SESSION 9B

IMPACT OF CHANGING WEATHER PATTERNS ON CROP PROTECTION AND CROP PRODUCTION

Chairman:	Dr Anthony Biddle *Processors and Growers Research Organisation, Peterborough, UK*
Session Organiser:	Dr Keith Walters *Central Science Laboratory, York, UK*
Papers:	9B-1 to 9B-4

Linking climate change predictions with crop simulation models

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ABSTRACT

Assessment of the effects of climate change on crop yields is based on two integral parts: (1) crop simulation models, and (2) climate change scenarios. Crop simulation models are used for analysing the causes of yield variations in response to climate and environmental variability and operate on a spatial scale of one kilometre and with daily time steps. Climate change scenarios are based on global or regional climate models (GCMs or RegCMs) with spatial and temporal resolutions inappropriate for crop simulations. Output on the scale of hundreds of kilometeres and monthly time-scale needs to be spatially and temporally downscaled. One down-scaling method, which is capable of producing daily site-specific weather, is a stochastic weather generator. By combining the output from GCMs with a stochastic weather generator we are able to produce climate scenarios with high spatial and temporal resolution, which are suitable as input for crop simulation models. An alternative approach to linking GCMs with crop simulation models is the development of a simplified crop simulation model, a metamodel, that is able to use the output from GCMs at coarse spatial and temporal resolutions. An example of the development of a metamodel based on analysis of the structure of the Sirius wheat simulation model is given.

INTRODUCTION

Crop simulation models have proved themselves to be powerful tools for analysing the causes of production variations in many crops. A common need of most crop simulation models is daily weather data as the principle driving variables. Such models are useful for impact assessment when linked with climate change predictions, assessing crop responses to potential climate changes. They are also useful for seasonal yield predictions when linked with seasonal weather forecasts, guiding management early in the season well before most growth has occurred.

Global climate models (GCMs), the tools most widely used for climate predictions, are very complex and their demand for computational power limits their output to spatial and temporal scales inappropriate for crop simulation. Output is on the scale of hundreds of kilometres and the associated time-scale is monthly, which means that sub-grid scale processes on a short time-scale, such as precipitation, are not adequately represented. Stochastic weather generators lack the predictive power of GCMs, but are able to reproduce site-specific climates on a daily time-scale quite well (Semenov *et al.*, 1998). The combination of these two methodologies should allow the development of climate scenarios for agricultural applications that (1) are site-specific with daily temporal resolution; (2) include the full set of climate variables required by the crop model; (3) contain an adequate number of years to permit risk analysis; and (4) include changes in means and climate variability. By combining the output from GCMs with a stochastic weather generator we are able to produce climate change scenarios with high spatial and temporal resolution. The importance of downscaling and the incorporation of climate variability into climate change scenarios are demonstrated in the next section of this paper.

An alternative to downscaling from GCMs is upscaling crop simulation models by simplifying them to metamodels with fewer parameters and equations, and that may run on inputs of coarser temporal resolution, e.g. monthly weather. An example of development of a metamodel from the Sirius wheat simulation model is presented in the third section of the paper, together with some performance data in comparison with its parent.

NON-LINEARITY IN CLIMATE CHANGE IMPACT ASSESSMENT

Climate change scenarios with high spatial and temporal resolution were constructed and used in agricultural impact assessments at two selected sites, Rothamsted (UK) and Seville (Spain). The climate change scenarios were produced in two steps. First, a stochastic weather generator (LARS-WG) was run for observed weather at each site, and parameter files characterising typical weather at these sites were generated. Second, changes in climate characteristics, derived from GCMs (including changes in mean and variability), were applied to these parameters. New parameter files were used to generate site-specific climate change scenarios with a daily time-step. To construct scenarios, we used data from the UK Met. Office GCM transient experiments (UKTR; Murphy & Mitchell, 1995). Instead of using climate change integration fields themselves, the change fields were constructed by calculating the difference between a period in the climate change integration and the corresponding years of the control integration.

In order to produce scenarios of climate change at a site scale required by crop simulation models, it was necessary to downscale the coarse spatial resolution GCM data to a site level. This procedure involved the development of relationships between the coarse- and local-scale data for the climate variables concerned. There are currently a number of downscaling methodologies in use, including circulation patterns (e.g. Bardossy & Plate, 1991; Matyasovszky *et al.*, 1993) and regression techniques (e.g. Kim *et al.*, 1984; Wigley *et al.*, 1990). Both methods use existing instrumental databases to determine the relationships between large-scale and local climate. Regression techniques develop statistical relationships between local station data and grid-box scale, area-average values of say, temperature and precipitation and other meteorological variables. The circulation pattern approach classifies atmospheric circulation according to type and then determines links between the circulation type and precipitation. At the selected sites, regression relationships were calculated between local station data (temperature and precipitation; i.e., the predictants) and grid-box scale, monthly anomalies of mean sea level pressure, the north-south and east-west pressure gradients, temperature and precipitation (i.e., the predictors). The regression relationships were based on anomalies from the long-term mean in order to facilitate the use of the GCM-derived changes in the equations. To calculate changes in climatic variability, daily data for the appropriate grid boxes from the control and perturbed integrations of the UKTR experiment were used to calculate changes in precipitation intensity, duration of wet and dry spells and temperature variances. These changes were then applied to the LARS-WG parameters previously calculated from the observed daily data at each site.

Incorporation of changes in variability into climate change scenarios could have a significant effect on agricultural impact assessments (Porter & Semenov, 1999), although it does not effect monthly statistics such as, for example, monthly total precipitation or monthly mean temperature. These means were compared for the UKTR scenarios with and without variability for Seville. There is no significant difference between monthly mean temperatures for the scenarios with and without variability for all months. Results from a t-test indicate that precipitation totals were significantly different for four months out of seven during the vegetation period for winter wheat (January - July) (Semenov & Barrow, 1997). For three of these months (May, June & July) precipitation for both scenarios was so low that it did not make a big difference to total precipitation over the vegetation period, 184 mm and 210 mm with and without variability, respectively, compared to 496 mm for the base climate. The effect of climate change scenarios with and without changes in variability for simulated crop yield is significant. This is partly because crop simulation models have non-linear responses to environmental variables (Semenov & Porter, 1995). For the base climate the grain yield simulated by the Sirius wheat simulation model (Jamieson *et al.*, 1998) was 5.6 t/ha and its coefficient of variation (CV) was 0.24 (Table 1). According to the UKTR scenario without variability, the grain yield does not change much (5.2 t/ha) and the CV remains about the same (0.23). If changes in climate variability are considered the results are very different. The grain yield drops to 3.9 t/ha and the CV almost doubles to 0.48. The reason for this is not the total amount of precipitation, but the change in precipitation distribution over the vegetation period and the prolonged dry spells. The probability of producing yields less than 3.5 t/ha is almost 50% for the UKTR scenario with variability and only about 10% for the UKTR scenario without variability or for the baseline climate. The high probability of obtaining low grain yields may make wheat an economically unsuitable crop in Spain under this climate change scenario.

