North–South divide: contrasting impacts of climate change on crop yields in Scotland and England

Michael H. Butterworth¹, Mikhail A. Semenov¹, Andrew Barnes²,
Dominic Moran², Jonathan S. West¹ and Bruce D. L. Fitt^{1,*}

¹*Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*

²*Scottish Agricultural College, West Mains Road, Edinburgh EH9 3JG, UK*

Effects of climate change on productivity of agricultural crops in relation to diseases that attack them are difficult to predict because they are complex and nonlinear. To investigate these crop–disease–climate interactions, UKCIP02 scenarios predicting UK temperature and rainfall under high- and low-CO₂ emission scenarios for the 2020s and 2050s were combined with a crop-simulation model predicting yield of fungicide-treated winter oilseed rape and with a weather-based regression model predicting severity of phoma stem canker epidemics. The combination of climate scenarios and crop model predicted that climate change will increase yield of fungicide-treated oilseed rape crops in Scotland by up to 0.5 t ha^{−1} (15%). In contrast, in southern England the combination of climate scenarios, crop, disease and yield loss models predicted that climate change will increase yield losses from phoma stem canker epidemics to up to 50 per cent (1.5 t ha^{−1}) and greatly decrease yield of untreated winter oilseed rape. The size of losses is predicted to be greater for winter oilseed rape cultivars that are susceptible than for those that are resistant to the phoma stem canker pathogen *Leptosphaeria maculans*. Such predictions illustrate the unexpected, contrasting impacts of aspects of climate change on crop–disease interactions in agricultural systems in different regions.

Keywords: climate scenarios; crop simulation model;
resistance to *Leptosphaeria maculans*; phoma stem canker; stochastic
weather generator; weather-based disease forecast model

1. INTRODUCTION

Worldwide climate change is affecting agricultural crops (Metz *et al.* 2007; Stern 2007) and the diseases that attack them (Chakraborty 2005; Garrett *et al.* 2006). Changing temperature and rainfall patterns can produce severe crop disease epidemics that threaten food security (Chakraborty *et al.* 2000; Anderson *et al.* 2004), especially in subsistence agriculture (Morton 2007; Schmidhuber & Tubiello 2007). While much attention has been given to modelling the predicted impacts of climate change on crop yields, little research has been done into predicting the effects of climate change on crop–disease interactions. To guide strategic government food security policy and industry planning for adaptation to climate change, there is a need for a detailed evaluation of future crop production in relation to predicted effects of climate change on both crop yield and disease severity. Such an evaluation requires outputs from quantitative models of crop–disease–climate interactions. However, much work on effects of climate change on crops and their diseases has been qualitative

(Coakley *et al.* 1999; Anderson *et al.* 2004) and there have been few attempts to produce combined crop–disease–climate models (Luo *et al.* 1995).

The increased concentrations of CO₂ associated with climate change are expected to increase crop yields due to a beneficial effect on photosynthetic efficiency (Ewert *et al.* 2002; Semenov 2009). However, these beneficial effects could be counterbalanced by increases in stress factors that have the opposite effect, such as summer water stress and heat stress. Winter (autumn-sown) oilseed rape is an important arable crop in the UK, with large areas grown in England (450 000 ha) and Scotland (400 000 ha) in 2006. Crops are often sown in late August and harvested in mid-July the following year. Most of the oilseed rape is grown in the eastern half of the UK because the hilly terrain and lower soil fertility are often unsuitable for arable crops in the west. The area grown is likely to expand, with increasing interest in the production of biodiesel from oilseed rape to replace fossil fuels. The crop simulation model STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard), developed by INRA (France), has been used to simulate oilseed rape growth and yield (Brisson *et al.* 2003) but assumes that diseases have been controlled with fungicides and does not account for disease losses.

*Author for correspondence (bruce.fitt@bbsrc.ac.uk).

Electronic supplementary material is available at <http://dx.doi.org/10.1098/rsif.2009.0111> or via <http://rsif.royalsocietypublishing.org>.

