Aspects of Applied Biology 88, 2008
Effects of Climate Change on Plants: Implications for Agriculture

Vulnerability of horticultural crop production to extreme weather events

By ROSEMARY COLLIER[1], JANE FELLOWS[1], STEVEN ADAMS[1], MIKHAIL SEMENOV[2] and BRIAN THOMAS[1]

[1]*Warwick HRI, University of Warwick, Wellesbourne, Warks, CV35 9NH, UK*
[2]*Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*

Summary

The potential impact of future extreme weather events on horticultural crops was evaluated. A review was carried out of the sensitivities of a representative set of crops to environmental challenges. It confirmed that a range of environmental factors are capable of causing a significant impact on production, either as yield or quality loss. The most important of these were un-seasonal temperature, water shortage or excess, and storms. Future scenarios were produced by the LARS-WG1, a stochastic weather generator linked with UKCIP02 projections of future climate. For the analyses, 150 years of synthetic weather data were generated for baseline, 2020HI and 2050HI scenarios at defined locations. The output from the weather generator was used in case studies, either to estimate the frequency of a defined set of circumstances known to have impact on cropping, or as inputs to models of crop scheduling or pest phenology or survival. The analyses indicated that episodes of summer drought severe enough to interrupt the continuity of supply of salads and other vegetables will increase while the frequency of autumns with sufficient rainfall to restrict potato lifting will decrease. They also indicated that the scheduling of winter cauliflowers for continuity of supply will require the deployment of varieties with different temperature sensitivities from those in use currently. In the pest insect studies, the number of batches of *Agrotis segetum* (cutworm) larvae surviving to third instar increased with time, as did the potential number of generations of *Plutella xylostella* (diamond-back moth) in the growing season, across a range of locations. The study demonstrated the utility of high resolution scenarios in predicting the likelihood of specific weather patterns and their potential effect on horticultural production. Several limitations of the current scenarios and biological models were also identified.

Key words: Climate change, model, pest insect, crop

The consensus of scientific opinion as represented by the International Governmental Panel on Climate Change (IPCC) assessment is that the global climate is warming. This change is taking place in response to changes in the composition of the atmosphere which are likely to include a significant contribution from human activities. The major atmospheric component forcing warming is carbon dioxide (CO_2). The level of CO_2 has doubled since pre-industrial times to about 380 ppm at present and is continuing to rise. UK Government policy is to reduce carbon dioxide emissions through domestic and international action by 26–32% by 2020 and 60% by 2050, taking 1990 as the baseline.

As a consequence of global warming, changes for the UK climate are predicted to involve seasonal and regional alterations in the pattern of rainfall. These include drier summers in the south and wetter winters in the north, with a net result of reduced rainfall on an annual basis. In the future, agricultural cropping in the UK is likely to be taking place against a background of changes in environmental factors which have an impact on productivity and the efficiency of land and resource usage. A critique of the Defra Programme on the Impacts of Climate Change on UK Agriculture from 1999 to 2005 concluded 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 is needed in "relation to climate change and food quality, plant and animal pests and diseases and extreme events."

This paper presents some findings from a study carried out to fill knowledge gaps relating to the occurrence of extreme events, whose frequency and spatial patterns are likely to change as a consequence of climate change. 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 (1 km, site-specific). These scenarios were constructed by using a stochastic weather generator linked with UKCIP02 projections of future climate. Specific examples presented include potential impacts on crop development, harvesting and pest insects and were drawn from reviews of published research and industry experience.

Materials and Methods

Future scenarios were produced by the LARS-WG1, a stochastic weather generator linked with UKCIP02 projections of future climate as described in Semenov (2007). LARS-WG produces synthetic daily time series of maximum and minimum temperature, precipitation and solar radiation with high temporal (daily) and spatial resolution (1 km, site-specific). The weather generator uses available observed daily weather for a given site to determine a set of parameters for probability distributions of weather variables, as well as correlations between them. After it has been obtained, this set of parameters is used to generate synthetic weather time series of arbitrary length by randomly selecting values from the appropriate distributions. For the analyses in this paper 150 years of synthetic weather data were generated for baseline (1960 –1990) and 2020HI and 2050HI scenarios at defined locations. The output from the weather generator was used either to estimate the frequency of a defined set of circumstances known to have an impact on cropping, e.g. dry or waterlogged soil or as inputs to models of crop scheduling or pest phenology/survival.