The disadvantage of regression downscaling is that it is data intensive: observed data from several sites are required in order to calculate observed means and anomalies. Construction of site-specific scenarios of climate change may be aided by the current development of Regional Climate model (RegCMs). This methodology has been recently developed for climate change studies (Giorgi & Mearns, 1991; Mearns *et al.*, 1999). The RegCM is run with a high grid resolution (approximately 50km) over a limited area of interest. The RegCM is a physically based model nested into the GCM and is able to reproduce regional climate in more detail than the GCM itself. The UK Climate Impact Programme has made available climate change scenarios, based on HadRM3 regional model with the spatial resolution of 50 km and monthly temporal resolution (Hulme *et al.*, 2002). Work on the validation of a RegCM has shown that there may be still large differences between model output and observed weather statistics, especially in the case of climate variability (Mearns *et al.*, 1995). This means that the construction of local climate change scenarios from these models may be as problematic as from GCMs and will require the use of a stochastic weather generator for temporal downscaling. Mearns *et al.*, 1999 recently compared scenarios, which have been produced using a regional climate model and a statistical downscaling method based on atmospheric circulation patterns. They demonstrated that substantial differences in the regional climate details of climate change are produced by two different means of downscaling from the same large-scale GCM experiments.

Table 1. The effect of climate variability on crop yield and its coefficient of variation (CV), as simulated by SIRIUS Wheat, for UKTR scenario at Seville, Spain. Total precipitation and cumulative mean temperature were calculated for the winter wheat vegetation period from January to July.

	Base	UKTR	UKTR with variability
Grain yield, t/ha	5.6	5.2	3.9
CV of yield	0.24	0.23	0.48
Total precipitation January-July, mm	296	210	184
Cum. Temperature January-July, °C	3630	4293	4323

SIMPLIFYING CROP SIMULATION MODEL

An alternative approach to linking global climate models with crop simulation models is the development of a simplified crop simulation model that is able to use the output from GCMs at course spatial and temporal resolutions. Recently a sensitivity analysis and analysis of the structure of the Sirius wheat simulation model led to the development of a simpler meta-model that used relationships between simulated crop variables and aggregations of weather input variables (Brooks *et al.*, 2000). The metamodel produced very similar yield predictions to its parent, Sirius, for both potential and water-limited yields where nitrogen was not a limiting factor. The meta-model aggregates the three main Sirius components, the calculation of leaf area index, the soil water balance and the evapotranspiration calculations, into simpler equations. This reduces the requirements for calibration to fewer model parameters and allows weather variables to be provided on a monthly rather than daily time-step, because the meta-model is able to use cumulative values of weather variables. This makes the meta-model a valuable tool for regional impact assessments with seasonal weather predictions, when detailed input data are not available. A brief description of the metamodel follows.

The metamodel calculates potential yield and then reduces it using a drought stress index. The essential elements of the metamodel are calculation of phenology to determine the duration of the main growth phases, calculation of the biomass accumulated during those phases, and calculation of a drought stress index.

The phenological submodel of Sirius is based primarily on the prediction of the rate of leaf production and the numbers of leaves produced on the mainstem of wheat, in response to temperature and daylength. This part of the model has been retained intact in the metamodel, but there are prospects for simplifying it. It is important because it determines both the duration of growth and weather experienced by the crop during the critical grain growth period. The timing of anthesis is important within the metamodel because biomass accumulated by this time makes a contribution to grain yield.

Biomass accumulated from sowing to anthesis $\boldsymbol{A}$ is calculated from the ratio of mean daily solar radiation to mean temperature during this phase, and the phase duration. The simplified relationship encapsulates canopy response to temperature, affecting the amount of solar radiation captured by the crop, and the solar radiation itself. Similarly, the biomass accumulated after anthesis $\boldsymbol{G}$, most of which is grain, is calculated from a single equation involving the ratio of mean solar radiation and temperature during the grain filling period. Potential grain yield is calculated as $0.25\boldsymbol{A} + \boldsymbol{G}$. This is reduced by a drought stress factor based on a simplified calculation of the crop water balance, and the ratio between potential evapotranspiration and water supply, analogous to the Penman drought response model (Penman, 1971).

A major difference of the metamodel from Sirius is that the growth of the plant is not simulated on a daily basis but, rather, biomass is related to the accumulated weather variables. Indeed, the only daily calculations are the adding up of the weather variables. An important characteristic is that the meta-model contains very little interaction between components. Once the anthesis date and leaf number are known, the anthesis biomass, the post-anthesis potential biomass and the water stress yield loss are all calculated separately.

The meta-model was run for Rothamsted 1961 – 1990 with 50% precipitation and for Edinburgh with a soil of low water holding capacity and the results compared with those from Sirius. Daily weather data was used in both cases. The scenarios were chosen to give a wide range of yields mainly due to variations in water stress. In both cases the meta-model performed well giving a root mean square error (RMSE) of 0.68 and 0.83 t ha^{-1} respectively on yields of 4-11 t ha^{-1} (cf. standard deviations in Sirius yields of 1.3 and 2.2 t ha^{-1}) and correlation coefficients of 0.92 and 0.95.

The good match of the meta-model yield values with those of Sirius indicates that the meta-model contains the most important aspects of Sirius and, in particular, that there are no other mechanisms within Sirius that substantially affect yield. The meta-model is based on analysis of the Sirius model, rather than just on its output, so it should be able to match the Sirius output well for most scenarios in Britain (e.g., different sowing dates or cultivars) and probably for many other climates, without serious modifications.

The parameters and data used by the meta-model are the ones that need to be determined accurately for Sirius to perform well. As noted above, phenological development is crucial, so the parameters governing plant performance (responses to daylength and temperature) need to be well known, and temperature well specified. Solar radiation is important because it affects both potential yield and the water deficit. However, solar radiation is often not directly measured but is estimated, for example from sunshine hours. To some extent the accuracy of the model will depend on the accuracy of those estimates.

Because the meta-model uses accumulated values of the weather variables, it is able to perform well with just monthly weather data. To demonstrate this, it was run at Rothamsted with 50% precipitation and at Edinburgh for the soil with low AWC (80 mm), using daily weather data and 30-days moving average weather data. The results of metamodel runs for daily and monthly weather were compared. RMSE for the anthesis day and water-limited yield are 1 day and 147 kg/ha, and 1.7 days and 470 kg/ha for Rothamsted and Edinburgh, respectively. Hence replacing daily data with disaggregated monthly data in the metamodel is unlikely to change the output significantly. This makes the concept of this type of model really useful in the forecasting arena where trends rather than daily weather data are the likely outputs of weather forecasting.

CONCLUSIONS

In this paper it has been shown that methodology exists for linking climate change predictions with crop models to allow agricultural risk assessment, either by downscaling GCM data, or by upscaling crop simulation models.

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Climate change and decreasing herbicide persistence

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ABSTRACT

A herbicide degradation model, run with historical weather data, was used to study the change in duration of weed control by autumn-applied isoproturon over the period 1980-2001. The results suggest that soil residues fell to the minimum for weed control by a mean of approximately 30 days earlier during the last five years of this period than in the first five years, equivalent to a reduction of approximately 25% in duration of weed control. This decline in persistence is attributed to increasing soil temperature. The results are discussed in relation to recent observations and predictions of climate change and their relevance to other autumn-applied pesticides and future weed control is considered.