The increase in temperature associated with climate change may increase the severity of crop disease epidemics (Evans *et al.* 2008). The most important oilseed rape disease in the UK is phoma stem canker (*Leptosphaeria maculans*), which causes severe losses each year despite expenditure of more than £12 million on fungicides (Fitt *et al.* 2006). Worldwide, the most severe epidemics occur in Australia, with its Mediterranean climate (Howlett *et al.* 2001). Globally, losses from phoma stem canker exceed £500 million per season (Fitt *et al.* 2008). Although phoma stem canker currently causes severe epidemics on winter oilseed rape in France (latitude 42–51° N; Fitt *et al.* 2006) and England (latitude 50–55° N), the disease does not cause yield loss further north, in Scotland (latitude 55–59° N; Evans *et al.* 2008). Although the initial phoma leaf spotting phase of the disease (West *et al.* 2001) occurs in autumn in all these regions, colder winters in Scotland mean that *L. maculans* is unable to spread along the leaf petiole and colonize the stem rapidly enough to cause damaging cankers (Evans *et al.* 2008). Predictions about the increase in severity of phoma stem canker epidemics in England and spread of the disease to Scotland as a result of global warming were made by combining climate change scenarios with a weather-based regression model for forecasting the severity of epidemics (Evans *et al.* 2008), but these predictions were not linked with predictions of changes in oilseed rape growth and yield under changed climate.

The predicted effects of climate change on severity of phoma stem canker were less on oilseed rape cultivars with resistance to *L. maculans* than on susceptible cultivars (Evans *et al.* 2008). Some resistance to *L. maculans* is temperature-dependent and can operate at 15°C but not 25°C (Huang *et al.* 2006). To adapt to climate change, there is a need to breed oilseed rape with increased resistance to *L. maculans* that can operate at the predicted higher temperatures. However, there has been no assessment of the benefit of resistance to *L. maculans*, in relation to an analysis of the effects of climate change on oilseed rape yield and yield losses from phoma stem canker. The aim of this paper is to estimate the impact of climate change on oilseed rape across the UK by assessing the effects of climate change on fungicide-treated yield and yield losses from phoma stem canker disease for oilseed rape cultivars differing in resistance to *L. maculans*.

2. MATERIAL AND METHODS

2.1. Climate change scenarios

Daily site-specific climate scenarios based on the UKCIP02 climate change projections (Semenov 2007) were generated to predict the effects of climate change on fungicide-treated oilseed rape yield and yield losses from phoma stem canker. These projections are based on the HadCM3 global climate model (Collins *et al.* 2001; Hulme *et al.* 2002) and global IPCC emission scenarios (Nakicenovic 2000). The LARS-WG stochastic weather generator was used to produce a baseline scenario after it had been calibrated with

Figure 1. Relationships between different components of the modelling and analysis. (1) Weather data were generated for five UKCIP02 climate change scenarios (baseline (1960–1990), 2020LO, 2020HI, 2050LO, 2050HI) for 15 sites over the UK (Semenov 2007). (2) These weather data were inputted into an oilseed rape crop growth simulation model, STICS (Brisson *et al.* 2003) and a weather-based regression model for predicting severity of phoma stem canker epidemics, PASSWORD (Evans *et al.* 2008). (3) The STICS model was used to generate yield data for crops treated with fungicides against diseases for each site/climate change scenario (figure 2). A yield loss model was used to estimate yield losses from stem canker severity predictions for oilseed rape cultivars that were susceptible (figure 3) or resistant (figure 4) to *Leptosphaeria maculans*. (4) Fungicide-treated crop yield data and yield loss data were interpolated according to UK government regions as used in the 2006 Defra Agricultural and Horticultural Survey and combined to estimate untreated crop yields (table 1).

observed weather from the baseline period 1960 to 1990. Using low (LO) and high (HI) CO₂ emission scenarios, climate scenarios were generated for the UK for the 2020s and the 2050s, thus producing five simulated scenarios: baseline, 2020HI, 2050HI, 2020LO and 2050LO (Semenov 2007). The values used for the CO₂ concentration in the UK atmosphere were 334 ppm (baseline), 422 ppm (2020LO), 437 ppm (2020HI), 489 ppm (2050LO), 593 ppm (2050HI), taken from the IPCC emission scenarios. Thirty years of daily weather data were generated for 15 sites located across the UK (electronic supplementary material, figure 1; Semenov 2007). The data generated were daily minimum temperature, maximum temperature, rainfall and solar radiation. These weather data were used as the inputs

into the models for predicting fungicide-treated winter oilseed rape growth and yield (STICS, Brisson *et al.* 2003) and the severity of phoma stem canker disease (PASSWORD, Evans *et al.* 2008) (figure 1).