Results

Physiological responses

Un-seasonal 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 1 presents the vulnerable stages of development or traits for a range of crop types.

High summer temperatures will have a negative impact on yield and quality for many horticultural crops. In all of the crops we studied, un-seasonal temperatures can have major effects on yield and quality (Table 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 (Gan *et al.*, 2004), peas (Mcdonald & Paulsen, 1977) and sunflower (Rondanini *et al.*, 2003). 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 (Sato *et al.*, 2003).

Table 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, yeild
Perennial fruit crops	Apples	Bud break, flower initiation, flower development, fruit growth
Perennial biomass crops	Miscanthus	Establishment

Table 2. *Effects of high temperature 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	Oilseeds, 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 temperature during early development can have major adverse effects on crop performance. High temperature can inhibit the germination of seed for vegetable brassicas, is associated with blindness, and can increase 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 are 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 (Adams *et al*., 2002).

Example 1: Crop scheduling in winter cauliflower

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 cultivar to get continuity of supply.

The winter cauliflower industry in the UK faces difficulties in predicting when crops will reach maturity. The crop is very sensitive to temperature and the unpredictable weather means that carefully planned production patterns are rarely achieved. Models of the phases of juvenility, curd induction and curd growth, driven by temperature have been developed for winter cauliflower types and were linked to enable prediction of the time of curd maturity. The models are described fully by Wurr *et al*. (2004).

In our studies, a model for the Roscoff X Walcheren cross cv. Renoir was used. The model was run from seven sequential starting dates defining the end of the juvenile phase of growth, and thus the beginning of the induction phase, beginning on 1 July and ending on 1 October. The induction phase is described by a rate function defined as a gamma curve with an optimum temperature of 9.0°C. Once a curd is initiated, it enters the curd growth phase, which is described by a quadratic relationship between the natural logarithm of curd diameter and accumulated ambient day-degrees >0°C from curd initiation. This sequence of two models was run until curds with a target diameter of 120 mm, a typical supermarket specification, were produced. The model sequence was run for 150 years of data for all time slices.

Fig. 1 shows output for a cv. Renoir model run with synthetic weather for Camborne in Cornwall. As predictions were made further into the future there was a trend for the differences in maturity time to diminish, so that by the 2050s the continuity of production was lost, as the example shows. 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.

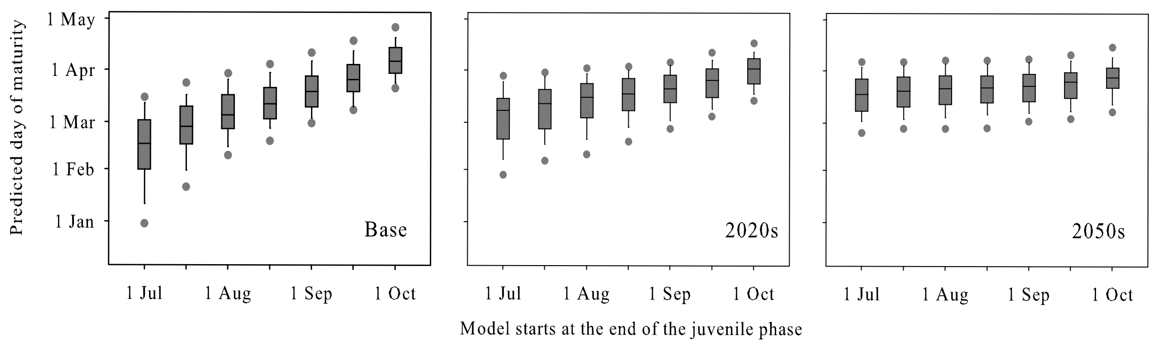

Fig. 1. Predicted day of maturity using models for CV Renoir and weather data for Camborne in Cornwall. The predicted dates of maturity for each of the 150 years of synthetic weather data are summarised in the box plots. The boxes represent the 25th and 75th percentiles and the line within the box represents the median. The whiskers represent the 10th and 90th percentiles and the dots show the maximum and minimum values.