INTRODUCTION

The herbicide degradation model developed by Walker and Eagle (Walker & Eagle, 1983) uses standard records of air temperature and rainfall to estimate soil moisture content and temperature at short time intervals. These in turn are used to calculate rates of degradation in the field of pesticides with different half-lives, using observed effects of soil moisture and temperature on degradation rate, (previously measured in laboratory incubation experiments). Each day, for a given meteorological area and pesticide laboratory half-life, the amount of pesticide remaining undegraded in the soil at the end of the day can be estimated as a percentage of that present at the start. Residues remaining at the end of longer periods, eg. months, can be determined by successive daily estimates.

A similar model (Walker & Barnes, 1981) has formed the basis of the degradation routine in other more complete pesticide dissipation models, in particular PELMO (Klein, 1991) and MACRO (Jarvis, 1993). The Walker & Eagle (1983) model is not used to estimate actual residues at a site, but to compare estimated residues in one year to those in others. By assessing relative changes in residues, the model has been used to give farm advice on either herbicide carryover risk to following crops, or the persistence of weed control in one year compared to others.

As an example of the former, atrazine residues at the end of September can be estimated, after its use on maize in May. If the estimated residues are found to be higher than the estimated long-term average, advice can be given that the risk of atrazine carryover into following crops is higher than normal. This might have major implications for cultivations and crop sowing dates. The persistence of weed control can be estimated in a similar manner. For example, the herbicide isoproturon, which has both foliar and soil activity, is applied to winter cereals in the UK, most commonly in November. By the end of the following February farmers need to establish whether any soil activity remains. The model is run for the period 1 November – 28

February and if the resulting estimated residues are less than the estimated long-term average, advice may be given that the duration of weed control is likely to be shorter than normal.

During the 1990s, it was noticed that estimates of isoproturon persistence at the end of February were less than the long-term average in almost every year. This paper investigates the trend using a 22-year dataset, from 1980 and relates the findings to observed changes in climate during this period.

METHODS

The original version of the Walker & Eagle (1983) model used weather data from a limited number of sites in England and Wales and provided little opportunity to the manipulate data. In January 1999, the model was upgraded. Daily meteorological data are now supplied for 650 areas covering the whole of Great Britain. Daily data are available for all 650 sites from January 1999. Retrospective data were also supplied from January 1980 onwards for six of these areas, selected from across England to represent arable farming in a range of climates, (Brize Norton in Oxfordshire; Heathrow near London; Leeming in North Yorkshire; Marham in Norfolk; Shawbury in Shropshire; Yeovilton in Devon). The updated model was used to estimate degradation for each month from January 1980, for four laboratory half-life categories (20, 40, 60 and 80 days, to reflect a range of pesticides), for these six areas. This required approximately 6300 runs of the model. The results were entered into spreadsheets, so that trends could be investigated.

These data were used first to estimate the residues of isoproturon remaining at the end of February, following an application on 1 November, for each year from 1980. Two of the six sites were chosen, Brize Norton representing a southern site and Leeming in the North. A 20-day laboratory half-life was selected, as suggested by Walker & Eagle (1983) for this herbicide.

The resulting change in persistence was then related to changes in the duration of weed control. To do this a threshold concentration of isoproturon in the soil was required, below which there would be little or no herbicidal activity. Little information was available to determine this threshold. However, previous research on damaging isoproturon levels for various crops (ADAS, 1983) had found that a soil concentration of 0.19 mg kg^{-1} in the top 15 cm was the minimum to cause damage to grass and a range of cereals. Assuming a soil bulk density of 1.3g cm^{-3} and an isoproturon application rate of 1500 g ha^{-1}, this residue is equivalent to approximately 25% of the applied rate. The model could now be run to estimate the date on which residues from a 1 November application declined to 25% of the initial amount, for each year from November 1980.

RESULTS

Figure 1 shows the estimated residue at the end of February, following an application on 1 November, for Brize Norton over the period 1980-2001. There is a downward trend in the five-year running average, suggesting there has been a general decrease in persistence over the 22 year period investigated.

The estimated dates on which residues declined to the minimum for weed control, at Brize Norton and Leeming, are shown in Figure 2. A trend to an earlier date on which the threshold was reached can be clearly seen. The threshold was usually reached slightly later at Leeming than Brize Norton.

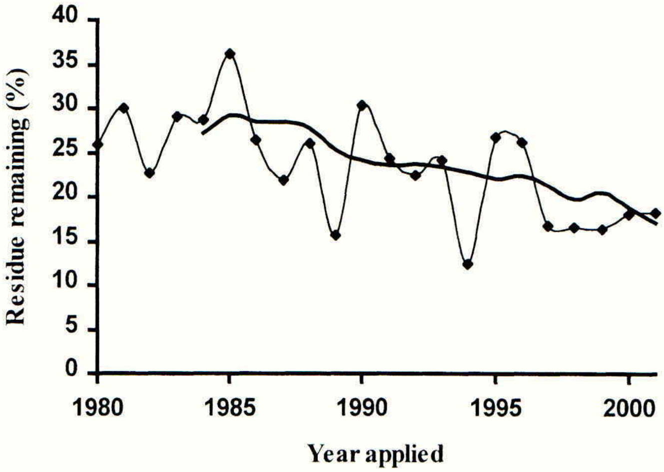

Figure 1: Estimated isoproturon residue on 28 February at Brize Norton (-•-), following application on 1 november (% of applied amount), and five-year running average (-), 1980-2001.

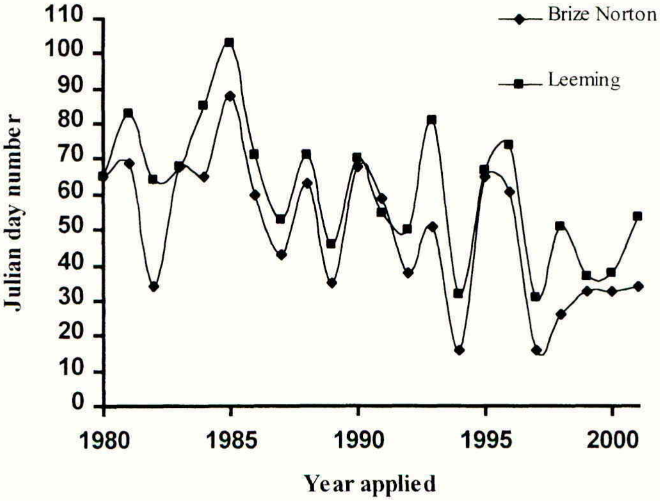

Figure 2: Estimated Julian date on which residues declined to 25% of the amount applied on 1 November, 1980-2001.

Table 1 presents the average date on which the 25% threshold was reached, for the first and last five year periods (1980-84 and 1997-01). These results suggest that isoproturon residues fell to below the 25% threshold on average 32 and 31days earlier in the last five years than in the first five years of this period, for Brize Norton and Leeming respectively.

Table 1. Estimated average date for isoproturon residues to fall to 25% of the initial amount applied, following application on 1 November.