2.2. Oilseed rape yield predictions

The STICS model was developed at INRA-Avignon, France and designed to simulate the development of several crops, including their water and nitrogen balances (Brisson *et al.* 2002, 2003). The simulated crop growth is dependent on the amount of solar radiation and the accumulated thermal time ($^{\circ}\text{C}\text{-days}$) and affected by stress indices (e.g. heat stress, water stress or nitrogen stress) decreasing crop growth. The model is divided into modules, with one for the physiological interactions of above-ground plant parts with the environment and another for soil and below-ground plant interactions. In allowing the user to alter a wide range of parameters, STICS can produce robust results at the local scale (Brisson *et al.* 2003). STICS model version 6.2 (<http://www.avignon.inra.fr/stics>) was used to simulate yield of winter (autumn-sown) oilseed rape for each of the 15 sites for fungicide-treated crops. The inputs into the model were the CO_2 concentrations and the daily site-specific weather data generated by LARS-WG for the five climate scenarios. These inputs were used to predict site-specific yields. Median values of simulated yields for 30 years were used since the predicted yields from the STICS model were not normally distributed.

The model was originally calibrated for the French cultivars of winter oilseed rape Goeland, Olphi and Pollen. Since most oilseed rape cultivars grown commercially in the UK are bred in France or Germany, the STICS parameter values calibrated for the French cultivars were generally applicable. In France, as in England, phoma stem canker is the main disease causing yield loss and thus the main target for fungicide applications. Parameters suitable for a typical soil in the UK were used. The sowing date was set to 23 August and the typical harvest date was set to 15 July. Radiation use efficiency (RUE) values were adjusted for UK crops. French oilseed rape yields are typically lower than UK yields (Brisson *et al.* 2002, 2003) and preliminary runs of the model confirmed this. The RUE values that determine the rate of crop growth in response to radiation were therefore increased by 36 per cent to produce an average yield for the UK baseline scenario (1960–1990) of approximately 3 t ha^{-1} . This corresponds with the average yield for UK winter oilseed rape from 1987 to 2007 (electronic supplementary material, figure 2). The STICS model was calibrated for crops sprayed with fungicides to control diseases but fungicides do not completely prevent yield loss from disease and thus the model underestimates the potential yield of the crop.

2.3. Phoma stem canker yield loss predictions

The phoma stem canker model of Evans *et al.* (2008) was used to predict the severity at harvest of phoma stem canker for each of the 15 sites and the five climate

Figure 2. Predicted yield of oilseed rape (treated against diseases). Predicted yields (t ha^{-1}) of fungicide-treated winter oilseed rape for (a) baseline, (b) 2020LO, (c) 2020HI, (d) 2050LO and (e) 2050HI climates. The maps are interpolated from yield data generated for 15 UK sites using the STICS crop growth model. Winter oilseed rape crops are generally grown in the eastern halves of England and Scotland; less fertile and mountainous areas in the west are unsuitable for arable crops.

change scenarios. The phoma stem canker model was developed and validated using disease and weather data from more than 40 experiments on winter oilseed rape done across England during the growing seasons from 1992/93 to 2001/02. The date of crop establishment was estimated as 26 September, which is

compatible with the 23 August sowing date used by the STICS model. The stem canker model operates by first predicting the start date of leaf spotting in autumn using the mean maximum daily temperature and total rainfall after the previous harvest to describe the maturation of the pathogen developed on crop debris during the summer period. This start date in autumn is an important factor affecting the severity of cankers in the following summer (West *et al.* 2001). The start date of phoma canker on stems in the following spring is predicted from the start date of leaf spotting and the accumulated thermal time in °C-days. The increase in the severity of these cankers in the period until harvest is predicted from the start date of cankers using the subsequent accumulated thermal time, which affects the colonization of stem tissues by the pathogen. Disease severity values were generated for the predicted canker severity at harvest. The typical harvest date of 15 July was assumed to represent the average date of harvest for the baseline scenario. However, the model altered the harvest date, depending upon the predicted maturity of the crop. The canker severity scores predicted were on a 0–4 scale (Zhou *et al.* 1999). The model was used to estimate phoma stem canker severity scores for each site and climate change scenario. These data were averaged by calculating the median values.