Example 2: Bone-dry soil

During the summer of 2006, industry reported that there were periods when it was impossible to transplant horticultural crops because the soil was bone-dry and it was very hot. Even where irrigation was available, the demand for water from the transplants made it impossible to proceed. Observations of the weather and estimates of the soil moisture deficits indicated that the maximum soil moisture deficit was 22 mm for sandy soil, 30 mm for sandy loam, 36 mm for clay loam and 42 mm for silt loam soil. Thus, when the soil moisture deficit reaches 22 mm for sandy soil, the soil would be bone-dry.

In the East of England, growers are unlikely to have access to irrigation currently and in future may not have the water resources to supply irrigation systems if they have them. To investigate this further, estimates of the soil moisture deficit (SMD) for silt loam at Kirton in Lincolnshire were summarised, based on 150 years of synthetic weather for three time slices. Fig. 2 shows a box plot of these data and shows that the incidence of these periods of bone-dry soil is likely to increase with time.

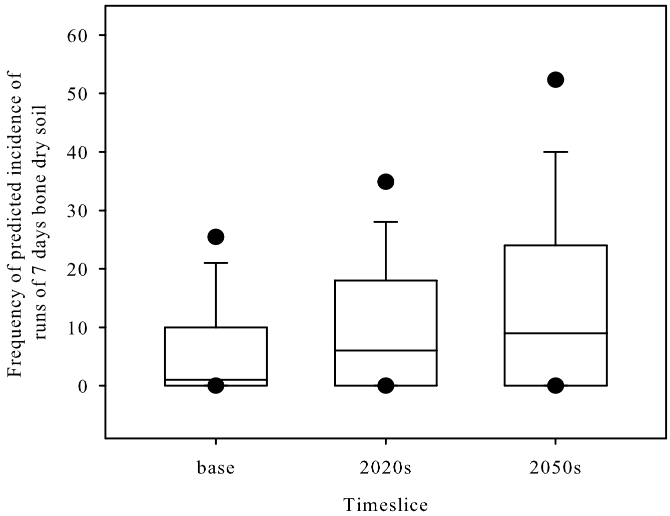

Fig. 2. Predicted incidence of runs of 7 consecutive days with bone-dry silt loam soil over the period from 1 March to 31 October for Kirton Lincolnshire. (Note: 10 consecutive days count as four runs). The predictions for each of the 150 years of synthetic weather data are summarised in the box plots. 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.

Example 3: Autumn rain and the potato harvest

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 waterlogging which was followed by fast drying. Compaction is a major problem for potato production.

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 the crop. At Christmas, 25,000 ha (~20% of the crop) had still not been lifted. We took the conditions that led to the problems in 2000, estimated a rainfall threshold of 10 mm per run of 7 days and modelled the likely incidence for the 2020s and 2050s compared to baseline data for two locations, Rothamsted in the south and Boulmer in the north (Fig. 3). 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.

Pest and disease effects

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 are a number of models available which can be used to predict generation times, which range from relatively simple day-degree models based on linear regression to more complex process-based simulation models (e.g. Harcourt,1954; Phelps *et al*., 1993) and these may be used to predict the effects of climate change (Collier *et al*., 1990).