Area	**1980[a] –1984[a]**	**1997[a] – 2001[a]**
Brize Norton	1 March	28 January
Leeming	14 March	11 February

[a] Application year

DISCUSSION

The results suggest that the period over which isoproturon gives effective weed control has reduced by approximately 30 days since the early 1980s. This is a reduction of approximately 25% in the duration of efficacy and represents a major decline in persistence.

A reduction in persistence of this magnitude would be expected to have a noticeable effect on weed control. Such an effect has frequently been reported by farmers and agronomists and attributed to a number of factors. Firstly, the maximum rate of isoproturon normally applied has declined over the 22-year period of this study, from 2500 g ha^{-1} in the 1980's, to 1500 g ha^{-1} in the winter of 2001-2. This, however, makes little difference to the predictions made by the model. The time taken to fall to the threshold concentration of 0.19 mg kg^{-1} is extended by four to five weeks by the higher application rate, but the date on which this concentration is reached still advances by approximately four weeks over the 22-year period of study. Weed resistance to herbicides is a widely reported phenomenon and has also been implicated to explain the declining levels of control, (Moss *et al.*, 1999). Thirdly, enhanced degradation of isoproturon by soil microorganisms, due to microbial adaptation, has been reported, (Cox *et al.*, 1996).

In addition to these factors, the above results suggest the weather has had a major effect over the last 22 years. Soil temperature and moisture content are the two environmental factors having the greatest effect on pesticide degradation in soil. Soil moisture content is unlikely to have been a major limiting factor on degradation over winter during the period studied, with soils close to field capacity. Hence, the trends found are likely to be primarily a result of changing temperatures. Records of the mean November – February air temperature (which directly affects soil temperature variation) for Brize Norton over this period reveals a clear upward trend. The slightly longer persistence of isoproturon in most years at Leeming than Brize Norton, shown in Figure 2, reflects the slightly lower temperatures at the more northerly site. The wide variation in dates shown in Figure 2 would also account for a large part of the year-to-year variation in weed control from isoproturon often remarked upon by agronomists.

Whether the effects found are the result of anthropogenic climate change is more equivocal. However, the trends are broadly consistent with some weather effects now being attributed to climate change. The recently published "Climate Change Scenarios for the United Kingdom" (UK Climate Impacts Programme or UKCIP02; Hulme *et al.*, 2002) reports that the annual average temperature for central England has increased by almost 1°C during the twentieth century and that the 1990's was the warmest decade in central England since records began in the 1660's. This is broadly consistent with the trend in estimated herbicide persistence described above.

The same report also presents four alternative scenarios of how climate change may affect UK climate over the next hundred years, based on a range of future global emissions of greenhouse gases. Of particular relevance are the following key projections:

by the 2080's, the annual average temperature across the UK may rise by between 1°C (low emissions scenario) and 5°C (high emissions scenario), with greater warming in the south and east;
winters are likely to become up to 30% wetter over the same period.

The time-scale of these projections is very long, but the magnitude of the changes could be considerably greater than those seen so far. The projections suggest that the persistence of herbicides such as isoproturon may be reduced further and that even over a timescale similar to that studied in this paper, the reduction could be much greater than has taken place so far.

It is important to stress that such an effect would not be limited to isoproturon. All autumn and winter-applied, soil active herbicides are likely to be affected in a broadly similar manner, as indeed would other pesticides present in UK soils at this time of year, because of the temperature dependence of degradation. Isoproturon is an old herbicide, but there are many other residual, autumn-applied herbicides in use (Table 2) and new ones continue to be developed.

Table 2. Autumn-applied herbicides with residual activity

Crop	**Herbicides**
Cereals	chlorotoluron, DFF, flufenacet, flupyrsulfuron-methyl, pendimethalin, propoxycarbazone-sodium, trifluralin
Winter beans	clomazone, simazine
Winter oilseed rape	cyanazine, metazachlor, propyzamide, quinmerac

The results suggest that the persistence of pesticide residues in soils over winter in the UK will have declined since 1980 and the magnitude of the effect will depend on the laboratory half-life of the pesticide. The Walker & Eagle (1983) model used in this study can be applied to all pesticides in soil for which there is a well-defined laboratory half-life and for which a first order degradation curve is a reasonable approximation. If the model were to be used to make the same estimates for other pesticides as for isoproturon, similar percentage declines in persistence are likely to be predicted. For pesticides that may contaminate water by movement through the soil, this loss of persistence may be of benefit to the environment. However, for pesticides with soil activity, such as residual herbicides, a significant loss of pest control is likely.

The overall effects of climate change on pesticides in general and weed control in particular are difficult to predict, because there will be many interacting factors involved. However, recent work by Harris & Hossell (2001) has suggested that predicted higher soil moisture deficits in autumn might bring fields to a condition which is too wet to conduct fieldwork at an earlier date than at present. This might encourage the earlier application of autumn herbicides. If this is combined with a reduction in herbicide persistence, autumn and winter weed control may become much more difficult than at present (Bailey, in Press).

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Turning up the heat on pests and diseases: a case study for Barley yellow dwarf virus

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ABSTRACT

Interactions between the various factors influencing the incidence of pests and diseases are always very complex, making modelling and prediction difficult. Environmental changes add another layer of problems and may influence the longevity of decision support systems. In many areas Barley yellow dwarf virus is likely to become more troublesome. In the UK, indications are that the risk of increase in BYDV incidence in autumn-sown cereals is greatest in the west where milder winters are expected to be accompanied by wetter summers than will occur in the east, both these factors aiding aphid survival.

INTRODUCTION

The World is getting warmer (I.P.C.C., 2001) and it is certain that this will affect arable agriculture. Whether the effect is positive or negative will depend on location and crops grown. It will also depend on the affect of changes in temperature and other factors, perhaps especially rainfall, not only on the crops themselves but also on their competitors, the pests and diseases of the crops and their own competitors, and the natural enemies of the pests. Indeed, even this is a gross oversimplification as the interactions between these factors are highly complex.

There are good reasons for trying to predict the impacts of climate change within the context of the protection of crops from pests and diseases. We need to determine whether we will be able to manage pests and diseases in the future as we do currently or, if not, the options that will be open to us. So far, generalisations have proved elusive and methodological frameworks controversial. However, the more diverse the range of problems studied and the methodologies used, the more likely it is that generic insights will emerge. In the mean time, the daunting task of integration should not deter studies of specific systems.

Potential means by which changes in climate may lead to changes in pest status of species, for example through changes in the physiology, phenology, distribution and abundance and through impacts on our ability to control pest species, have been reviewed elsewhere (Harrington *et al.*, 2001). This paper concentrates on how climatic changes may affect the incidence of Barley yellow dwarf viruses (collectively here termed BYDV) and some of their aphid vectors.

BYDV EPIDEMIOLOGY

Several authors have drawn attention specifically to the complexities of BYDV epidemiology (*e.g.* Irwin & Thresh, 1990; Burgess *et al.*, 1999). The so-called disease triangle, made into a pyramid by adding interactions with the environment to those between the viruses, vectors and host plants, is a bit hackneyed. However, it still serves a useful purpose in drawing attention to some of the issues that need to be addressed when considering potential impacts of climate change, and a brief summary is warranted.

The viruses

There are at least two species and a whole raft of strains and isolates involved in barley yellow dwarf disease, each of which may interact differently with vectors, host plants and the environment.

