



Final Report

AC0301: VULNERABILITY OF UK AGRICULTURE TO EXTREME EVENTS

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SUMMARY

The aim of the project was to predict the occurrence of extreme weather events, whose frequency and spatial patterns are likely to change as a consequence of climate change, and their impact on crop production in the UK. Analysis of extreme events and impacts was based on the set of climate change scenarios using a stochastic weather generator linked with UKCIP02 projections of future climate. Climate change scenarios were generated for selected emission scenarios at contrasting sites in the UK. The majority of the analyses focused on the 2020HI and 2050HI scenarios. The study identified that the impact of future weather changes may be positive in some instances and negative in others.

A modelling approach was used to assess extreme weather events and extreme yields under climate change and investigate their impacts on agricultural crops. Changes in magnitude and frequency of extreme weather events were increased. The average number of days with maximum temperature exceeding 30°C increased to 1.5 - 2 in July and August for the 2050HI scenario compared with expected 0.1-0.15 days for the baseline. This increased to > 5 for the 2080HI scenario. The expected frequency of heat-waves was very low for the baseline climate with the maximum length of 4 days long. For the 2050HI scenario the frequency increased significantly, the length of heat-waves increased to more than 6 days and the peak temperatures were higher. The predictions for 2080HI were considerably more extreme. More intense daily precipitation (95-percentiles showed an increase for all months except August for 2080HI) is likely to have an impact on the environment and also affect agricultural crops.

The Sirius wheat model was used to examine extreme impacts for two wheat cultivars, fast developing cv. Avalon and slow developing cv. Mercia. We evaluated the probability of high temperature episodes around flowering, which can substantially reduce grain yield by making a large proportion of flowers sterile, and computed a drought stress index, which shows the reduction of the grain yield due to prolonged water stress. Despite hotter and drier summers predicted for future climate scenarios, the relative reduction in grain yield due to the drought stress is likely to be smaller compared with the baseline for both wheat varieties. The likely explanation is that wheat matures earlier in a warmer climate, advancing maturity date by several weeks and avoiding summer drought stress. Wheat varieties have different abilities to mitigate climate change. Cv. Avalon, a fast developing variety, is better suited to avoid summer droughts and the heat stress around flowering than a slow developing cv. Mercia. An economic assessment of yield variability was carried out using a Value-at-Risk (VaR) analysis. VaR is the leading measure in the finance world for unexpected low returns. The analysis indicated that for wheat, in general the probability of very low yield levels is *reduced* with the subsequent climate scenarios. There are however some locations where for a specific cultivar the VaR may remain unchanged or increase slightly. By 2050 the impact on wheat is uniform: the probability of very low wheat yield levels (as measured by the VaR) is reduced with climate change for all locations and types of soil.

For sugar beet, simulations using temperature and rainfall predicted that sowing dates will become earlier and vary by a similar number of days as today. This will tend to increase yield, so too will warmer early summer weather, while the foliage canopy is

developing. However, hotter and drier summers will increase the risk of drought, and there is little prospect that valuable irrigation water resources will be used to overcome this. The consequence of these changes, plus the change in CO₂ concentration will be an increase in the national mean sugar yield in 2050, by an average of 3.5 t/ha (i.e. 35%). However there will also be an increase in yield range from one year to the next. The difference between the 5 and 95 percentiles for the national mean sugar yield will increase from 5.4t/ha to 7.9t/ha by 2050. Because beet is a perishable crop that cannot be stored from one season to the next, this increase will be very difficult for the farmers and processor to manage. However, the economic assessment showed that for U.K. sugarbeet, extreme events due to future climate change do not lead to adverse effects in terms of higher relative yield variability or an increased probability of very low yields. The probability of very low yield levels for sugarbeet (as measured by the VaR) is reduced with the subsequent climate scenarios for all locations and types of soil.

A series of reviews were carried out of the sensitivities of a representative set of crops to environmental challenges. They confirm that a range of environmental factors are capable of causing significant impact on production, either as yield or quality loss. The most important of these are temperature (heat waves, frosts), water (drought, waterlogging) and storms (wind, hail / inundation).

For all of the crops studied, unseasonal temperatures can have major effects on yield and quality. Flowering and seed production are particularly vulnerable. Targeted experimental work on reproductive temperature sensitivities is required to determine the risk of losses due to failed flowering under predicted future weather patterns for key crops including oilseed rape and peas. A combination of warmer winters and high summer temperatures are likely to result in a trend to earlier planting dates for summer annual crops. This strategy may avoid high temperature damage to flowering but may also lead to increased losses due to late frosts.

Extreme weather will affect crop production schedules, depending on the crop type. Crops which require continuity of supply e.g. salad leaves, cauliflowers, are particularly vulnerable to extreme weather events. Increases in temperature may result in a compression of harvest dates for some crops such as winter cauliflowers while for others, such as vining peas, the harvest window may be wider. It may be possible to overcome problems in continuity of supply by changing to varieties with altered temperature requirements but further research will be required to identify or breed such adapted varieties. Planting and crop establishment are particularly sensitive to periods of drought as experienced in years such as 2006 and which our models predict are likely to become more frequent in the future. Drought can also have adverse effect on quality in crops such as potatoes and oil seeds. The problem of drought is less critical for deep rooted perennial crops such as apple and can be countered with appropriate management strategies.

Potatoes are susceptible to problems caused by flooding and waterlogging as in 2007 and compaction is a major problem for potato production. Heavy rain in the autumn can have severe implications for lifting the main crop of potatoes as in 2000 when machinery was prevented from getting on to the land to harvest. However, our models predict that rainfall in the autumn at levels that can have a major impact on potato harvesting is likely to become less prevalent in 2020 and 2050.

Leafy salads, grown over a long season for continuous supply are vulnerable to extreme weather events causing quality thresholds to be exceeded. Overall the risk of exceeding the thresholds for heavy rainfall damage tended to decline over time. However, the risk of exceeding critical temperatures during the day or night increases and may have a detrimental effect on quality. Conversely, the number of occasions when night temperatures and day night differentials are expected to fall below critical values is predicted to decrease at most sites.

Climate warming will increase the pressures on crops from many pests. Climate has profound impacts on populations of pests (insects, mites, molluscs) and diseases, affecting their development, reproduction and dispersal. Many pests will be able to produce more generations per year in warmer conditions, many fungi are favoured by humid conditions, and wind may assist the dispersal of both.

The effect of extreme climate events on the complex web of biotic interactions (pests, diseases, vectors, host plants, predators, parasitoids) is hard to assess and yet it is likely to be an important component of the outcome to crops. Extreme temperatures and the increased frequency of heat waves will undoubtedly be deleterious to some current UK pests and diseases. The effects of water (drought or periods of heavy rainfall) on pest and disease populations will depend entirely on the species and the timing of the event. Some species will prosper in dry conditions, others will not. Although the current climate models do not contain a wind component, wind is likely to have a strong influence on extreme pest and disease events, both in the arrival of immigrants (and the timing of such events) and in their eventual spread within the UK.

Control by pesticides, biological control agents or host plant resistance is likely to be affected by the increased frequency of extreme climate events and in many cases this is likely to reduce their efficacy. The possible effects of extreme climate events on new pest and disease introductions should also be considered. Further work is required to overcome the limitations to the use of pest and disease forecasting models with UKCIP climate change scenarios in order to ensure more robust risk assessments in the future.

INTRODUCTION AND AIMS OF THE PROJECT

A critique of the Defra Programme on the Impacts of Climate Change on UK Agriculture from 1999 to 2005 proposed that “with respect to extreme events such as episodic high temperatures and storms, the degree of temporal overlap between such events and the sensitive periods of the farming calendar, crop development and seasonality needs examination”. The review also stated that further research was needed in “relation to climate change and food quality, plant and animal pests and diseases and extreme events.” Those comments form the background to this report on the vulnerability of UK agriculture to extreme events.

We have taken extreme events to be one of two types. The first is where a low probability extreme weather event leads to critical physical and/or physiological thresholds being exceeded during sensitive stages of crop development, resulting in crop failure or significant loss of quality. Extreme weather events would include heat waves, periods of heavy or extended rain, gales or frosts.

The second relates to extreme impacts where weather conditions affect crop growth or management resulting in substantial reduction in yield or quality. This could be a consequence of a single event, e.g. late spring frost, or prolonged weather conditions, e.g. warm winters or drier summers.

The study draws on the expertise of Rothamsted Research, the University of Warwick and the University of Manchester in an interdisciplinary approach involving crop and climate modelling, plant physiology, agronomy, crop protection and economics. UKCIP02 climate scenarios have limited spatial (5 km interpolated from 50 km grid-cell) and temporal (monthly) resolution and, as such, they are not well suited as input to the crop simulation or pest and disease prediction models commonly used in agriculture and horticulture. In this project, analysis of extreme events and impacts was based on a set of climate change scenarios with high temporal (daily) and spatial resolution (1km, site-specific). These scenarios were constructed by the Rothamsted group using a stochastic weather generator linked with UKCIP02 projections of future climate.

Potentially critical weather events were identified by literature reviews of sensitivities of particular phases of crop development to environmental conditions and susceptibilities to pest and diseases. In addition, consultation with industry representatives identified specific weather events that were proven to have an impact on crop management. Daily synthetic weather data were generated for the 2020HI and 2050HI scenarios at contrasting sites in the UK for comparison with baseline data. These simulations enabled the risk of critical weather events to be estimated and the outputs of the simulations were used as inputs to a range of decision support and prediction models to identify likely future impacts. Economic analyses were carried out for the major arable crops wheat and sugar beet.

1 WEATHER MODELLING

1.1. Construction of high resolution climate change scenarios

Analysis of weather extreme events relevant to agriculture and extreme impacts on agricultural crops requires climate change scenarios with high spatial (site-specific) and temporal (daily) resolutions. Late-spring frost is an example of a weather extreme event. An episode of hot temperature around anthesis, which may result in a large proportion of sterile grains in wheat and substantial yield losses, is an example of an extreme impact (Wheeler *et al.*, 1996). To use agricultural crop models in climate change studies, we have to construct climate scenarios with appropriate temporal and spatial resolutions, taking into account the model sensitivity to variations in climatic variables. Crop simulation models incorporate a mixture of non-linear interactions between the crop and its environment (Semenov and Porter, 1995; Porter and Semenov, 1999). A non-linear model can potentially produce very different predictions depending on how climate scenarios were constructed (Mearns *et al.*, 1997). It was demonstrated in (Semenov and Barrow, 1997) that climate change scenarios derived from a global climate model (GCM) that incorporated changes in climatic variability decreased mean wheat yield and significantly increased risk of crop failure compared with scenarios which accounted only for changes in mean values.

The coarse spatial resolution of GCMs and large uncertainty in their output at a daily temporal scale, particular for precipitation, means that GCM output is not appropriate directly for analysis of extreme events and extreme impacts. Despite an increasing ability of GCMs to model successfully present-day climate, the latest generation of GCMs has serious difficulties reproducing daily precipitation and temperature (Trigo and Palutikof, 2001). Regional climate models (RegCM) showed a substantial improvement in modelling spatial weather patterns compared with GCMs due to much finer spatial resolution (20-50 km). Nevertheless, an accurate reproduction of some of weather statistics, including extreme events, still remains problematic. In our project we used a methodology, based on a stochastic weather generator, to construct high resolution climate scenarios. This methodology links the output from GCM with the site-specific parameters of a weather generator spatially interpolated over the UK (Semenov and Brooks, 1999). We used the LARS-WG stochastic weather generator version 4.0 (Semenov, 2007), a short description of which is give in the Annex 1.

1.2. Skill of LARS-WG in reproducing weather extreme events

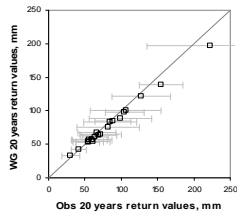
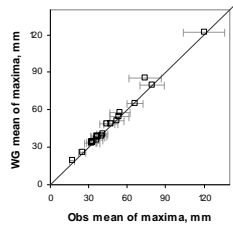
Despite an increasing need to use weather generators for analysis of extreme weather events and extreme impacts, especially in climate change studies, only on a few occasions skills of WGs in reproducing extreme weather events were tested. As part of the project we evaluated the performance of the LARS-WG weather generator to reproduce extreme weather events at 20 locations around the world with diverse climates, which represent a wide selection of ecoregion provinces (Bailey and Hogg, 1986; Bailey, 1989), varying from continental tundra at Baker Lake, Canada to desert at Boise, USA (Annex 2, Table 1).