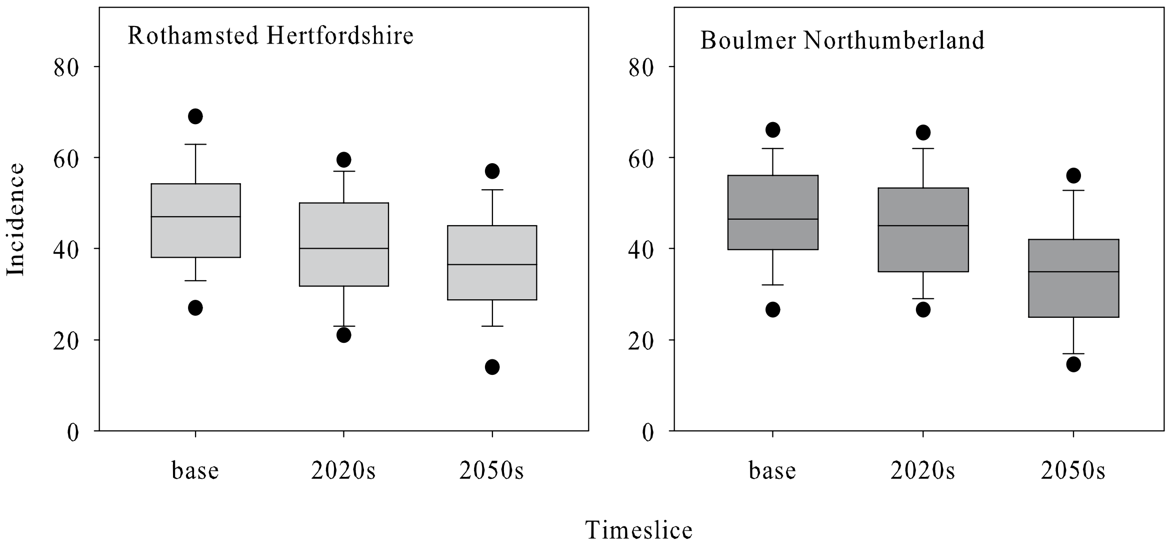

Fig. 3. Incidence of runs of 7 days with an accumulated rainfall total of 10 mm between 1 August and 31 October under baseline, 2020HI and 2050HI scenarios. (Note: 10 consecutive days count as four runs). The boxes represent the 25th and 75th percentiles and the line within the box represents the median. The whiskers represent the 10th and 90th percentiles and the dots show the maximum and minimum values.

There is abundant information available about the effects of temperature on aphids. For aphids such as *Myzus persicae* that can over-winter as active adults, warmer conditions in winter lead to earlier and larger spring migrations to crop hosts. Relationships between key events (e.g. the date of first capture of a particular aphid species in a suction trap) and weather parameters (e.g. winter temperatures) have been established by regression (Harrington *et al*., 1991, 2007). In the present study, dates by which the first alate *M. 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).

Extreme temperatures and the increased frequency of heat waves will undoubtedly be deleterious to some current UK pests and diseases and, if sufficiently high, cause mortality. Temporary exposure of populations to extreme temperature may induce dormancy and delay the subsequent generation (Finch & Collier, 1985; Harrison & Barlow, 1972). Whilst temperature optima are often studied, temperatures above 30°C are not tested routinely for temperate organisms. Consequently there are limited data published about the likely effects of periods of unusually warm weather on 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. The availability of free water is extremely important in the life cycle of many micro-organisms. For example, many types of fungal spores require free water for periods of several hours for germination (e.g. *Alternaria brassicae* (Hong *et al*., 1996)). Rain splash is used by many pathogens as a passive means of physical dispersal of spores or other propagules (e.g. Pielaat *et al*., 2002). 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 (Gilles *et al*., 2004; Kennedy, 2000). 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 models with pathogen models to predict the effects of extreme weather on diseases.

In contrast, too much water can be devastating for some pests. Water-intolerant pests, which may prosper in periods of drought include cutworms (*Agrotis segetum*). Wet soil as a result of heavy rainfall causes mortality of the early larval instars (Esbjerg, 1988).

Example 4: Predicting survival of Agrotis segetum *(cutworm) larvae*

A descriptive population model for *Agrotis segetum* (Bowden *et al*., 1983) was run using 150 years of synthetic weather data for two locations: Camborne in Cornwall and Kirton in Lincolnshire. The model estimates larval survival to third instar based on temperature-rate relationships and on mortality attributed to daily rainfall. In warm years a second generation of moths may occur in late summer. However, for this study it was assumed that there would be only one generation and that moths would lay egg batches nightly from 1 June to 31 July. The mortality factor in the model states that 0.1 mm of rainfall will kill 1% of surviving first and second instar larvae, but that rainfall will not affect the older larvae. So if 10 mm of rain was recorded, all larvae reaching the third instar on that day would be killed. The number of surviving third instar larvae was counted up to 31 July.