The vectors

Being a persistent, phloem-limited virus, aphids have to feed to acquire BYDV, rather than just probe for host plant identification cues. At least 28 species can do this, although it is probable that only a sub-set of these is important. Nonetheless this presents multiple complications, as the aphid species have different life cycles, fly at different times and in different places and have different behaviour patterns. Different clones within species may also vary in some or all of these characteristics. Environmental change will certainly have a different impact between, or even within, species.

The host plants

There is a whole range of crops and other *Poaceae* that are hosts to BYDV. All are potential reservoirs of infection and, again, they will respond differently to environmental changes. Changes to cropping patterns, such as the introduction of *Miscanthus* as a renewable energy source, will increase the potential BYDV reservoir and might also provide a green bridge for the disease. Expansion of the area of maize also has the potential to alter dramatically patterns of BYDV spread through its influence on aphid incidence and species composition and on virus strains present.

Virus - vector interactions

Some species of aphid can transmit more than one virus strain efficiently and some virus strains can be transmitted efficiently by more than one aphid species. Different clones of aphids also differ in their vectoring efficiency (Guo *et al.*, 1996) and behaviour. Furthermore a given virus isolate can be transmitted with different efficiency by different clones of a given aphid species and a given aphid clone can transmit different isolates with different efficiencies. Yet another complication is that the species of aphid which inoculated the virus may have a significant effect on the efficiency with which different aphid species can subsequently transmit virus (Gray *pers. comm.*). It is possible that such effects are even seen at aphid clonal level.

Virus - host plant interactions

Symptoms in host plants differ with virus strain or isolate, making it difficult to assign resistance ratings to cultivars. Also, under this heading, the latent period in the plant must be considered, *i.e.* the time between the plant becoming infected and itself acting as a virus source. This is affected by growth stage, virus strain and environmental conditions.

Vector - host plant interactions

Different aphids have different host plant preferences and this will clearly affect disease epidemiology. Also, crop growth stage will affect both aphid feeding behaviour and host plant preference.

Virus - vector - host plant interactions

Considering just the virus, the host range of each BYDV strain is similar. However, in the field there are differences in which virus strains are prevalent in different hosts. For example *Rhopalosiphum maidis* does not tend to feed on oats and so RMV, a virus strain which relies on this vector, is not usually a problem in oats. Changes in cultivars may have profound effects on epidemiology through effects on the vectors and viruses.

ENVIRONMENTAL CONSIDERATIONS AND CLIMATE CHANGE

Environmental factors interact strongly at every stage discussed above and make predictions of climate change impacts somewhat circumspect. However, there are some pointers.

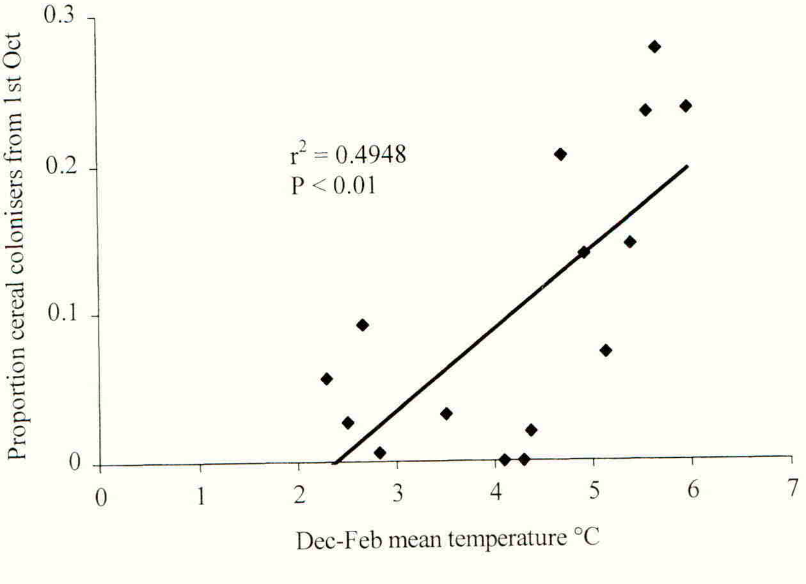

Figure 1. Relationship between previous winter temperature and proportion of cereal-colonising forms of the aphid *Rhopalosiphum padi* trapped at Rothamsted in autumn 1986-2000.

In the UK, general experience and some empirical evidence suggest that BYDV problems are greatest following two consecutive mild winters with a wet summer in between. The first mild winter leads to a high proportion of anholocyclic clones of *Rhopalosiphum padi*, a major vector, in the following year (Fig. 1). The anholocyclic clones are those which over-winter in the active stage on grasses, including cereals, rather than as an egg on their primary host, *Prunus padus*. Therefore, only the anholocyclic clones are important in transmission of BYDV in autumn-sown crops. The active forms are far less tolerant of low temperature than are the eggs and a tendency can be seen for the proportion of anholocyclic forms in autumn to be related to temperature in the previous winter, with a higher proportion following a mild winter. If, in the mean time, the summer is wet, there is a plentiful supply of good quality grasses to tide the aphids over between the ripening of one crop and emergence of the next. In the UK, there is a weak but significant relationship between numbers of *R. padi* in autumn, and summer rainfall. A second mild winter allows all these aphids of the right morph to move around the newly emerged crop, spreading virus. Thus, two mild winters with a wet summer in between provides the basis for increased risk of economically damaging virus spread. Figure 2 shows how the probability of encountering two consecutive mild winters (defined here as December to February mean temperature exceeding 4.5°C), with a wet summer in between (defined here as precipitation from June to August exceeding 190mm), is likely to change in different regions of the UK according to climate predictions to the end of this century. The BYDV risk is predicted to rise particularly in Northwest England and Southwest England. In other parts, although the criterion of warm winters is met more often in the future, the summers are expected to be particularly dry, hence reducing risk.

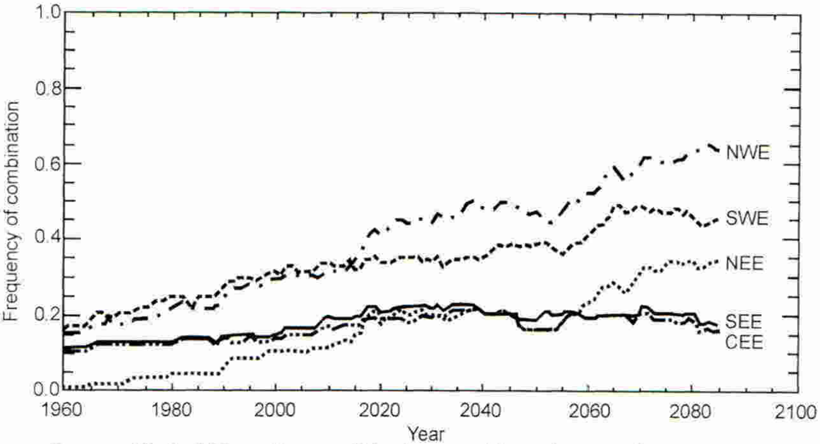

Figure 2 Probability of two mild winters with an intervening wet summer in Northeast England (NEE), Southeast England (SEE), Central and Eastern England (CEE), Northwest England (NWE) and Southwest England (SWE).