The following weather extreme events were compared: (1) yearly maxima of daily precipitation, (2) yearly maxima of daily maximum temperature and (3) yearly maxima of the length of heat-waves. A heat-wave is defined as a continuous period (2 days or more) with daily maximum temperature exceeding 30°C. For each extreme event the following statistics were compared: (1) means of maxima, and (2) return values for the 20-yr period. The 20-yr return value has 0.05 probability of being exceeded in any one year. For observed data the 95% confidence intervals were calculated for means of maxima and return values. If the value, calculated for synthetic data, falls within the 95% confidence interval of observed, then we assume that two statistics for observed and synthetic values are similar. 300 years of synthetic daily weather were generated by LARS-WG for this analysis for each site, using parameters estimated from the observed data.

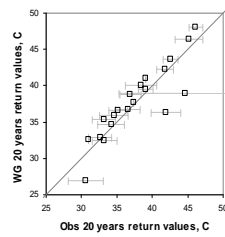
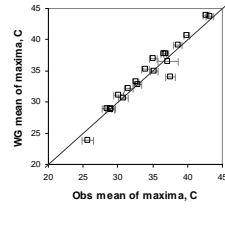
To compute return values for the 20-yr period we used the Generalized Extreme Value (GEV) distribution fitted to yearly maxima (Coles, 2001; Beirlant *et al.*, 2004). The GenStat 9 procedure was run to estimate three parameters (μ, σ, ξ) of the GEV distribution for observed and synthetic data.

1.2.1. Precipitation extremes. Mean of yearly maxima of daily precipitation was reproduced by LARS-WG well. For all sites means of yearly maxima computed for synthetic precipitation were within 95% confidence intervals of means of maxima for observed data (Figure 1.1). The largest difference between observed and generated means of precipitation maxima was 12 mm at Boise, USA. The discrepancies between observed and generated maxima at Boise could be explained by an abnormal shape of the precipitation distribution at Boise. The range of observed precipitation at Boise is large, 191 mm. As a result, intervals in semi-empirical distribution, used in LARS-WG, have to be large too, which reduces the accuracy of approximation, because within the intervals a cumulative probability function is approximated by a linear function. Return values for daily precipitation maximum for 20-yr period were reproduced by LAR-WG well (Fig. 1.1). All return values computed from synthetic data were within 95% confidence intervals of observed return values. The GEV distribution was fitted to observe and synthetic data in order to estimate return values. Because of the number of years with observed weather was not sufficiently large, 30 – 56 years depending on a site, uncertainties in calculating 20-yr return values were large. The 95% confidence intervals for return values were on average ± 31 mm for the 20-yr return period.

Yearly maxima of precipitation



Yearly maxima of max temperature



Year maxima of heat-waves

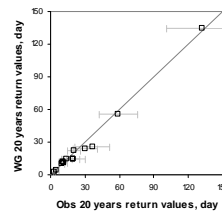
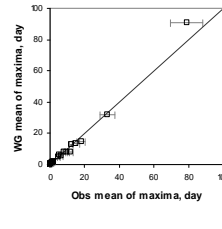


Fig. 1.1 A comparison between observed and synthetic weather extreme events at 20 sites: (a) mean of yearly maxima with 95% confidence intervals for observed data, (c) 20-yr return values with 95% confidence intervals for predictions based on observed data.

1.1.2. *Maximum temperature.* Means of yearly maxima of maximum daily temperature were reproduced less accurately. Means of maxima calculated for synthetic temperature were outside the 95% of confidence intervals of observed means for approximately half of the sites. However, the root mean squared error (RMSE) between means of yearly maxima for observed and synthetic data was relatively small, 0.94 °C. LARS-WG approximates normalised temperature residuals (after removing long-term mean and normalising variances) by the normal distribution. If the observed distribution is different from normal, then generated extreme values could be different from observed. 20-yr return values calculated for synthetic maximum temperature were within the 95% confidence interval of return values calculated for observed data for approximately 70% of sites. RMSE was relatively small for both 20-yr return values, 1.53°C, if we exclude two sites, Heraklion and Bologna, where approximation of maximum temperature by the normal distribution has produced poor results.

1.2.2. *Heat-waves.* Means of yearly maxima of length of heat-waves were reproduced well for most of the sites. Only at three locations, i.e. Tucson, USA, Boise, USA and Bologna, Italy, means of maxima calculated for synthetic data were outside the 95% confidence intervals for observed data (Fig. 1.1). Calculation of 20-yr return values for heat-waves was not possible for several sites, where heat-waves were very rare (or didn't exist), e.g. Jokioinen, Finland or Baker Lake, Canada. The MLE procedure did not converge for these sites. For the remaining sites, 20-yr return values for synthetic weather were within the 95% confidence intervals of observed return values.

At Rothamsted the extreme events from synthetic data were in good agreement with observations. Mean of yearly maxima of daily precipitation for observed and synthetic data were 32.6 and 34.0 mm and 20-yr return values were 54.6 and 53.7 mm, respectively. Mean of yearly maxima of daily maximum temperature for observed and synthetic weather were 29.0 and 28.9 °C and 20-yr return values yearly maxima were 33.2 and 32.4 °C. In conclusion, LARS-WG can be used with confidence for modelling extreme weather events in the UK.

1.3. Construction of climate scenarios using LARS-WG

The UKCIP02 climate change scenarios are based on a series of climate modelling experiments completed by the Hadley Centre, using HadCM3 and HadRM3 climate models (Hulme *et al.*, 2002). These climate scenarios, based on global emissions scenarios published in 2000 by the Intergovernmental Panel on Climate Change (IPCC) in their Special Report on Emissions Scenarios (Nakicenovic and Swart, 2000), describe four alternative future climates for the UK labelled, respectively, Low Emissions (LO), Medium-Low (Med-LO) Emissions, Medium-High (Med-HI) Emissions and High (HI) Emissions and available for three time periods 2020, 2050 and 2080.

The HadCM3 global climate model is a complex tool for simulating global climate. The model is based on physical principals, describing the transport of mass and energy; these equations are solved at intervals (30 minutes) at a number of points forming a grid over the globe. In the HadCM3 model this grid is 2.5° in latitude by 3.75° in longitude, corresponding to about 265 km by 300 km over the UK. However, most processes in the atmosphere, ocean and on land, which determine climate, take place at much smaller scales. The UKCIP02 scenarios are based on the output from the regional climate model HadRM3, which has a horizontal resolution of 0.44° by 0.44° (50 km), and a time step of 5 minutes. HadRM3 takes boundary conditions from coarser resolution HadCM3 simulations and provides a higher spatial resolution of the local topography and more realistic simulations of fine-scale weather features. The advantage of this approach is that it adds physically-based high-resolution information to the results of GCM experiments. For each grid-cell UKCIP02 scenarios provide changes in monthly mean variables, such as monthly precipitation, monthly mean minimum and maximum temperature and monthly mean radiation. These changes are provided for each time period 2020, 2050 and 2080 and for each emission scenarios LO, Med-LO, Med-HI and HI.

Daily climate change scenarios, generated by the LARS-WG stochastic weather generator, are based on the UKCIP02 monthly mean projections and daily precipitation from the HadRM3 climate model. The construction of a daily climate change scenario is a two-step procedure. First, for a site in the UK we calculate LARS-WG parameters for baseline weather, using the interpolation procedure described above. The second step is to derive changes in mean and variability of climate characteristics for this site, using UKCIP02 predictions and daily output from HadCM3. The mean changes in total monthly precipitation, changes in monthly mean maximum and minimum temperature and changes in monthly mean radiation are available from UKCIP02 directly. Changes in duration of monthly mean dry and wet series were calculated by using daily precipitation for 2065-95 from HadRM3. The scenario files are used to adjust the baseline parameter set, producing a new LARS-

WG parameter set for the chosen site and chosen climate change scenario. This new parameter set is used to generate daily weather with climatic statistics similar to those predicted by the UKCIP02 scenario. More details on this procedure are given in the Annex 1.

2 ANALYSIS OF EXTREME WEATHER EVENTS

We used the following statistics to compare temperature extreme events:

1. *Heat and frost indexes.* The heat index is defined as a number of days per month with maximum temperature exceeding a certain threshold T^* , e.g. $T_{\max} > T^*$. For the frost index, we calculate a number of days per month with $T_{\min} < 0$.
2. *Heat-waves and frost-spells.* A heat-wave is defined as a continuous period (2 days or more) with daily maximum temperature exceeding 30°C . Similar, a frost-spell is defined as a longest continuous period (2 days or more) with daily minimum temperature below 0°C .

To compare extreme events for precipitation we use the following statistics.

1. *Daily precipitation.* We compared 95-percentiles $R_{CC}^{0.95}$ and $R_{BS}^{0.95}$ for the baseline and future climate scenarios, where R stands for daily precipitation.
2. *3-days precipitation.* For each wet series, we find the three consecutive days within the series which have the maximum total precipitation

$$R_{3days} = \max_d \left\{ \sum_{i=1}^3 R_{d+i}, d+i \in \text{WetSeries} \right\}$$

Then we calculate 95-percentiles for 3-days precipitation, $R_{3days}^{0.95}$.

2.1. Precipitation extremes

Wet series are defined as series of consecutive days with precipitation greater than 0.1 mm. Changes in the mean length of dry and wet series were computed by comparing daily time series for precipitation from HadRM3 for control 1960-90 and 2065-95 runs. For the 2080HI scenario at Rothamsted the average duration of wet series is predicted to be shorter with the largest decrease of 40-50% during summer months. The length of dry series is predicted to increase by 40-60% during summer months and decrease slightly during winter months. Total monthly precipitation for the 2080HI scenario at Rothamsted is predicted to be lower by about 40-50% during summer and higher by about 20-25% during winter.

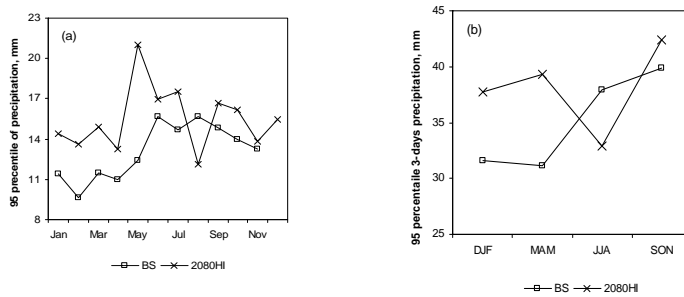


Fig.2.1 (a) 95 percentile of daily precipitation and (b) 95 percentile of 3-days precipitation for the baseline and 2080HI scenarios at Rothamsted, UK.

The combined effect of changes in the number of wet days per month, calculated from wet and dry series, and changes in total monthly precipitation, predicted by UKCIP02, determines daily precipitation. For the 2080HI scenario mean precipitation on wet days is predicted to increase for all months except August. Fig. 2.1.a shows 95-percentiles for daily precipitation for the baseline and 2080HI scenarios. We also calculated 95-percentiles of 3-days precipitation, as defined in Section 3.1, for each season (Fig. 2.1.b). More intense daily precipitation (95-percentiles showed an increase for all months except August for 2080HI) or 3-days precipitation totals (for all seasons except summer – June, July, August) may have an impact on the environment and also affect agricultural crops. An increase in precipitation intensity is likely to increase N leaching with possible contamination of ground water, and the risk of soil erosion. In addition, intense rainfall can reduce availability of water for agricultural crops (given that the total monthly precipitation remains unchanged). Intense rainfall may fill up the soil water capacity with the excess water running off or percolating to deep soil layers unavailable for plants.