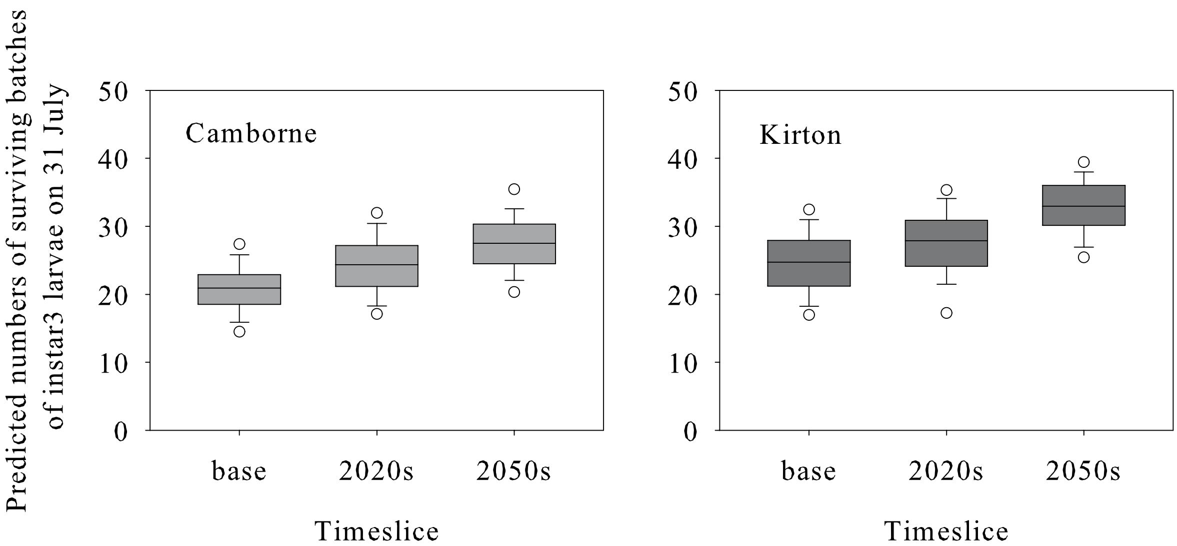

Fig. 4. Predicted number of batches of *Agrotis segetum* (cutworm) larvae surviving to third instar up to 31 July for Camborne in Cornwall and Kirton in Lincolnshire. The predictions for each of the 150 years of synthetic weather data have been summarised in the box plots. The boxes represent the 25th 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.

Fig. 4 shows box plots of the predicted numbers of batches of cutworm (*Agrotis segetum*) larvae surviving to third instar accumulated up to the end of July at both locations. In both locations, the numbers of surviving batches increase into the future.

Although the current climate models do not contain a wind component, wind is likely to have a strong influence on the occurrence and distribution of pests and disease. Some species are particularly well adapted to moving long distances in the air and these include several species of noctuid moth, such as the pest species *Plutella xylostella* (diamond–back moth) and *Autographa gamma* (silver Y moth). Since neither of these species survives particularly well during UK winters at present (Chapman *et al.*, 2002; Hill & Gatehouse, 1992), new infestations are generally the result of migrations from continental Europe, although both species may be able to over-winter successfully if winters become warmer in the future.

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 determined by wind direction (Chapman *et al*., 2002). Autographa gamma uses high-altitude air streams to return to the Mediterranean region in autumn. and selects its vertical altitude to pick appropriate wind directions for migration, using a 'compass mechanism' and a preferred direction to optimise the route (Chapman *et al*., 2008).

Example 5. Predicting the number of generations of Plutella xylostella *(diamond-back moth) in a year*

The possible effects of climate change on *P. xylostella* were investigated using data from earlier research. Harcourt (1954) predicted the generation time of *P. xylostella* from egg to adult using a day-degree sum with a base temperature of 7.3°C. The model was developed with a host crop of cabbage and the thermal sum indicating completion of a generation was 283 day-degrees. A further model (Butts & McEwen, 1981) uses the same base temperature but with a thermal sum 10 day-degrees greater than that of Harcourt's model. This model, based on a host crop of Brussels sprouts, was not used because the difference in the thermal sums was so small that the trends would be very similar.