Drought stress during the growing season can increase risk of spread. In laboratory experiments in which trays of plants were subjected to different levels of drought stress, aphids visited more plants at higher temperatures and at higher drought stress levels, and this was reflected in the number of plants infected with BYDV (Smyrnioudis *et al.*, 2000). There was a temperature - drought stress interaction: high levels of drought stress had a particularly strong effect at higher temperatures. Furthermore, there is likely to be an interaction between drought stress and BYDV with respect to plant vigour. Drought stress is likely to weaken the plant and increase its susceptibility to the disease. On the other hand BYDV is likely to weaken the plant and make it more susceptible to drought.

Climatic change may influence the prevalence of particular virus isolates in a region and the efficiency of their transmission by particular aphid species. For example, the RMV strain of BYDV is currently unimportant in small grain cereals in the UK. It is transmitted by *R. maidis*, which is uncommon compared to other vectors. With climate warming, maize may become more widespread, as may the maize-preferring strain of the aphid, which does not produce an egg and hence is not tolerant of cold winters. At higher temperatures, the more common vectors in the UK may become capable of transmitting the RMV strain to cereals such as wheat and barley (Lucio-Zavaleta *et al*., 2001). Therefore, warmer conditions, through their effect on interactions between host plants, aphids and viruses, may render the maize strain of BYDV important in wheat and barley for the first time in the UK.

These examples serve to remind us that changes in climatic variables may have unexpected effects on BYDV epidemiology. Thus, the extrapolation based on mild winters and wet summers (above) could turn out to be grossly over simplistic, whilst process-based modelling could turn out to be grossly over complex.

Extrapolation from current distribution

What can the distribution of BYDV incidence around the World today tell us about expected impacts of climate change in a given region? Can we find areas where the climate today is similar to that expected in our particular area of interest fifty years hence and infer that BYDV problems will be similar? Again, this is too simplistic. For example, even though climate may be matched, photoperiod may not, and that influences plant growth, insect life cycles and hence epidemiology in a range of ways. However, the review by Lister & Ranieri (1995) shows clearly that where there are cereals there is BYDV and, although prevalent strains and isolates may change in a given area, the disease is likely to be sufficiently adaptable to continue to be ubiquitous no matter how the climate changes. Nonetheless, there currently exists no summary of which strains of BYDV are prevalent in which areas of the World, and how abundant and damaging they tend to be in those areas. Such information would provide a useful base on which to build testable hypotheses concerning climate change impacts on BYDV.

Impacts on decision support

Various decision support systems (DSS) aimed at rationalising the use of insecticides to control BYDV are in operation or are under development (Knight & Thackray, in press). A major concern with any DSS is its upkeep following development and launch. This is particularly important in the case of computer-based systems which, if not updated, can become scientifically outdated surprisingly quickly whilst continuing to present a beguiling façade to users. We have seen that a BYDV DSS has to account for a large number of biotic and abiotic components of the disease system and for primary and lower level interactions between them. If any of these changes, the model parameters may become inappropriate. For example, new cereal varieties may interact in different ways to current varieties with the aphids and the viruses. In the longer term, environmental changes may have important effects. If a new DSS is found to be successful, growers should be prepared to reinvest some of the money saved through its use in its continued scientific development. The challenge for DSS developers is to provide systems that take account of the huge amount of variation, and potential for change that goes with any pest and disease problem and hence produce a system with wide and enduring applicability.

Wider considerations and mitigation options

There are at least three major problems when trying to assess mitigation options to offset the impacts of climate change on pests and diseases. The first is that generalisations are proving elusive. Even quite closely related pests or diseases respond to changes in different ways. The second is that pests and diseases are only a small component of agronomic considerations. For both of these reasons it is quite possible that changes designed to reduce one problem will exacerbate another. The third problem relates to the sheer complexity of interactions within and between the abiotic and biotic components of change (not only in climate) and the immense difficulty in accounting for this complexity in models. It is right the agricultural community is aware of what may lie ahead and that mitigation options are explored but there is much still to do to raise understanding to a level that can be translated into a holistic approach for growers.

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Predicting the potential distribution of alien pests in the UK under global climate change: *Diabrotica virgifera virgifera*

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ABSTRACT

Diabrotica virgifera virgifera, the western corn rootworm, a North American species, was first found in Yugoslavia in 1992, and has since spread widely in central Europe. In 2002, it was found near Paris, raising concerns regarding its potential threat to UK maize crops. The computer program CLIMEX was used to identify the critical parameter – accumulated temperature – which defines the northward limit of distribution of *D. virgifera virgifera* in North America, and this threshold was then applied to the UK, at improved spatial and temporal resolutions, under current and predicted future climates. Under current climate conditions, *D. virgifera virgifera*, appears to be at the edge of its range in the UK but by 2050, under global warming, a large area of SE England will be suitable for this species.

INTRODUCTION

The growth in the volume, frequency, diversity and speed of global plant, animal and commodity movements through man's activities has provided increasing opportunities for species to spread beyond their natural range (Levine & D'Antonio, 2003). In England and Wales, approximately 500 taxa are identified from organisms detected in imported consignments each year (C Malumphy, *pers.comm*). Pest risk analyses are undertaken to determine the likelihood of these species establishing and causing serious economic or environmental damage, and the strength of any measures that should be imposed (FAO, 2001). Assuming entry, successful establishment in a new area depends on the suitability of both abiotic factors, e.g. climate, and biotic factors, e.g. the presence of hosts. The extent to which intrinsic attributes, e.g. the reproductive rate, favour colonisation must also be taken into account (Baker, 2002). While all such factors and attributes may influence establishment, the suitability of the climatic conditions is fundamental (Baker, *et al.*, 2000). Reliable assessments of the climatic suitability of a new area depend on the extent to which the species' climatic responses are known or can be inferred, climatic data are available or can be predicted for the time period of interest, interpolation techniques accurately predict climatic conditions over the landscape and differences between the micro-climate in the species' niche and locations where the climate recording instruments are situated can be taken into account.

Taking climate change into account is also critical to the assessments, since, for example, increasing temperatures may make habitats which are currently marginal more suitable to warmth-loving organisms over time. Temperature directly affects herbivorous insects, and in general terms, insect pests are expected to become more abundant as temperatures increase, through a number of inter-related processes, including range extensions and phenological changes, as well as increased rates of population development, growth, migration and over-wintering (Bale, *et al.*, 2002; Cannon, 1998; Masters, *et al.*, 1998). Species range expansions, in response to the increased favourability of habitats could have a marked influence in countries, such as the UK, which include a large number of species at, or near, the limit of their current northern distributions. The ranges of many, non-migratory European butterflies shifted northwards, between 35 to 240 km, in response to increasing temperatures during the 20th Century (Parnesian, *et al.*, 1999).

For insects and other invertebrates, which are regularly moving in or on traded plants or plant products, an increase in the suitability – or establishment potential – of their favoured habitat, can have a marked influence on their occurrence and abundance. For example, the UK Plant Health Service has become aware of a number of newly established species in recent years, particularly those with a Mediterranean or southern European distribution (see Cannon, *et al.*, 2003). For example, the Cottony cushion scale (*Icerya puchasi*) has recently bred and over-wintered outdoors in Britain (London) for the first time (Watson & Malumphy, *pers. comm*). Whilst not all of these invasions have been directly linked to climate change, increasing temperatures combined with a human intervention, have probably been major factors in enabling them to increase their natural range.