2.2. Temperature extremes

Heat and frost indexes. Plants could be severely damaged if daily temperature exceeds a certain temperature threshold at a certain developmental stage (Porter and Gawith, 1999). It is known that many growth processes have a bell-shaped response curve to temperature with optimal growth conditions achieved when temperature is close to the middle point of the bell curve, and no growth when temperatures are outside the limits of the curve. For example, optimal temperature for wheat growth is 17-23°C over the growing season; when minimum temperature falls below 0°C or maximum temperature exceeds 37°C growth stops (Porter and Gawith, 1999). Different processes can have different temperature thresholds (Wheeler *et al.*, 1996). In Fig. 2.2.a an average number of days with maximum daily temperature exceeding 30°C is shown for each month for the baseline, 2050HI and 2080HI climate scenarios. The average number of days with maximum temperature exceeding 30° is greater than 5 in July and August for 2080HI compared with expected 0.1-0.15 days for the baseline scenario.

Heat-waves and frost-spells. Isolated incidents of extreme hot or cold temperatures could seriously damage a plant. A continuous period of extreme hot or cold temperature could be lethal not only for crops, but also for humans. Using 150 years of daily synthetic weather for the baseline, 2050HI and 2080HI scenarios at Rothamsted, we computed the expected frequency of heat-waves and cold spells of various lengths. For the baseline climate the expected frequency of heat-waves is very low and the maximum wave was 4 days long (Fig. 2.2.b). For the 2080HI scenario not only the frequency increased dramatically (an order of magnitude), but also the length of heat-waves (up to 12 days long) and their severity (peak temperatures during a heat-wave were higher). Frost-spells showed an opposite tendency (Fig. 2.2.c). The maximum length of frost spells decreased from 18 days for baseline to 9 for 2080HI, and the frequency of frost-spells was reduced by more than half.

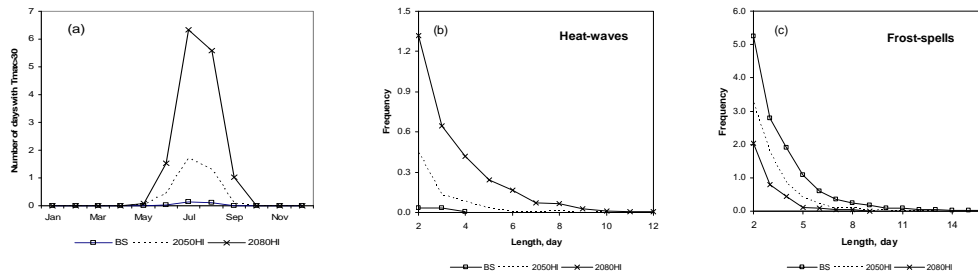


Fig. 2.2. Magnitudes and frequencies of extreme weather events: (a) average number of days per month with maximum temperature exceeding 30 °C for the baseline (BS), 2050HI and 2080HI scenarios; Expected frequencies of (b) heat-waves with temperature exceeding 30 °C and (c) frost-spells of various lengths in a single year for the baseline (BS), 2050HI and 2080HI scenarios at Rothamsted.

3 MODELLING EXTREME IMPACTS ON WHEAT AND SUGAR BEET

3.1. Extreme impacts on wheat

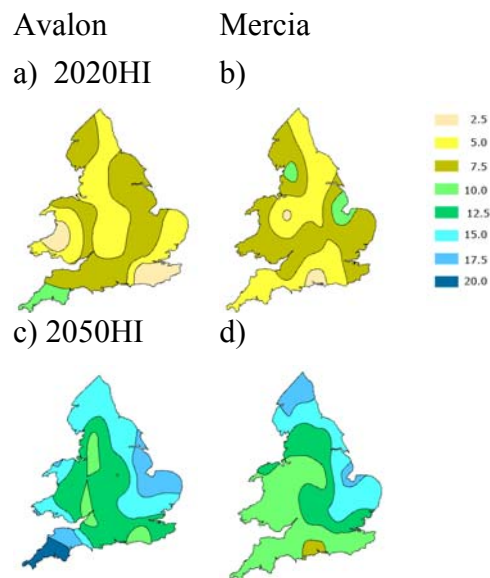


Fig 3.1. Relative changes in yield, %, for cv. Avalon and cv. Mercia for 2020HI and 2050HI climate scenarios compared with the baseline scenario.

We use the Sirius wheat simulation model, which predicts wheat growth and development in response to climate and environmental variations (Jamieson *et al.*, 1998; Jamieson and Semenov, 2000; Lawless *et al.*, 2005), to assess the extreme impacts of climate change on wheat. A short description of the model is given in the Annex 3. We limited our analysis to England and Wales, because the detailed soil information required by Sirius was only available for these regions.

Predicted relative changes in mean yield between baseline and 2020HI or 2050HI climate scenarios are presented on Fig.3.1 for *cv. Mercia* and *Avalon*. For two scenarios and both wheat cultivars average yields are predicted to increase, mainly because of yield stimulation with rising CO₂ concentration ([CO₂]). It was shown that elevated [CO₂] increases the photosynthetic rate in wheat (C3-plant) over a wide range of radiation (Lawlor and Mitchell, 1991; Long *et al.*, 2006). In Sirius radiation use efficiency (RUE) is proportional to [CO₂] and increases by 30% for doubling [CO₂] (Jamieson *et al.*, 2000; Ewert *et al.*, 2002). The magnitude and the spatial pattern of changes for the 2020HI scenario are similar for both cultivars (an increase up to 10%). However, for 2050 fast-developing *cv. Avalon* produced a larger increase in yield compared with *cv. Mercia*. For example, in the South West the increase in the

grain yield for Mercia was 7.5-10% whereas for Avalon the yield increase was 17.5-20%.

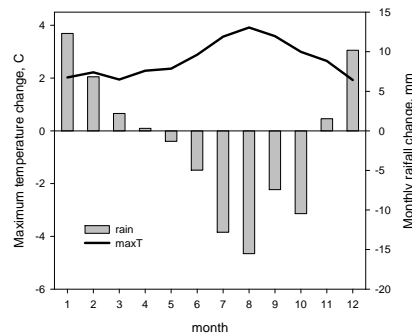


Fig 3.2. Changes in monthly means of maximum temperature and monthly precipitation between baseline and 2050HI climate scenarios at Rothamsted.

We use two statistics as examples of extreme impacts on wheat:

1. The first one is related to a single extreme weather event. It was reported that high temperature around anthesis can substantially reduce grain yield (Wheeler *et al.*, 2000). Half-way through anthesis temperature of 27°C can result in a high number of sterile grains (Wheeler *et al.*, 1996). We calculate the probability of the event, P_{ant+10}^{T27} , that the maximum temperature exceeded 27°C at least once during the ten days after anthesis began for any single year.
2. The second statistics is related to prolonged weather conditions experienced by the crop, that results to substantial yield losses. Crop drought stress index DSI_{crop} is defined as $DSI_{crop} = 1 - Y_{WL} / Y_{POT}$, where Y_{WL} and Y_{POT} are water-limited and potential grain yields. Both yields were calculated without nitrogen limitation, and the potential yield was calculated without water limitations.

Predicted increases in maximum temperature for 2050HI was between 2 and 4 °C (the highest increase was in August, Fig. 3.2). Probability P_{ant+10}^{T27} that maximum temperature exceeds 27 °C around anthesis is expected to be significantly affected by such large temperature increase if the anthesis day remains unchanged. However, because wheat development is driven by the thermal time, in a warmer climate anthesis will occur early in the season when temperature is cooler due to the seasonal cycle.

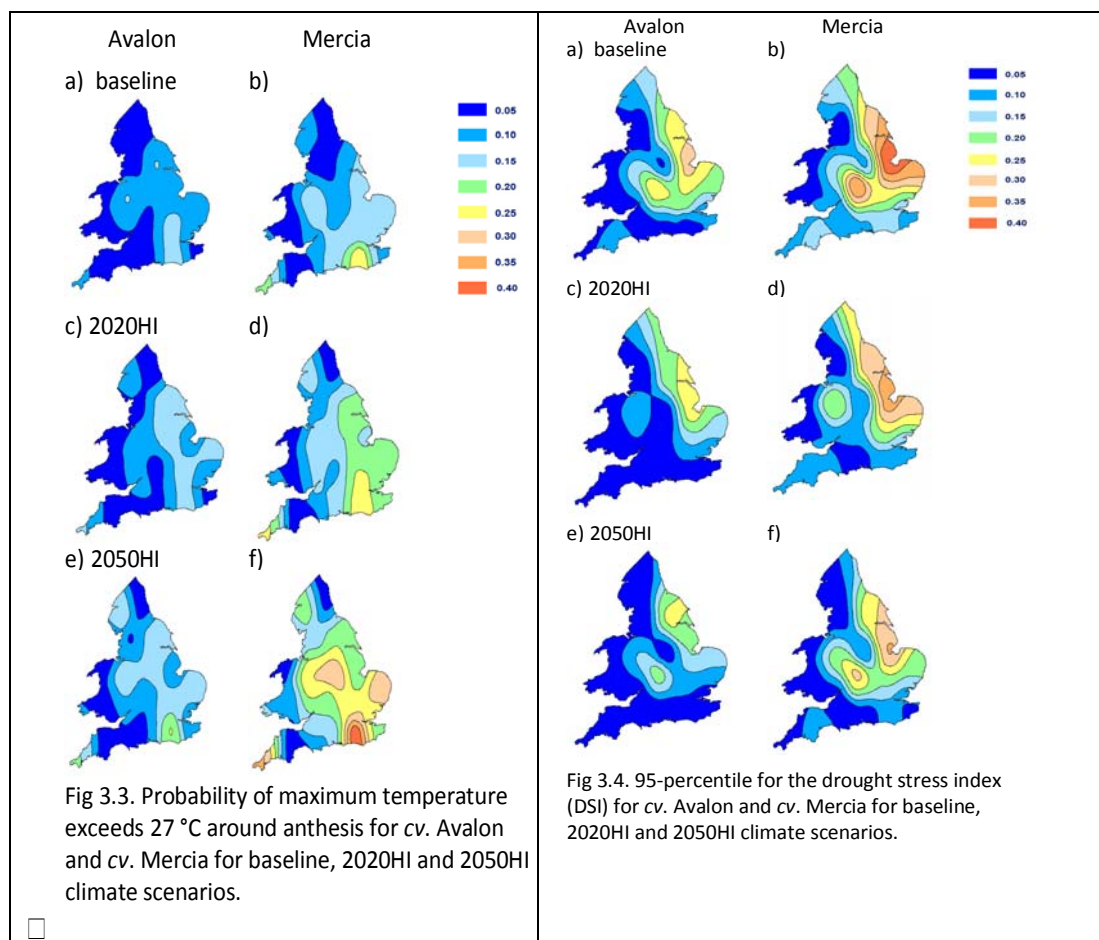
Cultivar		Baseline	2020HI	2050HI
Avalon	Anthesis	9 June	4 June	24 May
	Maturity	8 Aug	1 Aug	18 July
	T_{max} , °C	18.50	18.56	18.85
Mercia	Anthesis	19 June	15 June	5 June
	Maturity	23 Aug	16 Aug	2 Aug
	T_{max} , °C	19.36	19.87	20.42

Table 3.1. The average day of anthesis and maturity and average T_{max} for anthesis day at Rothamsted calculated for cv. Avalon and Mercia and for the baseline, 2020HI and 2050HI climate scenarios.

Table 3.1 shows the average day (day of the year) of anthesis and average maximum temperature T_{max} for this day for cv. Avalon and Mercia for the baseline, 2020HI and 2050HI climate scenarios. The predicted increase of temperature around anthesis is 2-2.5 °C (Fig. 3.2) for the 2050HI scenario. Nevertheless, the actual increase of T_{max} at anthesis was much lower, 0.35 and 1.06 °C for cv. Avalon and Mercia, respectively, because anthesis has occurred two weeks earlier in 2050HI. Probability P_{ant+10}^{T27} for cv. Avalon changed very little in the magnitude and the spatial pattern for 2020HI and 2050HI scenarios compared with the baseline scenario (Fig. 3.3). For slow-developing cv. Mercia changes in probability P_{ant+10}^{T27} were substantial. For the baseline scenario P_{ant+10}^{T27} was less than 0.15 for the majority of England and Wales. For the 2050HI scenario P_{ant+10}^{T27} was greater than 0.25 for more than half of England and Wales exceeding 0.35 for the South East of England (Fig 3.3).