Predictions were made using three different times for the start of egg-laying. Firstly, the assumption was made that the moths would successfully over-winter in the UK, and start laying eggs from 1 February onwards. The second and third scenarios for the start of egg laying were based on moths migrating into the UK from abroad, where eggs were laid on either 1 May or 1 June. For all three prediction model runs, the generations were counted until either the first autumnal frost, or if there was none, to the end of the calendar year. Predictions were made for four locations, Camborne Cornwall; Kirton, Lincolnshire; Wye, Kent and Leuchars, Fife. As egg-laying occurred earlier and predictions were made further into the future, the number of generations within the calendar year increased (Fig. 5).

Fig. 5 Predicted number of generations completed by *Plutella xylostella* (diamond-back moth) in different locations in the UK using synthetic weather data.

Discussion

In addition to identifying some of the vulnerabilities of future horticultural production to climate change, this paper demonstrates the value of the outputs of high resolution weather generators in predicting the risk of crop losses in response to extreme events. At the current time, weather generators have temperature and rainfall as the primary outputs. These are suitable for linking to models built on thermal time or to estimations such as SMD where historical data allows temperature and rainfall data to make predictions such as for bone-dry soil. These outputs can also be applied to comprehensive crop yield models such as the Sirius wheat model (Semenov, 2007). Limitations to using climate current models are that they do not make estimations of radiation, wind and humidity, the latter two being particularly important in pest and disease prediction models. For the available outputs, the weather models are beginning to outstrip the biology. For example, there is a need to establish good quantitative relationships between temperature and crop developmental stages, particularly reproduction and seed formation.

Where we used the weather generator to make predictions, we consistently found that changes between the baseline and 2020s were relatively modest, with any changes being much more pronounced for the 2050s. This is consistent with the acceleration of climate change through the 21st century predicted by the IPCC 2007 report. Importantly, not all changes were found to have a negative impact on crop production, e.g. the persistent rain experienced in 2000 that severely restricted potato lifting is predicted to become less prevalent in the future.

Crops which require continuity of supply e.g. salad leaves and cauliflower, are particularly vulnerable to extreme weather events. Normally these rely on a combination of successional plantings and appropriate genotypes for reliable scheduling. Greater fluctuations in temperature