Previous studies have focused on predictions of potential distributions under current and future climates for species such as the Colorado beetle, *Leptinotarsa decemlineata*, which have well known climatic responses, threaten areas and spend critical periods of their life cycle above ground where the micro-climate is not too dissimilar to that recorded by weather stations (Baker *et al.*, 1998). Predicting the distribution of species which spend most or part of their life cycle in environments which are markedly different from those where climatic conditions are recorded, e.g. soil, wood or artificial environments, is much more difficult. In this paper, we describe how we have attempted to predict the potential UK distribution of a species which, apart from the adult stage, spends all of its life cycle in the soil. Originally from North America where it is one of the most serious pests of maize (Oerke *et al.*, 1994), the western corn rootworm, *Diabrotica virgifera virgifera*, was first found in Yugoslavia in 1992 and has since spread widely in central Europe and to three locations in northern Italy. In 2002, it was found near Paris (EPPO, 2003). Larval root feeding is the primary source of damage, reducing nutrient uptake and growth (Gavloski *et al.*, 1992) weakening plants and making them more susceptible to lodging which can cause serious losses in yield, particularly where the crop is grown continuously. Evidence from European countries suggests that there is a time lag of approximately five years between the first finding of *D. virgifera virgifera* and reports of economic damage. During 1999, in counties of Yugoslavia where damage occurred, the mean yield of maize was reduced by an estimated 30% (EPPO, 2000).

MATERIALS AND METHODS

Although there is a considerable and growing literature covering all aspects of the distribution and biology of *D. virgifera virgifera*, the data on its distribution and climatic responses is difficult to interpret for three main reasons. Firstly, although the current distribution of *D. virgifera virgifera* in North America and Europe is well documented, since it is rapidly spreading in Europe, it is difficult to judge the extent to which the current limits to its distribution are caused by unfavourable climate or simply by the fact that *D. virgifera virgifera* has not yet had sufficient opportunity to spread further. Secondly, all stages, except the adults, live in the soil, whereas the temperature data which are primarily used for predicting climatic suitability are all based on measurements above ground and there is no simple relationship between air and soil temperatures. Environmental conditions in the soil depend on ground cover, soil type, water retention capabilities, conductivity and other factors. Thirdly the estimated environmental responses in the literature, particularly those which have been used to attempt to predict *D. virgifera virgifera* phenology in the soil based on air temperatures, show considerable variability (Elliott *et al.,* 1990). Soil type, maize variety and genetic variation in *D. virgifera virgifera* populations clearly all play a role in addition to the fact that individuals can be found at a range of depths down to 23 cm with larvae occurring between 0-15 cm (Bergman & Turpin, 1986).

To take account of these difficulties, CLIMEX (Sutherst *et al.,* 1999), a program which matches and configures climatic responses to the current distribution of the species and extrapolates these to the PRA area, has been applied to predict the distribution of *D. virgifera virgifera* in France (Reynaud, 1998) and Germany (Baufeld *et al.,* 1996). Climatic responses calculated originally for the soil have been applied even though CLIMEX only uses air temperatures. The key parameter chosen is an 11°C minimum threshold for development and the minimum number of degree days for the completion of *D. virgifera virgifera*'s life cycle is given as 670 based on studies by Jackson & Elliot (1988). Although these parameters overestimate the southern limits to its distribution in North America, the northern limits in North America predicted by CLIMEX are similar to those in the literature (Krysan & Miller, 1986), justifying the use of these parameters to predict the northern limit of climatic suitability in Europe. The annual total of degree-days was found to be critical for establishment at the northern boundary.

CLIMEX includes 1931-1960 monthly averages for 285 European weather stations. These data have two main disadvantages: firstly the climate has warmed up considerably since 1931-1960 and, secondly, the stations may be unrepresentative of the areas where crops are grown. Accordingly, we loaded CLIMEX with 1961-1990 mean monthly climate interpolated to a 0.5° latitude/longitude grid by New *et al.* (1999). However, whereas the 1931-1960 data indicate that four UK weather stations are climatically suitable for *D. virgifera virgifera*, none of the 0.5° latitude/longitude 1961-90 UK grid cells were found to be suitable. Examination of the outputs revealed that failure to reach the 670 degree days at a base of 11°C defines the northern limit to the distribution. We therefore concluded that climatic suitability maps for *D. virgifera virgifera* in the UK could be estimated from calculating accumulated temperatures without using CLIMEX and displaying these in a proprietary geographical information system (GIS). In the UK, maize is usually harvested by the end of October, so this was chosen as the cut-off date for degree day calculations.

In order to determine whether the apparent unsuitability of the UK climate based on 0.5° latitude/longitude 1961-90 grid cells was due to the use of data which are either at too coarse a spatial and temporal scale or reflect a cooler historical past, additional climatic datasets were employed. We increased the spatial resolution from 0.5° latitude/longitude to 5 km, and the temporal resolution from 30-year mean monthly data to annual means (using datasets from the

UK Met. Office). The maize distribution for England, also at a 5 km resolution, was provided by the Defra Economics and Statistics Division and so, using a GIS mask facility, accumulated temperature data for only the 5 km grids where maize is currently grown could be calculated and displayed. Accumulated temperature data were calculated at 5 km resolution for a cool (1996) and a hot (1995) year to provide an improved representation of the extremes of current climate and compared to the four UKCIP02 climate change scenarios predicting climates in 2050 under low, medium low, medium high and high emission scenarios (Hulme *et al.*, 2002). To explore the inter-annual fluctuation in degree days over a 30 year period, daily maximum and minimum air temperatures were obtained for 1970-1999 from Gatwick Airport.

RESULTS

The numbers of 5 km grid cells where accumulated temperatures reached 670 for the UK under current and climate change conditions are given in Table 1. By masking out those cells not used for maize production in 2001, it was found that only 3 cells in 1996 and 2333 cells in 1995 were both climatically suitable and likely to contain maize.

Table 1. Comparison of the number of 5 km grid cells in the UK climatically suitable for *Diabrotica virgifera virgifera* under current and future climatic conditions based on a threshold of 670 degree days above a base of 11°C.

Year	Number of climatically suitable 5 km cells
Hot year (1995)	4852
Cool Year (1996)	34
2050 UKCIP02 high emissions scenario	5137
2050 UKCIP02 medium high emissions scenario	4667
2050 UKCIP02 medium low emissions scenario	4407
2050 UKCIP02 low emissions scenario	3879

Figure 1 shows that the area suitable for *D. virgifera virgifera* establishment in the hot year of 1995 is very similar to predictions for the UKCIP02 high emission scenario for 2050. Figure 2 gives the annual variation in accumulated temperatures base 11°C for Gatwick airport from 1970-1999 and clearly shows how the years have become warmer over the 30 year period (maximum 1032 in 1995). For nine years out of the thirty analysed, annual accumulated temperatures were less than 670. The date when 670 degree days are achieved is also becoming earlier (earliest 14th August in 1995). An insignificant amount of degree days above 11°C is accumulated in November and December, so there is little difference between the annual accumulated temperature total and that reached at the end of October, by which time the maize is harvested.