To characterise extreme drought impact on wheat we calculated 95-percentiles of the DSI distributions Q_{DSI}^{95} for cv. Avalon and cv. Mercia based on crop simulations for 150 years of synthetic weather for the baseline, 2020HI and 2050HI climate scenarios. Q_{DSI}^{95} can be interpreted as the highest level of yield losses due water stress that is expected to be exceeded once every 20 yr. On Fig.3.4 Q_{DSI}^{95} for cv. Avalon and cv. Mercia are presented. For the baseline scenario the spatial patterns for Q_{DSI}^{95} are similar for both cultivars. Q_{DSI}^{95} is substantially higher for the eastern part of the region than for the western part reaching values of 0.3 for cv. Avalon and the value of 0.4 for cv. Mercia. For the baseline scenario Q_{DSI}^{95} for slow-developing cv. Mercia is predicted to be higher than for cv. Avalon by 0.1 with exception of the West of England and Wales where losses due to the water stress expected to be very low ($Q_{DSI}^{95} < 0.05$). For the future scenarios despite the fact that monthly precipitation would be lower for all months from May till October, Q_{DSI}^{95} is predicted to decrease by about 0.05 for 2020HI and by 0.1 for 2050HI for the East of England.

There are two contributing factors explaining a decrease of Q_{DSI}^{95} . The first factor is related to wheat phenology. In a warmer climate wheat will mature early, i.e. *cv. Avalon* and *cv. Mercia* are predicted to mature almost 3 weeks early for the 2050HI scenarios compare with baseline scenario. Because soil water deficit is increasing towards the end of crop growth, by maturing early crop will avoid most severe drought stress. The second factor is related to changes in the precipitation pattern. Although summer is predicted to be dryer for the UKCIP02 projections, winter is predicted to be wetter (Fig. 3.2). Additional precipitation received during winter and early spring would be store in the soil and made water available to the crop during late spring summer time.



3.2. Extreme impacts on sugar beet

Growth and sugar yield of the beet crop are primarily determined by the amount of solar radiation that the foliage can intercept and by the efficiency with which it is used (Werker and Jaggard, 1998). The date of sowing and the temperature during the canopy expansion phase have large impacts on sugar yield. The base temperature for germination of sugar beet seeds is 3°C (Gummerson, 1986). Because this is so cool, the sowing date of the crop is mainly determined by soil condition in spring. Soil

condition depends mostly on rainfall, which controls the ability of soil surface to be cultivated and to carry traffic. The growth model, plus the conditions for farm machine operation specified by Thomasson (1982), was used to determine the dates on which seeds drilling was possible.

Table 3.1 Changes in 5-, 50- and 95-percentiles of simulated national unit land sugar yield (t/ha) for rain-fed crops harvested on 31 Oct. under different weather scenarios

Scenario	5-percentile	50-percentile	95-percentile
Baseline	7.2	10.1	12.6
2020HI	7.9	11.6	14.3
2050HI	9.3	13.6	17.2
2080HI	10.6	15.5	20.2

Ten weather stations were selected in today's beet-growing areas. They were used to assess the extreme impacts on the UK sugar yield, assuming five different soil types. However, data from the weather station at Broom's Barn Crop Research Centre were used to assess the potential impacts on important aspects of sugar beet agronomy. The projection of future weather under high CO₂ emission scenarios will have positive impacts on the sugar yield in the UK. By 2050, the national median sugar yield is expected to increase by 35% (i.e. 3.5t/ha) (Table 3.1). Increases due to CO₂ enrichment are included in these predictions

Table 3.2 Changes in 5-, 50- and 95-percentiles of sugar beet crop sowing and emergence dates under different weather scenarios.

Event	Scenario	5-percentile	50-percentile	95-percentile
Sowing date	Baseline	21 Feb	23 Mar	18 Apr
	2020HI	23 Feb	19 Mar	14 Apr
	2050HI	14 Feb	14 Mar	05 Apr
	2080HI	14 Feb	11 Mar	06 Apr
Emergence date	Baseline	31 Mar	20 Apr	07 May
	2020HI	25 Mar	15 Apr	05 May
	2050HI	16 Mar	06 Apr	24 Apr
	2080HI	09 Mar	31 Mar	21 Apr

However, associated with these sugar yield increases are differences between extreme low (5-percentile) and extreme high (95-percentile) national sugar yields, which are also expected to increase. By 2050, this sugar yield variation will increase from 5.4t/ha in the recent past to 7.9t/ha. These annual variations will be difficult to manage because there is a finite period for processing each season's production and a finite processing capacity. Either some processing capacity will be under-utilized in the extreme low yield seasons or some crop will be wasted in the extreme high sugar years.

The ranges of weather anticipated in the future will also have large impacts on sugar beet agronomy. Firstly, warmer weather in the spring in the future will advance the seed drilling and seedling emergence dates (Table 4.2).

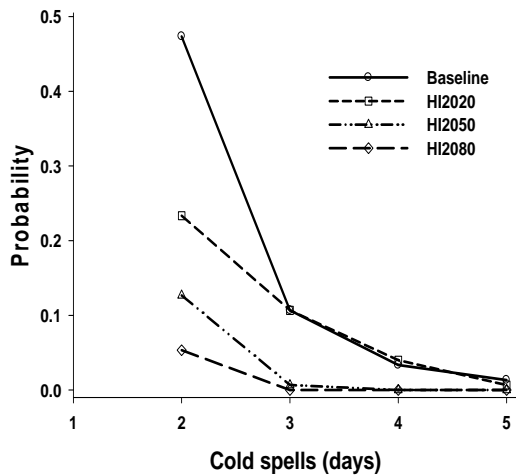


Fig. 3.4. The probability of cold spells (air minimum temperature colder than -5°C) of various lengths in a single growing season during December, January and February.

At present, it is still customary that beet roots are harvested and stored in insulated conditions, protected from damaging freezing temperatures while awaiting to be delivered to sugar factories for processing. Storage losses, due to respiration and the growth of saprophytic fungi, occur during this process. These losses have been estimated at 11% of total sugar produced by the UK crop in the past (Jaggard et al., unpublished). The losses can be avoided if the risk of frost damage in the field is sufficiently small. We estimated the frequency of potentially damaging cold spells in the recent past and in the future. As soon as 2020, cold spells during December, January and February may be rare enough for beet to be left in the field until immediately before delivery (Figure 3.4).

We used the weather generated for the future climate scenarios to predict the incidence of two important diseases, powdery mildew, virus yellows and an important pest, beet cyst nematode. All three are likely to be more prevalent in the future unless we can maintain or improve on the efficacy of current control measures. In addition, *Cercospora* leaf spot is likely to become a major problem as the weather in early summer gets warmer and days with temperature maxima exceeding 30°C become more frequent.

3.3. Future opportunities for Climate and Crop Modelling

Hadley Centre has developed a new set of probabilistic predictions of climate change. A new approach was used to quantify climate model uncertainties in climate prediction by making simulations with large numbers of variants of the model, each having slightly different parameters describing the physics of the climate system.

These probabilistic predictions will be soon released as UKCIP08 scenarios that describe in probabilistic terms changes for a number of climatic variables at the 25-km resolution in the UK. Extreme weather events and extreme impacts on agricultural crops should be re-analysed for probabilistic climate scenarios.

We have modelled the impact of the weather on the growth and yield of the healthy crop, and in a few cases we have modelled the impact of the weather on the incidence of diseases. Unfortunately, it was not possible to model the effect of the disease incidence on the growth and yield predictions. This is a serious gap in today's assessment of extreme impacts on agricultural crops.

4 ECONOMIC VULNERABILITY OF WHEAT AND SUGAR BEET TO EXTREME CLIMATE EVENTS

4.1. Introduction

Climate change affects agriculture mostly through changes in temperature, changes in precipitation amounts and changes in its distribution and the fertilisation effect of carbon dioxide in the atmosphere. Though a change in *mean* temperature and average precipitation can be hazardous in the sense that it represents a change in what the agricultural sector has adapted itself to, it is likely that the greatest impacts of climate change will be due to the change in the *variability* of climate. This is because the frequency of extreme events (heat-waves, frost-spells, drought or excess moisture and severe storms) is relatively more dependent on any changes in the variability than in the mean of climate (Katz and Brown, 1992).

Whereas agricultural production in general is well adapted to mean or average conditions it is susceptible to extreme conditions. Isolated incidents of extreme hot or cold temperature could seriously damage a plant. A continuous period of extreme hot or cold temperature could be lethal for crops. Isolated incidents of extreme hot or cold temperature could seriously damage a plant and a continuous period of extreme hot or cold temperature could be lethal for crops.

An agricultural region or a sector is considered vulnerable to climate change when it has difficulty to cope with climate variability and extremes. There are two major economic approaches to study the interaction between climate and agriculture: the bottom-up production function approach and the top-down econometric Ricardian approach. For a discussion see Annex 5. We used the so-called production function approach to quantify economic vulnerability as: (a) exposure to risk at the field level, and as (b) an aggregate measure taking into account the aggregate probability distribution that yield will lie below a predefined level. The production function approach relies on the results from crop growth simulations models and was applied for sugarbeet and wheat.

4.2. Exposure to risk at the field level: variability and Value-at-Risk

Changes in yield variability are defined by the properties (moments) of the cumulative distribution functions of the crop yields under different climate scenarios. Given our focus on extreme climate events we were particularly interested in changes in the tails of the yield distribution as reflected in the skewness. [Skewness](#) denotes that observations are not spread symmetrically around the [average](#) (as with the normal distribution). A positive/negative skewness means that the right/left tail is longer. Thus for yield distributions, a less negative skewness is desirable.

In addition to the skewness and other properties of the yield distribution, we assessed the Value-at-Risk (VaR). VaR is the leading measure in the finance world for unexpected low returns and this measure can be easily adapted for agriculture. In our application to agriculture and extreme weather events, VaR-95% would be the lowest expected yield per ha with 95% confidence. Thus there would be a probability of less than 5 % of a yield below this cut-off yield level. For future climate scenarios, we

assessed the probability of unexpected low yields using the cut-off yield for the baseline. Comparison then reveals whether there is an increase in the Value-at-Risk with the subsequent climate scenarios. The Value-at-Risk expresses risk in easily understood terms and that it focuses on true downside risk. Note that the VaR measure describes only the loss that will be exceeded with some level of confidence; it says nothing about the absolute worst possible yield level.

Next, we took into account the total yield distribution by means of plotting the cumulative distribution functions for the baseline and the scenarios by location and crop. If for example the distribution function of wheat yield has a higher mean after a certain climate change than before and these two yield distributions do not overlap, one ought to expect that everyone will consider the new situation better than the old situation. Then we have what is called First-Degree stochastic dominance (FSD). Thus FSD holds whenever one cumulative probability distribution lies entirely under another and it simply assumes that decision-makers prefer more to less. When the distributions cross one another Second-Degree Stochastic Dominance (SSD) can be helpful. SSD obtains when the area under one cumulative probability distribution is equal to, or larger than, the area under the other distribution. SSD assumes that in addition to preferring more to less, the decision-maker is risk-averse. Risk aversion implies that farmers are made worse off by any mean-preserving increase in the variance of income (and thus by a ceteris paribus increase in the variance of yield).

4.3. Vulnerability at the aggregate, sectoral level

For the purpose of our study we also needed a measure of vulnerability at the sectoral level. The set of indices for this purpose has its origin in poverty measurement (Table 4.1). Application means an inescapable need for a vulnerability threshold level, W_0 . In climate applications, this threshold level would be the location specific average yield of the baseline situation. This assumes that producers do not want to be worse off in the future.

4.4. Data

The sugarbeet model and weather scenarios described in sections 1, 2 and 3 were used to generate yield data for different soil types within the nearest site of each weather station and within each factory region (Appendix II). For aggregation the sugar beet crop area (ha) in 2007 was used because this is the most likely sugar beet crop growing area in the future. For wheat only soil type information was available for the locations, data on the acreage used for wheat by location was unavailable.