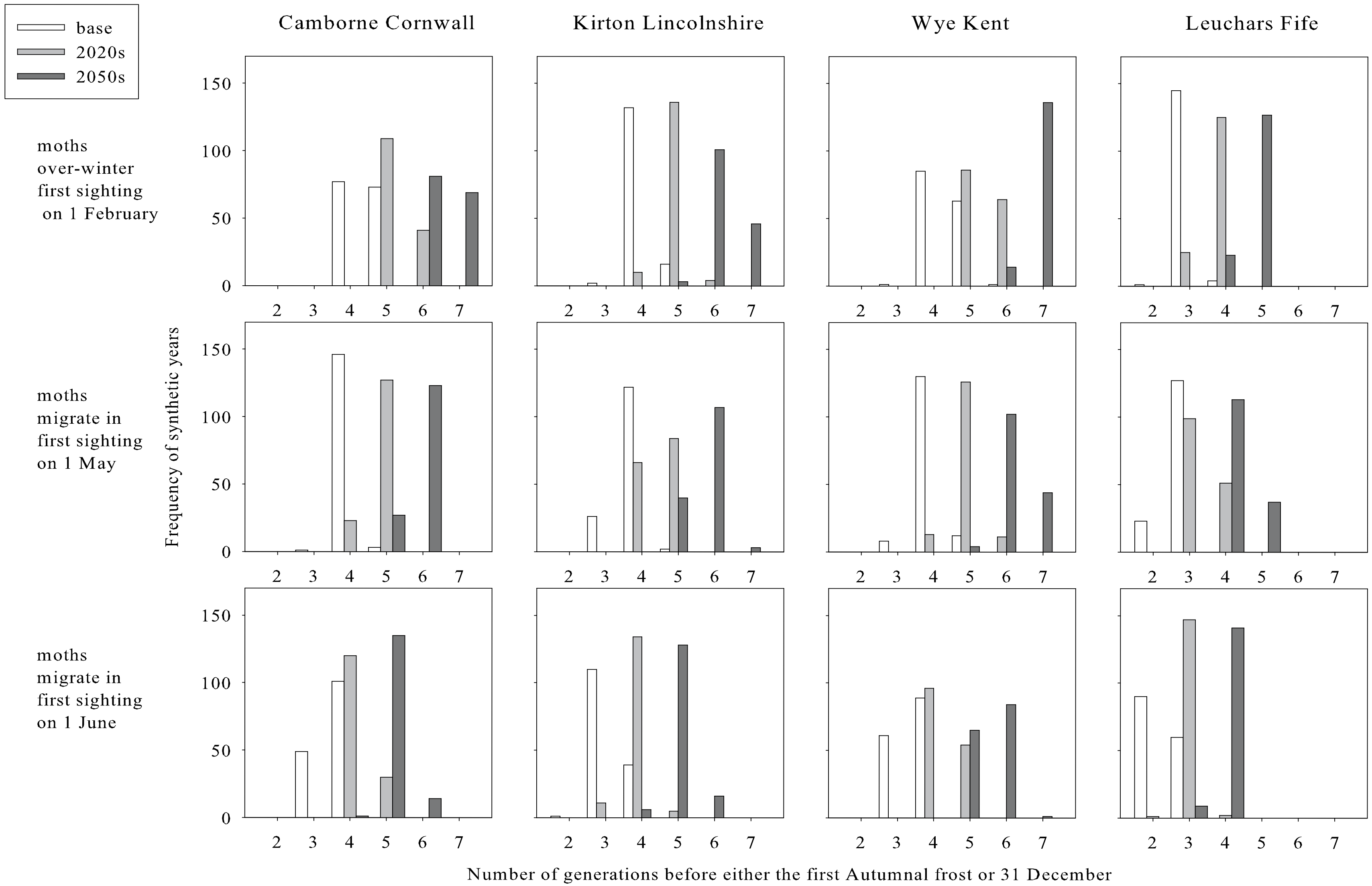

Fig. 5. Predicted number of generations completed by *Plutella xylostella* (diamond-back moth) in different locations in the UK using synthetic weather data and different estimated dates for the start of egg laying.

may result in a compression of harvest dates. Planting and crop establishment are also vulnerable to periods of drought which can result in gaps in production. Problems experienced in years such as 2006 are likely to become more frequent. 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. A further general point from this study is that in addition to a direct impact on crop development and yield, extreme weather has major impact by its physical effect on soil and farmland, either because of drought or waterlogging. Under these circumstances planting or harvesting grind to a halt or farmers are unable to take machinery on to the land.

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. 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.

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 pest and disease occurrence and spread. Finally, control by pesticides, biological control agents or host plant resistance is also likely to be affected by the increased frequency of extreme climate events and in many cases this is likely to reduce their efficacy.

Acknowledgements

We would like to thank the following organisations who supplied us with invaluable information and feedback on the issues relevant to their sectors: Bakkavor, Brassica Growers Association, British Potato Council, Cambridge University Farm, Elsoms Seeds Limited, Marshalls.

The work described in this paper was funded by Defra project AC0301, Vulnerability of UK Agriculture to Extreme Events

References

Adams S. R, Valdés V. M. 2002. The effect of periods of high temperature and manipulating fruit load on the pattern of tomato yields. *Journal of Horticultural Science & Biotechnology* **77**: 461–466.

Bowden J, Cochrane J, Emmett B J, Minall T E, Sherlock P L. 1983. A survey of cutworm attacks in England and Wales, and a descriptive population model for *Agrotis segetum* (Lepidoptera: Noctuidae). *Annals of Applied Biology* **102**:29–47.

Butts R A, McEwen F L. 1981. Seasonal populations of the diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae), in relation to day-degree accumulation. *Canadian Entomologist* **113**: 127–131.

Chapman J W, Reynolds D R, Smith A D. Riley J R, Pedgley D E, Woiwod I P. 2002. High-altitude migration of the diamondback moth *Plutella xylostella* to the U.K.: a study using radar, aerial netting, and ground trapping. *Ecological Entomology* **27**:641–650.

Chapman J W, Reynolds D R, Mouritsen H, Hill J K, Riley J R, Sivell D, Smith A D, Woiwod I P. 2008. Wind selection and drift compensation optimize migratory pathways in a high-flying moth. *Current Biology* **18**:514–518.

