, unfavourable conditions during land preparation or establishment are a potential problem but UKP09 does not foresee significant alterations in the number of days when the soil is predicted to be wet. In the case of wheat we were able to take a more holistic view of climate change on the crop because well-developed crop models exist. For wheat, increased yields are predicted because of the higher levels of CO_2, which more than offset the negative effect of warmer temperatures. The main risks we identified were reduced yields from high summer temperatures around anthesis and a potential impact of greater diurnal temperatures in spring causing sexual asynchrony. In consultation with the experts we identified root diseases, of which Take-all is a major threat, wheat bulb fly and slugs to be the three most important pest and disease threats. Neither wheat bulb fly nor slugs are predicted to become more prevalent in the future. However, conditions favourable for Take-all, primarily as a result of warmer winters, are predicted to become commonplace, with most of the change occurring by the 2030s time band. Possible adaptations could include breeding for resistance to Take-all or switching to Spring-sown crops.

Oil seed rape

Oil seed rape is grown as either a winter or spring crop although winter oil seed rape represents more than 95% of the area grown in the UK. Winter rapes are sown at the end of August and the beginning of September and harvested the following July. The most important stage is getting to 3-4 leaves, after which the crop is very sturdy. If the soil is wet during this period it can become anaerobic and impair germination. However, UKCP09 synthetic weather outputs indicate that rainfall is not likely to increase in the late summer period and dry, rather than wet, soil may be more of a problem for planting and establishment. Similarly, potential problems experienced by growers, including low temperatures or large diurnal temperature changes in spring are predicted to become less frequent. Thus, oil seed rape crop development is predicted to be relatively unaffected by climate change. For pest and diseases, cabbage stem flea beetle, slugs and Phoma stem canker were identified as the most important threats. As for Wheat, the threat from slug damage is not predicted to get worse, but for both cabbage stem flea beetle and Phoma, the indications are that these will become more of a threat to the oil seed rape crop. Much of the increased threat occurs by the 2030s time band and the increase is more pronounced in the more southerly location (Cambridgeshire) than in the northerly locations (Northumberland). Adaptation could therefore involve migration of the areas for growing the crop northwards as well as breeding for resistance or improved crop management strategies.

Potatoes

UK potato production is highly complex with different cultural practices relating to the market for which the crop is produced. We concentrated on maincrop potatoes, which are grown in widespread locations across the UK. We chose three locations, Camborne in Cornwall, Kirton in Lincolnshire and Fowlis in Angus to cover the geographical range of the crop. During the consultation, it was suggested that planting might take place earlier, in either mid-March or even 1 March, if the risk of frosts were to diminish. Our analysis showed that the risk from late frosts in March is predicted to decrease in all regions and by the 2050s appears to have a low probability of occurring in the Cornwall region. These data suggest that earlier planting will become increasingly feasible in the South West but will remain a risky strategy in more northerly locations. At present, wet spells in the autumn cause problems in lifting, the extreme situations, as faced by the industry 2000 is a rare event. In the 2030s and 2050s time slices, the forecast prevalence of wet spells decreases in Cornwall and Lincolnshire but remains fairly constant in Angus. The adaptations currently used by the industry are therefore likely to remain adequate and the overall problem is predicted to ease, particularly in the South West.

The main pest and disease threats identified in the consultation were the aphid *Myzus persicae*, Late Blight and Slugs. As described for other crops, the threat from slugs is not predicted to increase. For Myzus, models predict that number of generations increases with time to the 2050s, but with the biggest shift being between the base and 2030s time slices. Sightings will be earliest at the Lincolnshire site, followed by Fife, with Cornwall being the latest to see the aphids. The likelihood of Late Blight is predicted to decrease. The predicted decrease is least for Cambourne in Cornwall, indicating that by the 2050s time slice there would be significantly more risk of Blight in the South West than elsewhere in the country. However, the risk would still be less than at present, and one can anticipate that more blight-resistant varieties will become available over this time period. In addition, the South West is likely to be least affected by the increase in aphid generations, is likely to be the most suitable for early planting and as described earlier, be less affected by the increased requirement for irrigation. On balance, our analyses suggest that moving more production to the South West could form part of a strategy for adaptation of potato production to climate change.

Tomato

We also looked at the potential impact of climate change on tomatoes as an example of a protected crop. We found that despite the fact that a glasshouse environment is controlled via sophisticated heating and ventilation control systems, climate change will still have an effect on protected cropping systems. Energy use will tend to decrease, while yields might well increase due to higher ambient CO_2 concentrations. The main detrimental effect is likely to be the impact of higher summer temperatures on fruit quality and scheduling.

Sheep

We also looked at Sheep production as an example of a livestock system. There are approximately 13 million breeding ewes in GB and around two thirds of these sheep are grazing upland areas and the remainder are in lowland production. Our analysis included a lowland location, Benson in Oxfordshire and a hill location, Pwllpeiran in Mid Wales. A key area where the sheep industry is vulnerable to the impact of the weather is during lambing, both outdoor lambing and the prevailing weather when young lambs are turned out to pasture. Warmer dry weather during lambing would be greatly beneficial for this and earlier outdoor lambing would allow more lambs to be finished straight off grass. We found that rainfall is relatively unchanged but the likelihood of look at cold wet days decreases in the 2030s and 2050s for both the upland and lowland locations. Whether increased temperature will significantly reduce the incidence of hypothermia depends on the relative contribution of cold and wet, along with other factors such as wind, that are not projected in the UKCP09 synthetic weather. However, increased temperature is likely to result in earlier grass growth. This will be an important factor that might allow earlier lambing outdoors or indoors to take advantage of being able to turn out on to grass.

The two major pest and disease threats looked at in this study were Liver Fluke and Blow Fly Strike. For Liver Fluke, the risk of disease is predicted to be low in Benson but higher in Pwllpeiran and to reduce for both locations in the 2030s and 2050s for both summer and winter infection. We were unable to include the risk of transmission of the disease caused by flooding and this could affect the predictions for future incidence. For Blow Fly Strike, earlier reproduction and more generations in the season could lead to larger epidemics. Adaptation could involve earlier shearing and further analysis would be required to determine how the likely earlier onset of strike would play out across the season.

Overall summary of findings

The predicted impact of climate change on susceptible aspects of production systems is summarised in Table 10.1 and reveals a different pattern for each system. For all of the systems studied, one or more potential vulnerabilities are likely to become exacerbated by climate change. Temperatures are projected to increase to a greater or lesser extent in all seasons throughout the UK. As a consequence, certain diseases, including Wheat Take-all, Phoma in oil seed rape, Fusarium root rot in peas and Fire blight in apples are predicted to be come significantly more threatening and damage caused by some insect pests, including Peach-potato Aphid, Diamond Back Moth and Blow Fly strike sheep may be worse because they begin earlier or produce a larger number of generations per year. In contrast, other pests, including Pea Aphid and Wheat Bulb Fly and diseases, including late blight of potatoes are predicted to become less of a problem. For crop development, issues related to summer heat, such as reproductive development and quality, become more of a problem. Although changes to rainfall patterns are relatively modest, increased temperatures are likely to result in increased water loss by evapotranspiration. In areas that are currently under pressure for water, predominantly the South and East, demand for water for irrigated crops is predicted to increase significantly over the next 20 years and may influence the relocation of water-demanding crops such as potatoes and vegetables.