Table 4.1. Vulnerability measures and their interpretation

Measure	Interpretation
Proportional vulnerability $V_0 = q/n$	The proportion of the relevant population (fields or farms) that are classed as vulnerable. This is a ‘headcount’ indicator and does not account for the degree of vulnerability.
Vulnerability gap $V_1 = \frac{1}{n} \left[\sum_{i=1}^q \left(\frac{W_0 - W_i}{W_0} \right) \right]$	The aggregate scope of vulnerability: the summed distance for each individual field or farmer from the vulnerability threshold level.
Vulnerability severity $V_2 = \frac{1}{n} \left[\sum_{i=1}^q \left(\frac{W_0 - W_i}{W_0} \right)^2 \right]$	The severity of vulnerability reflects the distribution of the vulnerability gap within the vulnerable population. The more skewed the distribution the greater the severity.

Source: Adger, 2006.

4.5. Sugarbeet

The simulated sugarbeet yields (tonnes of sugar per hectare, t/ha) for each of the 10 locations, five soil types and four scenarios were treated as samples and estimates of the moments of the dataset samples were calculated. This provides the mean, the variance, the skewness and the VaR of the yield distributions for each of the weather scenarios by location and soil type (Annex 5, Appendix III). These results can be summarised as follows:

- Mean yields increase significantly with each of the scenarios compared with the baseline.
- The variance increases but in general the skewness becomes less negative with the subsequent climate scenarios.
- In general lower value for kurtosis (less of the variance is due to infrequent extreme deviations (‘thinner tails’).
- The probability of very low yield levels (as measured by the VaR) is reduced with the subsequent climate scenarios for all locations and types of soil.

Future sugar yield at field level exceeds the baseline yield for all different soil types. Yield increase is more for some soil types than others. Yield increases are highest for clay loam and for peat/organic soil. For Wattisham for example, the increase in average yield between the baseline and 2020HI is 17% and 19% for clay loam and peat soil and about 13% for sandy loam soil. By 2050 these increases are 44 % and 47% for clay and peat soil respectively and 34 % for sandy loam soil.

Next, the distribution functions were graphed and visually inspected. As an example, Figure 4.1 presents the distribution functions for the baseline and 2020HI for Wattisham and Figure 4.2 presents the distribution functions of the baseline and 2050

for sandy loam at Terrington. These two figures serve to further illustrate the results summarised above; the simulated yield distributions for the various climates scenarios do not overlap and there is a marked increase in the expected average yield.

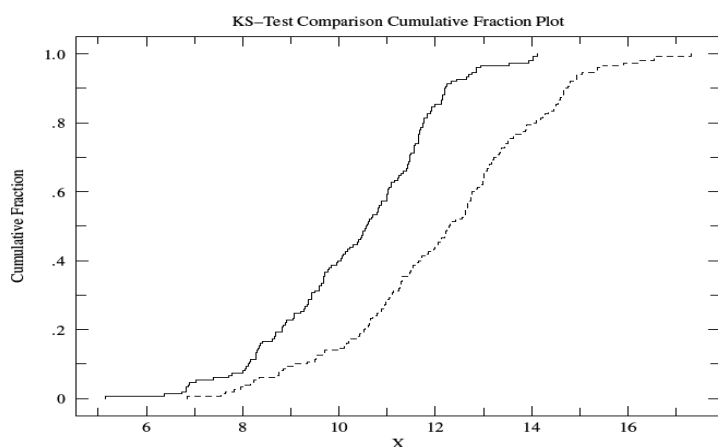


Figure 4.1 Cumulative yield distribution on clay soil Wattisham, baseline (solid) versus 2020HI (dotted line) (x denotes yield in t/ha).

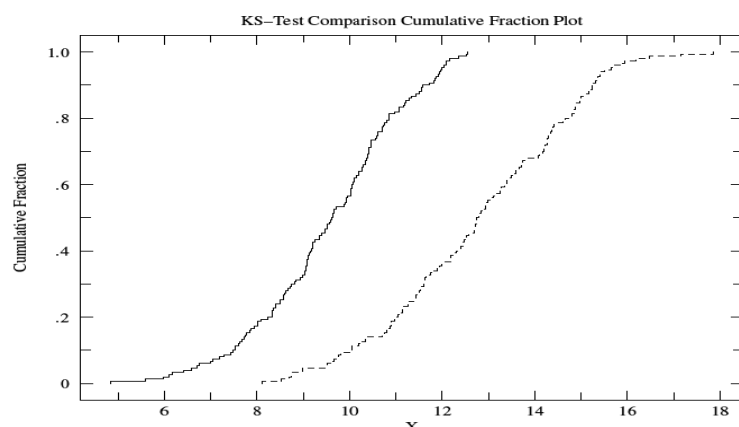


Figure 4.2 Cumulative yield distribution on sandy loam Terrington, baseline (solid line) versus 2050HI (dotted line) (x denotes yield in t/ha).

The changes in the yield distributions translate to a statistically significant increase in the total sugarbeet yield. The expected aggregated (national) yield by 2020 is **13.8% higher** compared with the baseline. This figure was calculated using the 2007-acreage in the UK (Appendix II) and the statistical results in Appendix III. In addition to the increase in the expected average, yield levels currently exceptional will become very common with climate change. This is because of the shift in the cumulative yield distributions to the right (see Figures 4.1 and 4.2). For example on clay loam soil at Wattisham, the probability of a yield of 12.8 t/ha is only 5 % in the baseline situation but this is 40 % by 2020.

Given these results, future research should look into the issue of overproduction because of the limit of processing capacity and the total limit each grower is entitled to produce.

The results suggest that for U.K. sugarbeet, extreme events due to future climate change do not lead to adverse effects in terms of higher yield variability or an increased probability of very low yields. Because of these field level results, we felt there was no need to apply the aggregate/sectoral vulnerability indices of Table 4.1.

4.6. Wheat

For wheat the impacts of extreme events was evaluated for two varieties (MERCIA and AVALON) for 15 different location in England and Wales. The simulated yield distributions (kg per hectare, kg/ha) were again treated as samples and estimates of the moments were calculated. This provided the mean, the standard deviation, the skewness and the VaR of the yield distributions for both cultivars by climate scenario and location (see Annex 5, Appendix IV for six of the 15 locations).

The economic results for wheat can be summarised as follows:

- Mean yield increases significantly with each of the scenarios compared with the baseline.
- In general the probability of very low yield levels (as measured by the VaR) is reduced with the subsequent climate scenarios.
- There are however some locations where for either MERCIA or AVALON by 2020 the VaR remains unchanged or increases slightly.
- By 2050 this effect disappears and the probability of very low yield levels (as measured by the VaR) is reduced with climate change for all locations and types of soil.

Figures 4.3 and 4.4 visualise the difference in results by 2020 for the two cultivars at Boulmer. At this location the VaR for MERCIA increases slightly as shown by the overlapping tails of the cumulative yield distributions for the baseline and 2020. In contrast the yield distributions for AVALON do not overlap.

As mentioned above, the area used for wheat by cultivar in recent years was not readily available and thus the impact of the change in yield levels on the total wheat harvest for England and Wales could not be calculated. Finally, the field level results for wheat suggested no further need for the application of the aggregate/sectoral vulnerability indices of Table 4.1.

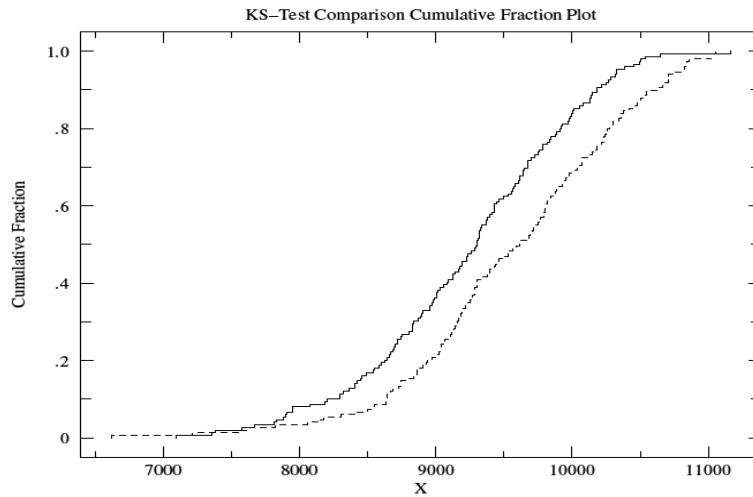


Figure 4.3 Cumulative yield distribution wheat (Avalon) on Brickfield soil, Boulmer, baseline (solid line) versus 2020HI (dotted line) (x denotes yield in kg/ha).

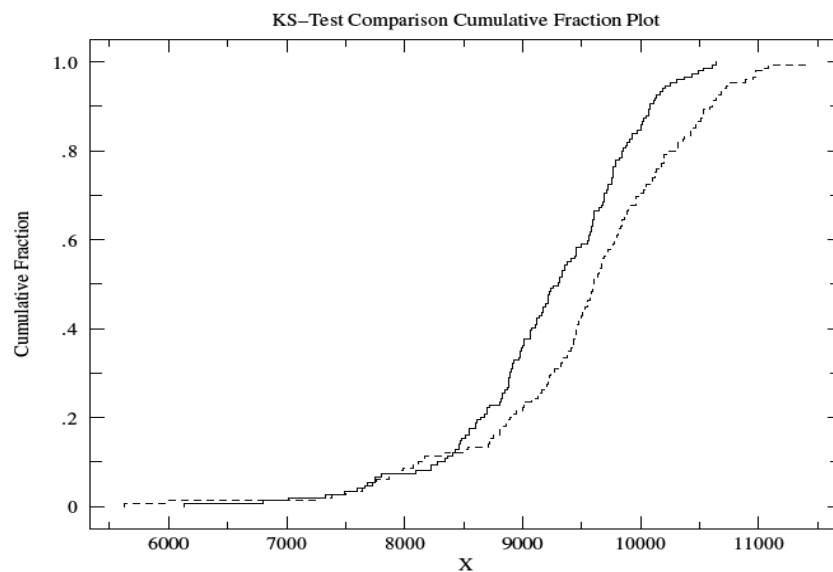


Figure 4.4 Cumulative yield distribution wheat (Mercia) on Brickfield soil, Boulmer, baseline (solid line) versus 2020HI (dotted line) (x denotes yield in kg/ha).

4.7. Conclusion

- The economic assesment showed that for U.K. sugarbeet, extreme events due to future climate change do not lead to adverse effects in terms of higher yield variability or an increased probability of very low yields.
- The probability of very low yield levels for sugarbeet (as measured by the VaR) is reduced with the subsequent climate scenarios for all locations and types of soil.

- The expected aggregated sugarbeet yield by 2020 is 13.8% higher compared with the baseline (based on 2007 acreage distribution).
- For wheat, in general the probability of very low yield levels (as measured by the VaR) is reduced with the subsequent climate scenarios.
- There are however some locations where for a specific cultivar the VaR may remain unchanged or increase slightly.
- By 2050 the impact on wheat is uniform: the probability of very low wheat yield levels (as measured by the VaR) is reduced with climate change for all locations and types of soil

5 EXTREME WEATHER: CROP AND INDUSTRY IMPACTS

5.1. Physiology and crop production

While comprehensive crop models incorporating growth development and yield exist for the major arable crops wheat and sugar beet grown in the UK, models for other e.g. horticultural crops are more limited. To predict likely impacts on these crops we used a combination of literature reviews, industry consultations and modelling of specific conditions.

Extreme weather can affect crops directly or through production conditions

We carried out literature reviews of the physiological sensitivities of several representative crops grown in the UK, including vegetable brassicas, oilseed rape, potatoes, peas, Miscanthus, sunflower, apples and protected tomatoes (for full reviews, with references, see Annexes 6 and 7). Reviews of the literature confirm that several environmental factors are capable of causing a significant impact on production, either through yield or quality loss. The most important of these are temperature (heat waves, frosts), water (drought, waterlogging) and storms (wind, hail / inundation). Most crops are vulnerable to storm and hail damage but the methodology used in this study does not have the spatial or temporal resolution to allow the prediction of individual storms, although it is generally accepted that these are likely to be more frequent in the future. Protection through netting may be available for outdoor perennial crops such as apple and cherry and soft fruit is being increasingly grown under glass or poly tunnel protection. For other crops strategies for minimising damage will include reducing risk by growing the crop across several geographically distributed planting sites.