Collier R H, Finch S, Phelps K, Thompson A R. 1990. Possible impact of global warming on cabbage root fly (*Delia radicum*) activity in the UK. *Annals of Applied Biology* **118**:261–271.

Esbjerg P. 1988. Behaviour of 1st- and 2nd-instar cutworms (*Agrotis segetum* Schiff.) (Lep., Noctuidae): the influence of soil moisture. *Journal of Applied Entomology* **105**:3:295–302.

Finch S, Collier R H. 1985. Laboratory studies on aestivation in the cabbage root fly (*Delia radicum*). *Entomologia experimentalis et Applicata* **38**:137–143.

Gan Y, Angadi S V, Cutforth H, Potts D V A, McDonald C L. 2004. Canola and mustard response to short periods of temperature and water stress at different developmental stages. *Canadian Journal of Plant Science* **84**:697–704.

Gilles T, Phelps K, Clarkson J P, Kennedy R. 2004. Development of MILIONCAST, an improved model for predicting downy mildew sporulation on onions. *Plant Disease* **88**: 695–702.

Harcourt D G. 1954. *The biology and ecology of the diamondback moth,* Plutella maculipennis *(Curtis), in eastern Ontario*. Ph.D. Thesis, Cornell University, Ithaca, N.Y. 107 pp.

Harrington R, Tatchell G M, Bale J S. 1991. Weather, life cycle strategy and spring populations of aphids. *Acta Phytopathologica et Entomologica Hungarica* **25**:423–432.

Harrington R, Hullé M, Plantegenest M. 2007. Monitoring and forecasting. In *Aphids as crop pests*, pp. 551–536. Eds H F van Emden and R Harrington. Wallingford, UK: CAB International.

Harrison J R, Barlow C A. 1972. Population-growth of the pea aphid, *Acyrthosiphon pisum* (Homoptera: Aphididae) after exposure to extreme temperatures. *Annals of the Entomological Society of America* **65**(5):1011–1015.

Hill J K, Gatehouse A G. 1992. Effects of temperature and photoperiod on development and pre-reproductive period of the silver Y moth *Autographa gamma* (Lepidoptera: Noctuidae). *Bulletin of Entomological Research* **82**:335–341.

Hong C X, Fitt B D L, Welham S J. 1996. Effects of wetness period and temperature on development of dark pod spot (*Alternaria brassicae*) on oilseed rape (*Brassica napus*). *Plant Pathology* **45**(6):1077–1089.

Kennedy R. 2000. Brassicas: spot the savings. *HDC News August 2000*, pp. 18–19.

McDonald G K, Paulsen G M. 1977. High temperature effects on photosynthesis and water relations of grain legumes. *Plant and Soil* **196**:47–58.

Phelps K, Collier R H, Reader R J, Finch S. 1993. Monte Carlo simulation method for forecasting the timing of pest insect attacks. *Crop Protection* **12**:335–342.

Pielaat A, van den Bosch F, Fitt B D L, Jeger M J. 2002. Simulation of vertical spread of plant diseases in a crop canopy by stem extension and splash dispersal. *Ecological Modelling***151** (2–3):195–212.

Rondanini D, Savin D, Hall A J. 2003. Dynamics of fruit growth and oil quality of sunflower (*Helianthus annuus* L.) exposed to brief intervals of high temperature during grain filling. *Field Crops Research* **83**:79–90.

Sato S, Peet M M, Thomas J F. 2002. Determining critical pre- and post- anthesis periods and physiological processes in *Lycopersicon esculentum* Mill. exposed to moderately elevated temperatures. *Journal of Experimental Botany* **53**:1187–1195.

Semenov M A. 2007. Development of high-resolution UKCIP02-based climate change scenarios in the UK. *Agricultural and Forest Meteorology* **144**:127–138.

Sparks T H, Dennis R L H, Croxton P J, Cade M. 2007. Increased migration of Lepidoptera linked to climate change. *European Journal of Entomology* **104**:139–143.

Wurr D C E, Fellows J R, Fuller M P. 2004. Simulated effects of climate change on the production pattern of winter cauliflower in the UK. *Scientia Horticulturae* **101**:359–372.