In the model of Evans *et al.* (2008), cultivars with an HGCA rating for resistance to *L. maculans* of 1–5 (susceptible; www.hgca.com) were given a resistance value of $A = 0$, and cultivars with an HGCA resistance rating of 6–9 (resistant) were given a resistance value of $A = 1$. The outputs of this model were also estimated for a representative crop with an average resistance rating of $A = 0.5$. Equation (2.1) was used to predict the canker severity on a specific date (e.g. last sample before harvest). Sc_p is the mean stem canker severity of plants (0–4 scale; Zhou *et al.* 1999), D_h is the pre-harvest sample date, Dc_p is the predicted start date of stem canker in spring and T_i is the temperature in °C on day i :

$$Sc_p = (0.00135 - 0.00035A) \sum_{i=Dc_p}^{D_h} T_i. \quad (2.1)$$

This equation can be used to estimate the canker severity at harvest (S) for cultivars that are susceptible or resistant to *L. maculans*. Using the stem canker severity scores produced by this model, the yield losses attributable to phoma stem canker were calculated using a yield loss model (electronic supplementary material, figures 3 and 4, table 1). This model estimates the relationship for UK winter oilseed rape between canker severity at harvest and associated yield loss as linear, and described by the equation

$$Y = 99.1 - 15.2S, \quad (2.2)$$

where Y is the yield of crops with stem canker expressed as a percentage of the maximum potential yield produced in fungicide-treated crops and S is canker severity score at harvest (0–4 scale). The data used to construct and validate this model were from winter oilseed rape experiments in England. Those used to

Figure 3. Predicted yield loss from phoma stem canker for cultivars susceptible to *L. maculans*. Predicted yield loss (% of maximum yield from fungicide-treated plots) from phoma stem canker for susceptible cultivars (HGCA resistance rating 1–5), for (a) baseline, (b) 2020LO, (c) 2020HI, (d) 2050LO and (e) 2050HI climates. The maps are interpolated from yield loss data generated for 15 UK sites using a weather-based canker severity model, a yield loss model and the crop model.

estimate this relationship were from experiments with 20 winter oilseed rape cultivars and unsprayed/fungicide sprayed plots harvested at Rothamsted in 2006 and 2007 (electronic supplementary material, table 1). The data used to validate the relationship between canker severity and associated yield loss were from a UK winter oilseed rape experiment harvested

Figure 4. Predicted yield loss from phoma stem canker for cultivars resistant to *L. maculans*. Predicted yield loss (% of maximum yield from fungicide-treated plots) from phoma stem canker for resistant cultivars (HGCA resistance rating 6–9), for (a) baseline, (b) 2020LO, (c) 2020HI, (d) 2050LO and (e) 2050HI climates. The maps are interpolated from yield loss data generated for 15 UK sites using a weather-based canker severity model, a yield loss model and the crop model.

at Withington (1993) with one cultivar and 22 fungicide treatments. The yield loss was estimated by comparing the yields of plots treated with fungicide with those that were untreated from winter oilseed rape experiments where phoma stem canker was the main cause of yield loss.

2.4. Regional treated and untreated yield predictions

The outputs from the oilseed rape model provided data on the predicted effects of climate change on oilseed rape yields for the 15 sites across the UK for the five different climate change scenarios. The results for each site were then mapped onto the oilseed rape growing areas of the UK. Data for county and regional boundaries and areas of oilseed rape grown in each county were taken from the 2006 Defra Agricultural and Horticultural Survey, obtained from the UK government's National Statistics archive, available online at www.defra.gov.uk (electronic supplementary material, figure 1). The simplifying assumption was made that the areas grown in the future in each county/region will remain the same as in 2006. The results were compiled at the scale of county (e.g. Hertfordshire) and then accumulated to be presented by geographic region (e.g. South East), and as totals for England, Scotland and the UK. The yield figures for each site were mapped onto the growing regions using a nearest point scheme. Where counties were approximately equidistant from two or more of the 15 sites, the average yield data for the relevant sites were used. A county was considered approximately equidistant when the mid-point between any two sites lay within its boundary. Similarly the phoma stem canker yield loss predictions were mapped onto these counties and regions. The fungicide-treated yield and yield loss data (mean for susceptible and resistant cultivars) were then combined to estimate the untreated yields for each region for each scenario (figure 1).