Additional to these effects, are those where the weather affects agricultural practice and husbandry, e.g the ability to prepare land, plant or harvest crops because of soil conditions, or through pest and disease pressures. In identifying such factors and their impact on production, we have used experiences from recent extreme weather events to define thresholds or weather patterns that lead to extreme impacts.

Unseasonal or extreme weather can affect a wide range of crop production variables depending on the nature of the crop, stage of development or the time of year. Table 5.1 presents the vulnerable stages of development or traits for a range of crop types.

Table 5.1: Crop types and vulnerable stages of development..

Crop Type	Examples	Vulnerable Process
Annual seed crops	Cereals, oilseeds, peas	Planting, establishment, flowering, seed formation
Annual vegetable crops	Brassicas, potatoes	Planting, establishment, development, lifting or harvesting, quality
Annual Protected crops	Tomatoes	Quality, yield
Perennial fruit crops	Apples	Bud break, flower initiation, flower development, fruit growth and quality
Perennial Biomass Crop	Miscanthus	Establishment

High summer temperatures will have a negative impact on yield and quality for many horticultural crops

In all of the crops we studied, unseasonal temperatures can have major effects on yield and quality (Table 5.2). High temperatures are a particular problem. In the summer they can cause yield loss, particularly when they occur around the flowering and seed development stages and their effect is often carried through into loss of quality. Flower development was found to be a potentially sensitive stage in almost all of the crops studied. From the literature survey, examples of crops sensitive to high temperature around anthesis include oilseed rape, peas and sunflower. In tomato, high temperatures around anthesis reduce the number of pollen grains released and their ability to germinate, both of which will have a negative impact on fruit set.

We found that most of the studies on this problem (an exception is sunflower) look at the effect of specific temperatures on flowering and yield and quality. They did not establish the quantitative relationship between temperature exposures e.g. critical temperatures and duration, and impaired flower development. We propose that targeted experimental work on reproductive temperature sensitivities of key crops including peas and oil seed rape is required to determine the risk of losses due to failed flowering under predicted future weather patterns. The results from wheat presented in this report show that the risk of high temperature damage can be affected by changes in flowering time that occur as a consequence of climate change. Such studies would therefore need to include the effect of increased temperatures and carbon dioxide concentrations on flowering time.

High temperature during early development can have major adverse effects on crop performance. Evidence, some of it from the hot summer of 2006, can be found for high temperature inhibiting the germination of seed for vegetable brassicas, associated with blindness, increased leaf production and buttoning.

In addition to their impact on crop yield and production, high temperature effects on reproduction will have a direct impact on seed production. Most seed is produced under protection in the EU but there already problems with extreme temperatures. The hot summer of 2006 led to shortages of certain varieties in 2007 and these can be expected to continue into following years. For hybridisation, breeders rely on simultaneous flowering for both parents and plant at different times to achieve this. This has proved to be increasingly difficult in recent years.

Extreme climate change events are likely to have less of an impact on crops, such as tomato, which are grown under protection when compared with those grown outdoors. Nevertheless, periods of high summer temperatures are likely to cause fruit/truss quality problems. For protected tomatoes, it is likely that there will be more erratic yields and increased wastage due to uneven ripening, soft fruit, poor/late set and delayed ripening of truss varieties.

Table 5.2; High temperature effects on development of different crops

Extreme Weather	Physiological impact	Crops affected
High temperatures in summer	Reproductive (flower) development impaired	Cereals, oil seeds, peas, tomatoes, apples
	Flower bud formation– effects seen the following year	Apples
	Crop development and yield impaired	Vegetable brassicas, tomatoes
	Crop quality impaired	Oil seeds, cereals, tomatoes, apples, vegetable brassicas
High temperatures in winter	Cold hardiness limited	Winter cereals, winter oilseeds, apples
	Early bud break and frost susceptibility	Apples
	Delayed curd induction	Winter cauliflowers
	Impaired flower development	Apples, blackcurrants

High temperatures in winter are likely to be a problem for crops that have an overwintering stage, particularly when they are combined with late frosts

A combination of warmer winters and high summer temperatures are likely to result in a trend to earlier planting dates for summer annual crops. This strategy may avoid high temperature damage to flowering but may also lead to increased losses due to late frosts. Many traditional varieties of perennial fruit crops such as apple and blackcurrant require a sustained period of cold in the winter for vigorous flowering and fruit production. Warmer winters in the future may have an impact on fruit production. As an example, in 2001 following an unusually mild winter in France flower production in Apples was greatly reduced. Where flowers were produced they were small and badly formed, leading to yield losses in the trees affected. Blackcurrant growers have also linked warmer winters in recent years with reduced yields and quality.

Effects of extreme weather on crop production schedules will depend on the crop type

Brassica production is closely linked to annual temperature cycles. Brassicas have three phases of growth: a juvenile phase where plants produce leaves, the curd or head induction phase and finally the curd or head growth phase. Cauliflower can be harvested all the year round in the UK by growing in production areas with slightly different temperatures and by using different maturity types which mature in early summer, summer/autumn and winter through to spring. Broccoli can be harvested from Summer through to early Autumn in the UK by using multiple plantings of the same CV to get continuity of supply.

One potential problem can be seen when we modelled how increases in temperature in the autumn and early winter can delay maturity for the early plantings of cultivars of winter cauliflowers currently in use (Annexe 8, case study 1). This leads to a compression of harvest dates (Figure 5.1). It may be possible to overcome problems in continuity of supply by changing to varieties with altered temperature requirements but further research will be required to identify or breed such adapted varieties.

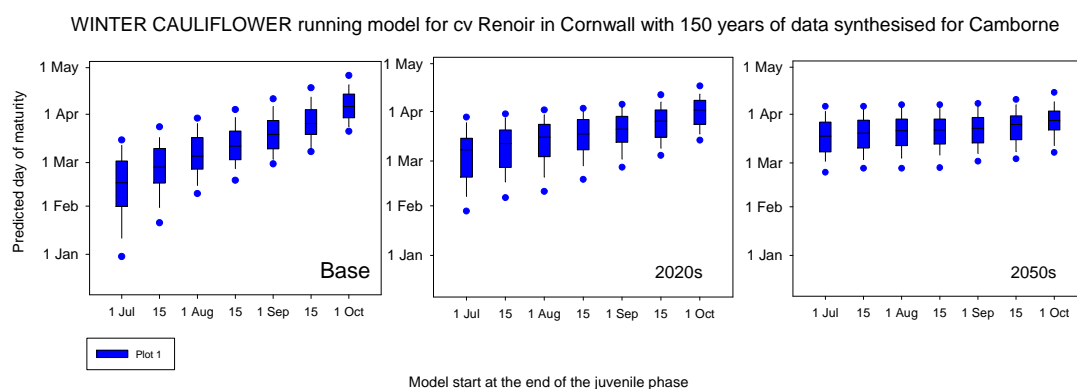


Figure 5.1 Predicted day of maturity using models for CV Renoir and weather data for Cornwall. The predicted dates of maturity for each of the 150 years of synthetic weather data have been summarised in the box plots. The boxes represent the 25th and 75th percentiles and the line within the box represents the median. The whiskers represent the 10th and 90th percentiles and the dots show the maximum and minimum values.

In the UK vining peas are harvested at a specified stage of maturity which is determined by measurement of samples using a tenderometer. We used a crop scheduling model to predict the harvesting window for crops at different planting dates (Annexe 8, case study 2). For all sites the time of the average harvesting window for a specific sowing was reduced by the 2050s and the variation in the duration of the harvest window over the 150 years of data was also reduced. However, crop development was accelerated more for early sowings than later ones. The overall harvesting window for vining peas would be predicted to be longer. Predicted changes in the harvesting window for vining peas may have implications for the logistics of harvesting and processing of the UK crop in the future (Annexe 8, case study 2).

Water availability will have an adverse effect on yield and quality of many crop

Most field grown crops, including brassicas, peas, sunflowers and potato are susceptible to drought. The stage at which drought has most impact on yield varies with different crops. For some, such as oil seed rape and sunflower, the critical period is around flowering time, while pea is more susceptible early in development. Drought can also have adverse effect on quality in crops such as potatoes and oil seeds. The problem of drought is less critical for deep rooted perennial crops such as Apple and can be countered with appropriate management strategies. Potatoes are susceptible to problems caused by flooding and waterlogging. In 2007, approx 2000 ha crops were lost to flooding and yields were low. Also, in that season, there were problems with greening, probably caused by water running and exposing the developing tubers as ridges were knocked down. There was also cracking after water-logging which was followed by fast drying. Compaction is a major problem for potato production.

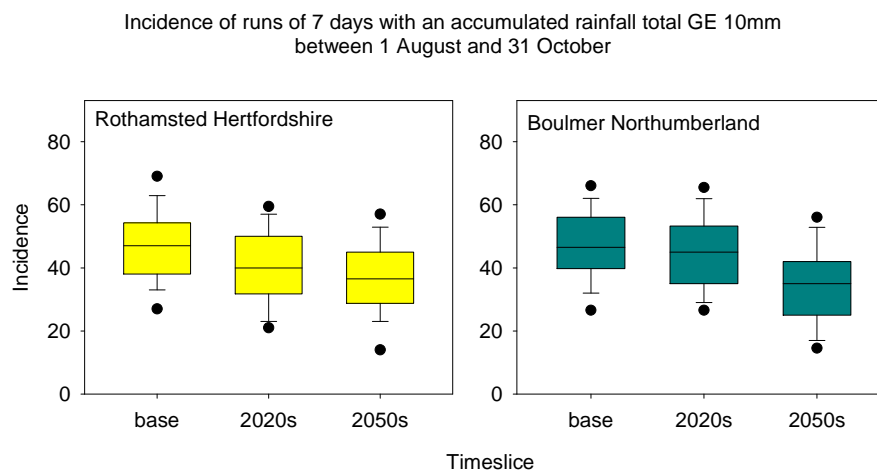


Figure 5.2. Incidence of runs of 7 days with an accumulated rainfall total of 10 mm between 1 August and 31 October under baseline, 2020HI and 2050HI scenarios. (Note: 10 consecutive days count as 4 runs). The boxes represent the 25th and 75th percentiles and the line within the box represents the median. The whiskers represent the 10th and 90th percentiles and the dots show the maximum and minimum values.

Heavy rain in the autumn can have severe implications for lifting the main crop of potatoes. A recent example was in 2000 when heavy rain prevented machinery from getting on to the land to harvest (Annexe 8, case study 3). At Christmas, 25,000 ha (~20% of the crop) had still not been lifted. We took the conditions that led to the problems in 2001, estimated a rainfall threshold of 10mm per run of 7 days and modelled the likely incidence for 2020s and 2050s compared to baseline data for two locations, Rothamsted in the south and Boulmer in the north (Figure 5.2). The main conclusion is that rainfall in the autumn at levels that can have a major impact on potato harvesting is predicted to become *less prevalent* with similar trends at both locations.

Crops which require continuity of supply e.g. salad leaves, cauliflowers, are particularly vulnerable to extreme weather events

Extreme weather conditions can cause major problems with brassica crops, leading to under – supply, over-supply, shortages and gluts. This causes problems for growers as prices are usually fixed by multiples over the long term. Erratic weather also leads to quality problems.

Direct-drilled baby leaf salad crops are particularly vulnerable. The market for these crops is volatile and heavily weather-dependent. The harvest window for these crops is only 1 or 2 days whereas whole head can be cut earlier or later. There are problems with conditions affecting land preparation and drilling, particularly when wet.

Crop establishment is also a key issue for potatoes. The conditions in April to June are really crucial. Potatoes need to form a good root structure in well-prepared soil. Otherwise both yield and quality will suffer. During establishment heat is not a problem but shortage of water is.

Important long-season crops such as salads and vegetable brassicas are vulnerable to periods of drought that lead to bone-dry soils, resulting in gaps in production. The most susceptible period to drought is around planting and crop establishment.