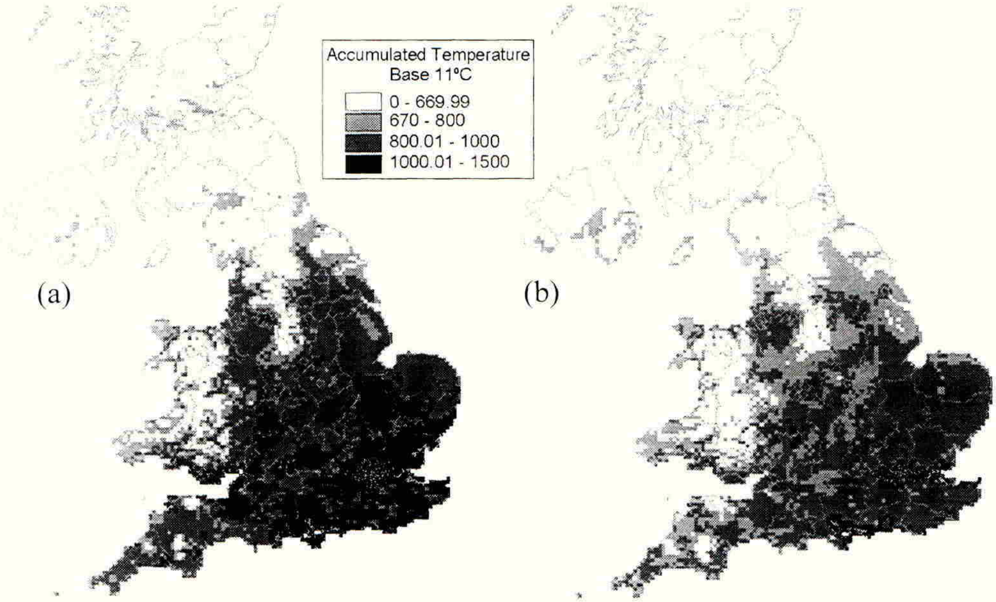

Figure 1. Comparison of the area of the UK climatically suitable for establishment by *Diabrotica virgifera virgifera* in (a) 1995 (a hot year) and (b) 2050 (under the UKCIP02 high emissions climate change scenario).

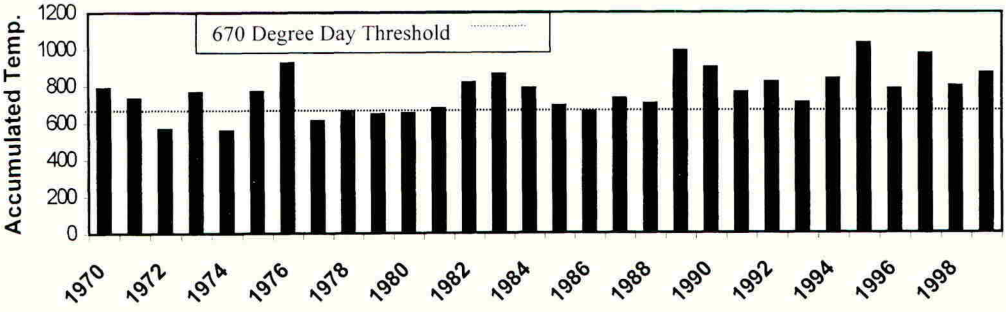

Figure 2. Annual accumulated temperature base 11°C calculated from daily 1970-1999 data at Gatwick Airport, UK

DISCUSSION

The procedure adopted here, applying CLIMEX to identify the parameter which is critical to defining the northward limit of distribution in North America, i.e. an accumulated temperature threshold, and then applying this to the UK at improved spatial and temporal resolutions under current and future climates, depends for its success on a number of assumptions. The host plant is grown widely in England but other biotic factors must also be non-limiting. For example, although crop rotation is an effective control method, a small proportion of eggs may exhibit prolonged diapause (Levine *et al.,* 1992). Since CLIMEX predictions of potential distribution are partly based on existing distributions, differences between the microclimate at climate stations and the pest niche are accounted for to some extent. An alternative approach would require comprehensive soil temperature profiles for the maize crop in the UK or could follow Elliot *et al.,* (1990), who adapted models by Gupta *et al.*, (1983) of soil temperature profiles related to above ground temperatures, the soil type and the crop. Soil temperature data at various depths under a grass sward are available for a few locations in the UK, though they are usually recorded at 9 am and are thus not a mean which can be used to calculate degree days. We conducted an exploratory study of locations south of London with hourly temperature measurements and a soil temperature profile, and found that, at 10 cm depth, annual temperature accumulations at a base of 11ºC are approximately 200 day degrees higher than those above ground. If this is added to the 1970-1999 annual accumulated air temperatures at Gatwick airport, then the 670 day degree threshold for *D. virgifera virgifera* to complete its life cycle is exceeded in every year.

Considerable uncertainty remains as to the choice of the minimum threshold of 11°C and the limit to the annual accumulated temperature being set at 670. Jackson & Elliott (1988) and Davis *et al.* (1996) highlight the difficulties of estimating the minimum threshold for development and the appropriate number of degree days for the development of each life stage. *D. virgifera virgifera* is extremely adaptable and environmental response data taken from populations in Ontario, at the current northerly limit to its distribution in North America, and from European populations would be more appropriate.

Increasing the spatial and temporal resolution of climatic data significantly influences predictions of the establishment potential of warmth loving organisms in the UK. The 5 km resolution data for 1995 and 1996 show that there is considerable annual variation in the area available for establishment. However, by 2050 under global warming the very hot summer of 1995, with its large area suitable for *D. virgifera virgifera*, is likely to be representative of the mean rather than an exception (Hulme *et al.,* 2002). At 5 km resolution, monthly accumulated temperature calculations for 1996 produced only 34 cells above the 670 threshold, one on the south coast and the rest in London, whereas daily calculations from one location, Gatwick airport, for the same year produced a total of 783 degree days. This strengthens the conclusions of Jarvis & Baker (2001) who showed how increasing the spatial and temporal resolution of climatic data influences predictions of climatic suitability.

Under current climate conditions, *D. virgifera virgifera*, appears to be at the edge of its range in the UK. Predictions of climatic suitability for *D. virgifera virgifera* are not easy to make because all stages, except the adult, live in the soil. Similarly, *D. virgifera virgifera*'s environmental responses which have been reported in the literature are difficult to extrapolate to UK conditions primarily because there are no comprehensive soil temperature profiles for the maize crop in the UK. Nevertheless, comparisons of air and soil temperatures at different depths from locations south of London indicate that *D. virgifera virgifera* could complete its life cycle in most if not all of the last thirty years and the warmer summer temperatures in the most recent years have greatly increased the likelihood of this occurring. Outside southern England, the likelihood of *D. virgifera virgifera* completing its life cycle rapidly diminishes. The increasing area of forage maize, sweet corn and game cover are also enhancing the potential for *D. virgifera virgifera* establishment in the UK.

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