3. RESULTS

3.1. Oilseed rape yield predictions

The predictions obtained by combining the climate scenarios and STICS model suggest that climate change will generally increase the yield of winter oilseed rape crops treated with fungicide to control diseases such as phoma stem canker (figure 2). It is predicted that the greatest yields will be in eastern Scotland and north-east England in the 2020s and 2050s. The predicted increases in yield, by comparison with the baseline scenario, will generally be greater for the high CO₂ emission scenarios than for the low CO₂ emission scenarios. The predicted increases will also generally be greater for the 2050s than for the 2020s, with the greatest median yield increase, from 3.20 to 3.65 t ha⁻¹, predicted for eastern Scotland for the 2050s high CO₂ scenario. When interpreting these predictions, it is important to remember that most oilseed rape is grown in the eastern halves of England and Scotland, since the west is often unsuitable for crop production.

3.2. Phoma stem canker yield loss predictions

The predictions obtained by applying the stem canker severity model, combined with a yield loss model and the yield predictions from the crop model, suggest that climate change will greatly increase the yield losses from phoma stem canker by comparison with

Table 1. Effects of climate change on the yield of treated oilseed rape (Tr) and untreated oilseed rape (Unt) after phoma stem canker losses, calculated by region. (The oilseed rape yields were calculated as the means of values for resistant and susceptible cultivars. The area grown per region (2006) and the predicted average regional yield are given for the baseline (1960–1990) scenario. The predicted regional yield as a percentage of the baseline scenario is given for the 2020LO (low CO₂ emission), 2020HI (high CO₂ emission), 2050LO and 2050HI climate scenarios. The figures were calculated after interpolating the results from the treated oilseed rape yield predictions and the stem canker yield loss predictions according to UK government region.)

region ^a	area of oilseed rape grown (ha) ^b	baseline yield (t ha ⁻¹)		yield (% of baseline yield)							
		treated (Tr)	untreated (Unt)	2020LO		2020HI		2050LO		2050HI	
				Tr	Unt	Tr	Unt	Tr	Unt	Tr	Unt
North East	22 787	3.16	2.78	93.4	90.1	103.1	98.3	103.9	96.5	105.1	93.3
North West	3601	2.98	2.48	96.5	92.5	88.7	84.2	100.9	92.4	103.4	89.8
Yorkshire and Humberside	61 068	3.12	2.64	95.0	90.7	102.8	97.3	102.4	93.8	103.1	89.3
East Midlands	113 479	3.11	2.59	100.7	95.2	100.4	94.0	101.1	91.1	102.7	86.9
West Midlands	34 419	3.00	2.37	99.6	94.2	83.4	78.2	103.5	94.0	107.6	91.4
Eastern	103 488	3.16	2.58	100.0	94.5	99.7	93.1	103.0	92.8	104.7	88.3
London and South East	79 063	3.01	2.34	100.8	95.4	100.9	94.4	103.7	93.0	106.9	89.1
South West	44 858	3.05	2.41	100.3	95.1	100.5	94.2	103.1	93.7	106.7	90.7
England total	462 764	3.09	2.52	99.3	94.1	99.5	93.4	102.6	92.9	104.8	88.9
Scotland	398 720	3.15	3.06	104.8	103.2	107.1	105.0	109.7	96.9	111.5	103.6
UK total	861 484	3.12	2.77	101.8	98.7	103.0	99.3	105.9	94.9	107.9	96.4

^aGovernment regions can be found at http://www.statistics.gov.uk/geography/downloads/uk_gor_cty.pdf.

^bArea of winter oilseed rape grown in each region in harvest year 2006 (www.defra.gov.uk).

the baseline, especially in England (figures 3 and 4). They suggest that the greatest losses (up to 50%, i.e. 1.5 t ha⁻¹) will be in southern England under the high CO₂ emission scenario in the 2050s for cultivars susceptible to *L. maculans* (figure 3). By comparison, the yield losses for resistant cultivars will be much less, and losses will be less under low CO₂ emission scenarios (figures 3 and 4). Furthermore, the predictions suggest that phoma stem canker epidemics will cause much smaller yield losses in the oilseed rape growing areas of eastern Scotland, under low or high emission scenarios, with losses of only 10 per cent for the 2050s under the high CO₂ scenario.