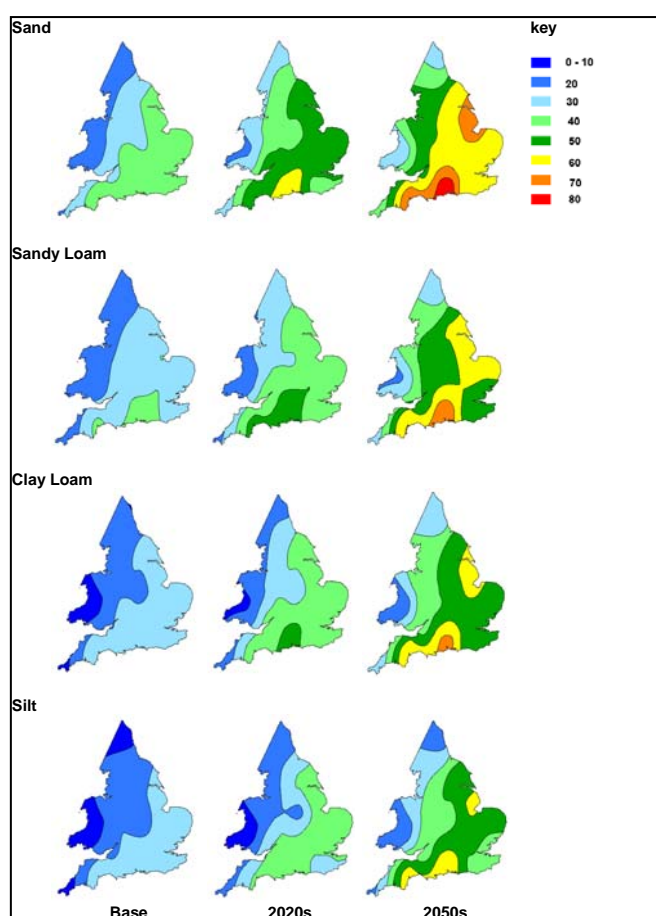


Figure 5.3 The 95th percentile for the incidence of runs of 7 consecutive days of bone dry soils for different locations and soil types for baseline 2020HI and 2050HI scenarios. (Note: 10 consecutive days count as 4 runs). (Annexe 8, case study 4)

In order to identify weather patterns that give rise to bone-dry soil conditions we used the example of July 2006 when planting and establishment was prevented by dry soil conditions (Annexe 8, case study 4). From consultations with growers we concluded that 7 continuous days of bone dry soil would have a significant impact on crop continuity. We calculated the likely incidence of runs of 7 days dry soil in different parts of the country on different soil types based on 150 years synthetic weather data from 2020 and 2050 compared to baseline (Figure 5.3). The predictions indicate that for the worst case (equivalent to once every 20 years), the incidence of runs of 7 consecutive days of bone - dry soil will increase, particularly in the South and East and on sandy soils.

Matching supply with demand

Weather has a huge impact on demand for prepared salads as well as supply. Industry reports that recent weather-related peaks in demand are much greater now than they used to be, making it difficult to plan and schedule production. Weather drives

consumer demand and also affects crop production but, the timescales for impact of external factors are very different. For example, if it is warm early in the season consumers can tire of buying and eating salads. When 2-3 warm weeks occur in succession, it is very difficult to satisfy demand.

For crops grown primarily through the spring and summer, higher mean temperatures and elevated CO₂ levels will result in earlier maturity. We found this to be the case when we carried out supply simulations using a scheduling model for iceberg lettuce cv. Saladin run using synthetic meteorological data for Kirton simulated by the weather generator. (Annexe 8, case study 5). The main trend appeared to be earlier cropping due to higher mean temperatures. We found little evidence to suggest that the weekly variation in supply would be more greatly affected in the future than in recent years.

Extreme weather can have an impact on quality

Leafy salads, grown over a long season for continuous supply are vulnerable to extreme weather events causing quality thresholds to be exceeded. Discussion with industry indicated that *heavy rainfall*, (defined as >12mm in a day, >25mm in a week, or >50mm in a month); *high temperatures*, (defined as >28°C during the day and >14°C at night); *low temperatures*, (defined as <5°C); and *differences in day/night temperature* <8°C would be expected to lead to a negative impact on quality. To assess the impact of extreme weather events on the production of leafy salads, the risks of exceeding quality thresholds were estimated for the period 1 March to 31 October based on synthetic weather data simulated for 16 locations across the UK.

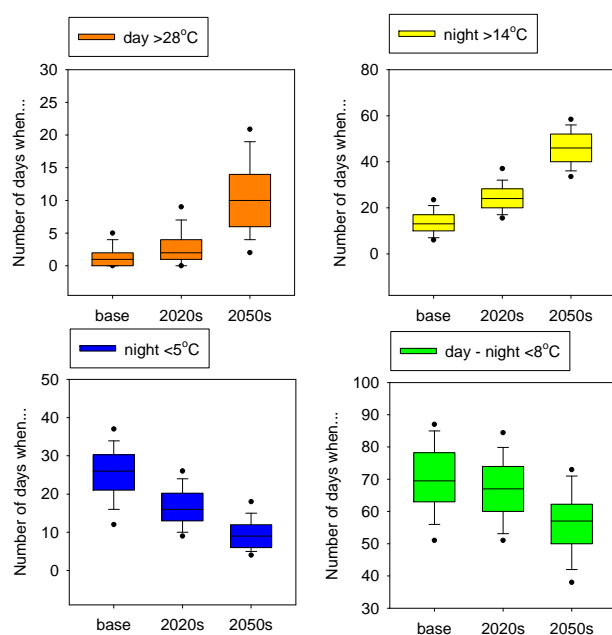


Figure 5.4. The likelihood of temperatures a) exceeding 28°C during the day, b) exceeding 14°C at night, c) falling below 5°C and d) the difference between day and night being less than 8°C. Data are based on 150 years of synthetic data simulated for Kirton (1 May to 31 Oct). The boxes represent the 25th and 75th percentiles and the line within the box represents the median. The whiskers represent the 10th and 90th percentiles and the dots show the maximum and minimum values.

Overall the risk of exceeding the thresholds for rainfall remained relatively similar in the short to medium term. The risk of exceeding 50mm per month tended to show a greater decline over time. However, there would appear to be a much greater risk of exceeding 28°C during the day or 14°C at night as a result of climate change (Figure 5.4); this may have a detrimental effect on quality. Conversely, the number of occasions when night temperatures are expected to fall below 5°C (between 1 May to 31 Oct) is predicted to decrease and the number days when the difference between day and night temperatures is less than 8°C is predicted to decrease at most, but not all sites.

The net impact of climate changes on new crops, where UK is at the northern limit of their distribution, is likely to be positive

In this study we included both traditional UK crops for which there is a well established industry i.e. cereals, oilseeds, peas, potatoes, vegetables, tomatoes, apples and new crops which may be expected to become more important in the future i.e. sunflower, maize, miscanthus. For the new crops, maize and miscanthus, the UK is at the Northern extreme of their current distribution. While some events such as high temperatures, hail and drought will be detrimental, the net effect of climate change on the viability of new crops will be positive. For the established crops, increased temperature in summer and winter, water availability and the incidence of storms will pose increased threats to production in future.

5.2. Pest and disease effects

The effect of extreme climate events on the complex web of biotic interactions (pests, diseases, vectors, host plants, predators, parasitoids) is hard to assess and yet it is likely to be an important component of the outcome to crops

Most invertebrate pests have temperature-dependent rates of development and particular threshold temperatures defining the temperature range within which development can occur. Some pest species may be able to complete more generations with higher temperatures (if these are below lethal high temperatures). There is abundant information available about the effects of temperature on aphids. For aphids such as *Myzus persicae* (peach-potato aphid) that can overwinter as active adults, warmer conditions in winter lead to earlier and larger spring migrations to crop hosts (Annexe 8, case study 6). Dates by which the first alate *Myzus persicae* will be captured in the Rothamsted suction trap located at Kirton, Lincolnshire were predicted to be 9 days earlier in the 2020s and 20 days earlier by the 2050s than the date of 26 May predicted from the baseline data (using an equation provided by Richard Harrington, Rothamsted Research). Pathogenic micro-organisms are rarely limited to one life cycle per year, but will complete as many as conditions allow.

Extreme temperatures and the increased frequency of heat waves will undoubtedly be deleterious to some current UK pests and diseases

Peronospora viciae (downy mildew), *Hyaloperonospora parasitica* (downy mildew), *Synchytrium endobioticum* (potato wart disease), *Plesiocoris rugicollis* (apple capsid), *Psila rosae* (carrot fly) and *Deroceras reticulatum* (grey field slug) are all examples of disease or pest organisms that ‘prefer’ cool temperatures. Whilst temperature optima are often studied, temperatures above 30°C are not tested routinely for temperate organisms. Consequently there are less data published about the likely effects of periods of unusually warm weather on UK pests and diseases. However, temporary exposure of populations to extreme temperature (e.g. 39°C) may decrease the rates of growth of surviving individuals and delay the subsequent generation, particularly if the teneral stage was exposed to the extreme temperature.

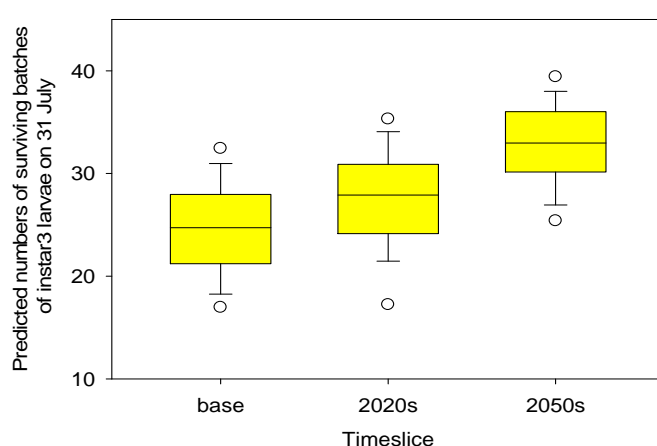


Figure 5.5 A descriptive population model for turnip moth (*Agrotis segetum*) was developed in the UK and forms the basis of a 'cutworm' forecast. The figure shows box plots of the predicted numbers of batches of larvae surviving to third instar accumulated up to the end of July at Kirton, Lincolnshire. The predictions were made using 150 years of synthetic weather data. The symbols show the 5th and 95th percentile outliers.

The effects of water (drought or periods of heavy rainfall) on pest and disease populations will depend entirely on the species and the timing of the event. Some species will prosper in dry conditions, others will not

The availability of free water is extremely important in the life cycle of many micro-organisms. Many types of fungal spores require free water for periods of several hours for germination (e.g. *Botryotinia fuckeliana* (grey mould), *Alternaria brassicae* (dark leaf spot)), and zoospores (produced by many fungal pathogens) spread through swimming (e.g. *Phytophthora*, *Pythium*). Bacteria are also often actively motile in water. Rain splash is used by many pathogens as a passive means of physical dispersal of spores or other propagules. Modelling leaf wetness is consequently of great importance to disease forecasting. In contrast, too much water can be devastating for some pests. Raindrops can physically dislodge the pest from its host plant and behaviour patterns can be disrupted, such as the ability to fly and spread to new crops, or to hide and feed. Water-intolerant pests, which may prosper in periods of drought include cutworms (turnip moth - *Agrotis segetum*) (Figure 5.5) (Annexe 8,

case study 7), wireworms (*Agriotes* spp.), potato tuber nematodes (*Ditylenchus destructor*) and diamond-back moth larvae (*Plutella xylostella*).

Although the current climate models do not contain a wind component, wind is likely to have a strong influence on extreme pest and disease events, both in the arrival of immigrants (and the timing of such events) and in their eventual spread within the UK

The English Channel is a relatively narrow stretch of water and many flying insects arrive from continental Europe. Some species are particularly well adapted to moving long distances in the air and these include several species of moth, such as *Plutella xylostella* and *Autographa gamma* (silver Y moth). Since neither of these species survives particularly well during UK winters at present, new infestations are generally the result of migrations from continental Europe, although both species may be able to overwinter successfully if winters become warmer in the future (Figure 5.6) (Annexe 8, case study 8). There has been increased migration of moths and butterflies to the UK during the last two decades and recent research has linked this to a pattern of rising temperatures in south west Europe (Sparks *et al.*, 2007). This study suggests that for every one degree Celsius rise in temperature in south west Europe, 14 new species of moth or butterfly can be expected to arrive on the south coast of the UK, although most of these will never become pests. Most of these migrants originate from due south of the UK and will have flown over many kilometres of open sea. Wind direction, and high altitude wind in particular, is important to the flights of migratory pests. The arrival of *P. xylostella* is known to be determined by wind direction. *Autographa gamma* is a migrant which uses high-level north winds to return to North Africa/the Middle East in autumn. It is possible that some insects are able to select their vertical altitude to pick appropriate wind directions for migration.