3.3. Regional treated and untreated oilseed rape yield predictions

The total area of oilseed rape grown in the UK in 2006 was over 850 000 ha, with most of the oilseed rape grown in the east of the country (table 1). The baseline fungicide-treated winter oilseed rape yield was greatest in eastern England and Scotland (3.15 t ha⁻¹). The total production was only slightly greater in England (1 430 000 t) than Scotland (1 256 000 t). The yield losses from phoma stem canker (regional total treated yield (STICS) minus stem canker yield loss (PASSWORD)) for cultivars of average resistance were greatest in south-eastern England and the total losses for England (264 000 t) meant that total baseline production of untreated oilseed rape was predicted to be less than in Scotland. The predicted effects of climate change in the 2020LO scenario are to decrease the untreated yields of winter oilseed rape crops in all regions of England by comparison with baseline yields, by between 5 per cent (South West) and

10 per cent (North East); conversely, the effect of climate change in Scotland will be to increase the yield by 3 per cent. Under the 2020HI scenario, it is predicted that the untreated yield will decrease by more than in the 2020LO scenario in some English regions (e.g. 16%, North West) but by less in other regions (e.g. 2%, North East), so that the overall decrease by comparison to the baseline is similar for both scenarios. In contrast, in Scotland there will be a further predicted increase in yield (5% above the baseline). In the 2050LO scenario, it is predicted that there will be an increase in the treated yield but a decrease in the untreated yield, for both England and Scotland. In the 2050HI scenario, there is a predicted increase in yield for treated yield for both England (5%) and Scotland (12%) but a predicted decrease in untreated yield for England (11%) in contrast with a predicted increase for Scotland (4%). These predictions suggest that total production of fungicide-treated winter oilseed rape will increase to 2.90 Mt from the baseline of 2.69 Mt, with the proportion produced in Scotland increasing from 47 to 48 per cent in the 2050HI scenario. In contrast, they suggest that in this scenario total production of untreated winter oilseed rape in England will decrease to 1.04 Mt from 1.17 Mt under the baseline scenario but production in Scotland will increase from 1.22 to 1.26 Mt.

4. DISCUSSION

The results suggest that climate change will increase the productivity of oilseed rape in the UK but with the greatest benefits in Scotland in the north rather than England in the south. The predicted increase in the productivity of oilseed rape in Scotland is attributable to the higher CO₂ concentration in the atmosphere that

increases RUE and yield (Brisson *et al.* 2002, 2003; Semenov 2009). There is evidence that increased concentrations of CO₂ may also affect crop diseases, either indirectly through effects on the crop (Chakraborty *et al.* 2000) or directly through effects on the pathogen (Garrett *et al.* 2006). Although the predicted increases in productivity of UK oilseed rape are greatest if fungicides are applied to control diseases, fungicides may not be needed in Scotland. While it has been predicted that phoma stem canker will spread north to Scotland (Evans *et al.* 2008), the estimates suggest that epidemics will not cause substantial yield loss. In contrast, light leaf spot (*Pyrenopeziza brassicae*), the disease that is currently most damaging in the colder, wetter climate of Scotland, and much less important in England and France (Fitt *et al.* 1998; Gilles *et al.* 2000; Boys *et al.* 2007), is likely to become less severe as the climate becomes warmer there (N. Evans, personal communication). Thus use of fungicides on winter oilseed rape in Scotland may no longer be economically justified.

In contrast with the predictions for Scotland, the results suggest that climate change will considerably decrease yields in southern England unless phoma stem canker epidemics are controlled. These decreases will occur because the increase in severity of phoma stem canker epidemics in England as a result of increased temperatures (Evans *et al.* 2008) will considerably increase the yield losses from the disease and outweigh yield increases associated with increased CO₂ concentrations. These yield losses are predicted to be greatest for susceptible cultivars, suggesting that in the absence of improved resistance to *L. maculans* there will be an even greater need for correctly timed fungicide sprays to control phoma stem canker (West *et al.* 2001; Fitt *et al.* 2006) in the future. The increased temperatures associated with climate change are also predicted to increase the severity of other fungal diseases affecting crops (Anderson *et al.* 2004), forest trees (Bergot *et al.* 2004) and even amphibians (Bosch *et al.* 2007). These predictions emphasize the need for inclusion of disease threats in long-term strategic planning by government and industry of regional and local cropping patterns and crop species, for adaptation to climate change.

They also indicate the importance of breeding crop cultivars with resistance to pathogens, since predicted losses were much less for cultivars with resistance to *L. maculans* (UK mean 0.30–0.59 t ha⁻¹, 9.5–17.6% loss) than for susceptible cultivars (UK mean 0.39–0.79 t ha⁻¹, 12.6–23.5% loss). Use of cultivars with improved disease resistance also helps to mitigate climate change since it increases crop productivity (yield per hectare) per unit of nitrogen fertilizer applied so that greenhouse gas emissions associated with crop production are less (Berry *et al.* 2008; Glendinning *et al.* 2008). Strategies for breeding cultivars with improved resistance to pathogens will need to include trials in countries which today have the climate that the UK is predicted to have in the future. Since some temperature-dependent genes for resistance to pathogens are ineffective at increased temperatures (Huang *et al.* 2006) and epidemics of UK diseases such as phoma stem canker are more severe in the Mediterranean climates of France and Australia (Howlett *et al.* 2001),

such trials will help to identify resistance that can operate effectively under the predicted climates.