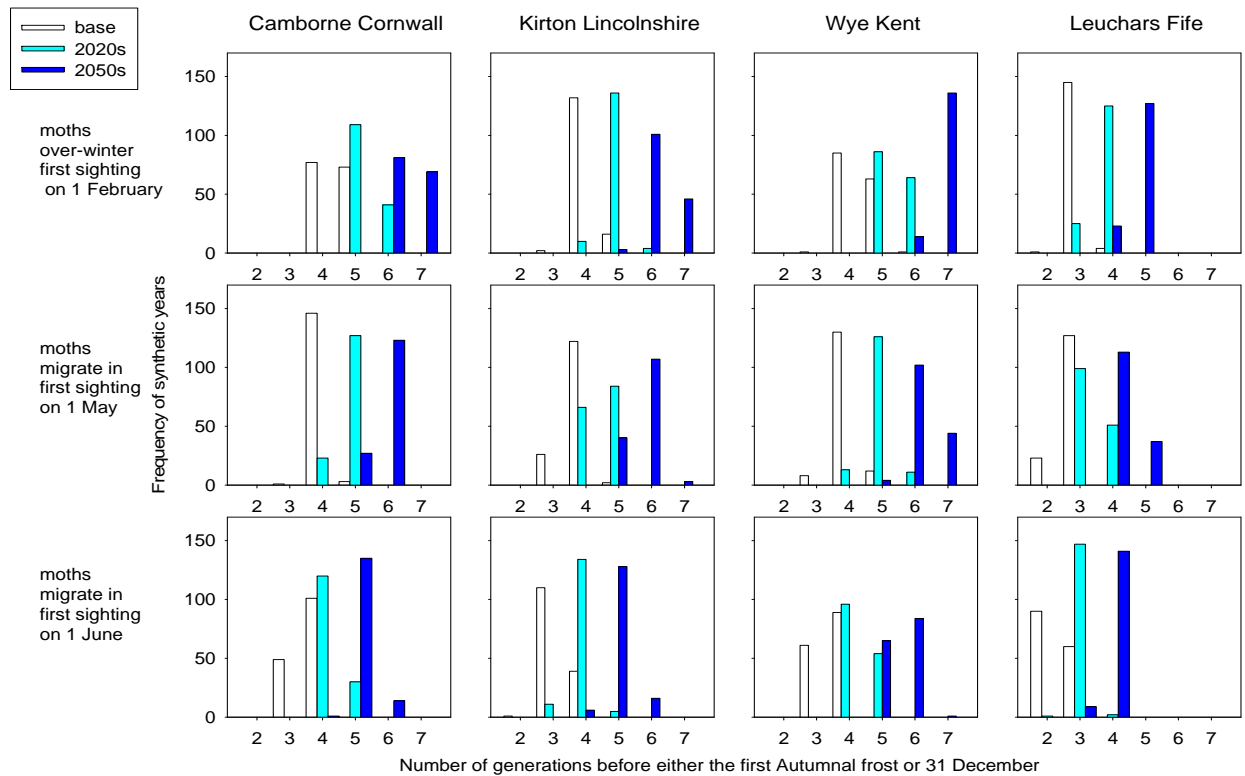


Figure 5.6. Predicted number of generations completed by *Plutella xylostella* (diamond-back moth) in different locations in the UK using synthetic weather data and three scenarios of either overwintering in the UK or migration to the UK after the winter.

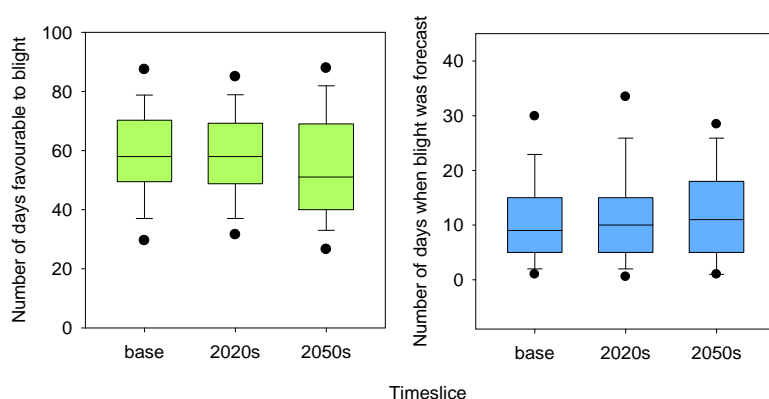
Control by pesticides, biological control agents or host plant resistance is likely to be affected by the increased frequency of extreme climate events and in many cases this is likely to reduce their efficacy

Control by chemicals (pesticides/fungicides/biocides etc.) can be affected by weather, for example, high temperature is reported to reduce the effectiveness of some chemical controls or increase others. Humidity levels can also modify the efficacy of some pesticides, as can the timing and the amount of rain following the application of pesticides. On a simpler level, rain can affect the ability to apply a pesticide at the time of most need, e.g. *Aculus schlechtendali* (apple rust mite) was reported to be numerous in the Netherlands after a wet spring when conditions prevented the usual sprays, possibly an increasingly likely scenario. Approaches which favour control by natural enemies are increasingly common, particularly in glasshouses and orchards. Parasitic insects and predators will have their own climate optima, although not necessarily the same as their hosts, e.g. *Eriosoma lanigerum* (apple woolly aphid) can be controlled by *Aphelinus mali* but currently this is only effective in the south east of the UK because the parasite needs warmer drier climates. It is pertinent to ask whether extreme events will affect natural enemies to the same extent/in the same direction as the pests they are intended to control. The effectiveness of host plant resistance genes can break down under changed climatic conditions, particularly at 30°C and above. Although *Fulvia fulva* (leaf mould) is no longer considered to be of

serious concern to tomato growers due to the availability of resistance genes, some of these genes break down above 30°C, for example at 33°C there is a (reversible) failure of the necrotic resistance response.

The possible effects of extreme climate events on new pest and disease introductions should also be considered

Some of the more notable agricultural alien pathogens and invertebrate pests recently intercepted on arrival in the UK include significant numbers of *Leptinotarsa decemlineata* (Colorado potato beetle), *Anoplophora chinensis* (citrus longhorn beetle), *Trialeurodes abutiloneus* (banded-winged whitefly), *Trialeurodes ricini* (castor whitefly), *Thrips palmi* (melon thrips), *Bemisia tabaci* (tobacco whitefly), *Helicoverpa armigera* (Old World bollworm caterpillars) and *Xanthomonas fragariae* (angular leaf spot of strawberry). Additionally, there have been new UK outbreaks of important new invasive alien pests such as *Diabrotica virgifera virgifera* (Western corn rootworm), *Lymantria dispar* (gypsy moth) and *Cacopsylla fulguralis* (*Elaeagnus* psyllid).



*Figure 5.7 A model was run to estimate the numbers of days favourable to potato blight (*Phytophthora infestans*) and to forecast blight within a window from 1 May to 31 October. The figure shows box plots of the predicted numbers of days at Camborne in Cornwall. The predictions were made using 150 years of synthetic weather data. The symbols show the 5th and 95th percentile outliers.*

Pest and disease forecasting models can be used to predict the effects of extreme weather events

However, there are limitations: 1) models exist for a limited number of pests and diseases; 2) some models use weather parameters that cannot be derived from the current UKCIP climate change scenarios and 3) few (if any) models take account of the effects of weather on interactions between different organisms. The effect of water is often incorporated into modern forecast models for pathogens using measurements of relative humidity or leaf wetness rather than rain measurements. Unfortunately there is no simple mechanism to calculate these parameters from the rainfall data predicted by climate change models. Consequently it has been very difficult to integrate the climate and pathogen models to predict the effects of extreme weather on diseases (Figure 5.7) (Annexe 8, case study 9).

6 OUTPUTS AND KNOWLEDGE TRANSFER

6.1. Presentations

Seminars and conferences

- Qi, A. and Jaggard, K.W. (2008). The impact of past and future climate change on sugar beet yield in the UK. In: Proceedings of 5th International Crop Science Congress, April 13-18, 2008 Jeju, Korea
- Semenov M.A., Modelling the impacts of climate change, Information Technology in Agriculture, Hungary, 2006
- Semenov M.A., Stochastic weather generators: theory and applications, AGRIDEMA: Climate change and agricultural decision-making, Spain, 2007.
- Semenov M.A., Predicting crop yields using probabilistic weather ensembles, International Symposium on Crop Modelling and Decision Support, ISCMDS 2008, April 19-22, 2008 Nanjing, China
- Thomas B., Climate change and agriculture: Will extreme weather leave us hungry? Climate Change Policy Seminar Series. Warwick. June 2007
- Thomas B., Climate change and agriculture: Will extreme weather leave us hungry? Café Scientifique September 2007
- Thomas B., Vulnerability of crop development in a changing climate. RSS Seminar, Wellesbourne, October 2007

Workshops and industry events

- Adams SR. 2007. Vulnerability of UK agriculture to extreme events. At: Defra Research meeting on Adaptation and Agriculture. London UK. 9 August 2007.
- Adams SR. 2007. Climate change and agriculture: trends and implications. At: The VCA AGM and Conference. Oakham, UK. 6 December 2007
- Collier R, Predicting the effects of climate change on pest insects. Meeting of the AAB 11 October 2007 'Advances in pest management'.
- Collier R, Improving pest control – Brassica Growers Association Conference, 9 January 2008
- Thomas B, Climate change and agriculture: Trends and Implications. At: Autumn Seminar on Climate Change, British Institute of Agricultural Consultants, Kenilworth, UK, 6 November 2007.

6.2. Publications

- Semenov, M.A. (2007). Development of high resolution UKCIP02-based climate change scenarios in the UK, *Agric. Forest Meteorology*, 144: 127–138
- Jaggard, K. W, Qi, A. and Semenov, M.A. (2007). The impact of climate change on sugar beet yield in the UK: 1976-2004. *Journal of Agricultural Science* 145:367-375
- Jaggard, K.W. & Qi, A. (2007). The Broom's Barn sugar beet growth model and its uses, *Proceedings of 39th Meeting of the Agricultural Research. Modellers' Group*, *Journal of Agricultural Science* 145: 644-645.
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- Evans, N., Baierla, A., Fitt, B.D.L., Semenov, M.A., Gladders, P. & Hall, B. (2008) Range and severity of plant disease increased by global warming, *Journal of the Royal Society Interface* 5:525-531
- Semenov, M.A. Extreme impacts of climate change on wheat in England and Wales. *Journal of the Royal Society Interface* (submitted)

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FUTURE WORK

In this report we show how modelling future scenarios based on synthetic daily weather rather than climate has provided new insights into changes that include both beneficial and deleterious impacts on UK agriculture and food production. We have also identified areas where the application of this approach is limited by knowledge gaps in the quantitative response of crop plants to environmental parameters or where the weather models do not produce the relevant outputs for pest and disease forecasts. The combination of flowering time and temperature sensitivity is critical for seed production and for yield in seed crops. Experience from the summer of 2006, particularly for seed production, has highlighted this as a vulnerable area, but further work on the quantitative relationship between temperature and seed production would be needed to fully evaluate the future risk.

Extreme weather can negatively affect quality as well as yield. Modelling the future occurrence of elevated night temperatures and temperature differentials which are believed by industry to reduce quality, suggests that this will be an increasing problem. Further work on the responses of crops to day/night temperature combinations is required to understand the reasons and to develop effective strategies for adaptation.

Models linking weather patterns to pest and / or disease prevalence cover a limited number of organisms and few, if any, include the interactions between different organisms, such as pests and their natural enemies. Also, some models require weather parameters, such as humidity, leaf wetness or wind strength and direction, which cannot be derived from the current UKCIP climate change scenarios. Additional research will be needed to develop predictive modelling for these instances.

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