The differences between Scotland in the north and England in the south of the UK in the predicted effects of climate change on oilseed rape productivity demonstrate the complexity of the interactions between climate change, crop growth and disease epidemic severity. They confirm that simple, qualitative predictions of such effects are unlikely to be accurate (Coakley *et al.* 1999; Garrett *et al.* 2006) and emphasize the need for more work combining crop and disease models with climate scenarios (Luo *et al.* 1995). However, such work is possible only when good, long-term crop growth, disease severity and weather data sets have been collected and collated. Nevertheless, such work is essential to provide strategic guidance for industry and government policy for adaptation to climate change so that national production is able to meet the food demands of the future. For example, these results suggest that, unless there is effective control of phoma stem canker, it may be necessary to move future production of oilseed rape from the south to the north of the UK. Furthermore, strategies for adapting to climate change will make an invaluable contribution to sustainable crop production (Glendinning *et al.* 2008) and global food security (Morton 2007; Schmidhuber & Tubiello 2007).

We thank the UK Biotechnology and Biological Sciences Research Council (BBSRC) and Department for Environment, Food and Rural Affairs (Defra, OREGIN) and the Sustainable Arable LINK programme (PASSWORD, CORDISOR, CLIMDIS) for funding this research, and the British Society for Plant Pathology for supplementary funding. We also thank Marie Launay (INRA Avignon) for her STICS tutorial and help, Neal Evans (Rothamsted Research), Peter Gladders (ADAS) for the use of their data and advice and Andreas Baierl (University of Vienna), Steve Powers and Rodger White (Rothamsted Research) for advice on the yield loss model.

REFERENCES

- Anderson, P. K., Cunningham, A. A., Patel, N. G., Morales, F. J., Epstein, P. R. & Daszak, P. 2004 Emerging infectious diseases of plants: pathogen pollution, climate change and agrotechnology drivers. *Trends Ecol. Evol.* **19**, 535–544. (doi:10.1016/j.tree.2004.07.021)
- Bergot, M., Cloppet, E., Pérarnaud, V., Déqué, M., Marcais, B. & Desprez-Loustau, M. L. 2004 Simulation of potential range expansion of oak disease caused by *Phytophthora cinnamomi* under climate change. *Global Change Biol.* **10**, 1539–1552. (doi:10.1111/j.1365-2486.2004.00824.x)
- Berry, P. M., Kindred, D. R. & Paveley, N. D. 2008 Quantifying the effects of fungicides and disease resistance on greenhouse gas emissions associated with wheat production. *Plant Pathol.* **57**, 1000–1008. (doi:10.1111/j.1365-3059.2008.01899.x)
- Bosch, J., Carrascal, L. M., Duran, L., Walker, S. & Fisher, M. C. 2007 Climate change and outbreaks of amphibian chytridiomycosis in a montane area of Central Spain; is there a link? *Proc. R. Soc. B* **274**, 253–260. (doi:10.1098/rspb.2006.3713)
- Boys, E. F., Roques, S. E., Ashby, A. M., Evans, E., Latunde-Dada, A. O., Thomas, J. E., West, J. S. & Fitt, B. D. L. 2007 Resistance to infection by stealth: *Brassica napus*

- (winter oilseed rape) and *Pyrenopeziza brassicae* (light leaf spot). *Eur. J. Plant Pathol.* **118**, 307–321. (doi:10.1007/s10658-007-9141-9)
- Brisson, N. *et al.* 2002 STICS: a generic model for the simulation of crops and their water and nitrogen balance. II. Model validation for wheat and corn. *Agronomie* **22**, 69–93. (doi:10.1051/agro:2001005)
- Brisson, N. *et al.* 2003 An overview of the crop model STICS. *Eur. J. Agron.* **18**, 309–332. (doi:10.1016/S1161-0301(02)00110-7)
- Chakraborty, S. 2005 Potential impact of climate change on plant–pathogen interactions. *Australas. Plant Pathol.* **34**, 443–448. (doi:10.1071/AP05084)
- Chakraborty, S., Tiedemann, A. V. & Teng, P. S. 2000 Climate change: potential impact on plant diseases. *Environ. Pollut.* **108**, 317–326. (doi:10.1016/S0269-7491(99)00210-9)
- Coakley, S. M., Scherm, H. & Chakraborty, S. 1999 Climate change and plant disease management. *Annu. Rev. Phytopathol.* **37**, 399–426. (doi:10.1146/annurev.phyto.37.1.399)
- Collins, M., Tett, S. F. B. & Cooper, C. 2001 The internal climate variability of HadCM3, a version of the Hadley Centre coupled model without flux adjustments. *Clim. Dynam.* **17**, 61–81. (doi:10.1007/s003820000094)
- Evans, N., Baierl, A., Semenov, M. A., Gladders, P. & Fitt, B. D. L. 2008 Range and severity of a plant disease increased by global warming. *J. R. Soc. Interface* **5**, 525–531. (doi:10.1098/rsif.2008.1136)
- Ewert, F. *et al.* 2002 Effects of elevated CO₂ and drought on wheat: testing crop simulation models for different experimental and climatic conditions. *Agric. Eco. Envir.* **93**, 249–266. (doi:10.1016/S0167-8809(01)00352-8)
- Fitt, B. D. L., Doughty, K. J., Gladders, P., Steed, J. M. & Sutherland, K. G. 1998 Diagnosis of light leaf spot (*Pyrenopeziza brassicae*) on winter oilseed rape (*Brassica napus*) in the UK. *Ann. Appl. Biol.* **133**, 155–166. (doi:10.1111/j.1744-7348.1998.tb05813.x)
- Fitt, B. D. L., Brun, H., Barbetti, M. J. & Rimmer, S. R. 2006 World-wide importance of phoma stem canker (*Leptosphaeria maculans* and *L. biglobosa*) on oilseed rape (*Brassica napus*). *Eur. J. Plant Pathol.* **114**, 3–15. (doi:10.1007/s10658-005-2233-5)
- Fitt, B. D. L., Hu, B. C., Li, Z. Q., Liu, S. Y., Lange, R. M., Kharbanda, P. D., Butterworth, M. H. & White, R. P. 2008 Strategies to prevent spread of *Leptosphaeria maculans* (phoma stem canker) onto oilseed rape crops in China; costs and benefits. *Plant Pathol.* **57**, 652–664. (doi:10.1111/j.1365-3059.2008.01841.x)
- Garrett, K. A., Dendy, S. P., Frank, E. E., Rouse, M. N. & Travers, S. E. 2006 Climate change effects on plant disease: genomes to ecosystems. *Annu. Rev. Phytopathol.* **44**, 489–509. (doi:10.1146/annurev.phyto.44.070505.143420)
- Gilles, T., Evans, N., Fitt, B. D. L. & Jeger, M. J. 2000 Epidemiology in relation to methods for forecasting light leaf spot (*Pyrenopeziza brassicae*) severity on winter oilseed rape (*Brassica napus*) in the UK. *Eur. J. Plant Pathol.* **106**, 593–605. (doi:10.1023/A:1008701302853)
- Glendining, M. J., Dailey, A. G., Williams, A. G., van Evert, F. K., Goulding, K. W. T. & Whitmore, A. P. 2008 Is it possible to increase the sustainability of arable and ruminant agriculture by reducing inputs? *Agric. Syst.* **99**, 117–125. (doi:10.1016/j.agry.2008.11.001)
- Howlett, B. J., Idnurm, A. & Pedras, M. S. C. 2001 *Leptosphaeria maculans*, the causal agent of blackleg disease of brassicas. *Fungal Genet. Biol.* **33**, 1–14. (doi:10.1006/fgbi.2001.1274)
- Huang, Y.-J., Evans, N., Li, Z.-Q., Eckert, M., Chevre, A. M., Renard, M. & Fitt, B. D. L. 2006 Temperature and leaf wetness duration affect phenotypic expression of Rlm6-mediated resistance to *Leptosphaeria maculans* in *Brassica napus*. *New Phytol.* **170**, 129–141. (doi:10.1111/j.1469-8137.2006.01651.x)
- Hulme, M. *et al.* 2002 Climate change scenarios for the United Kingdom: the UKCIP02 scientific report. University of East Anglia, Norwich, UK.
- Luo, Y., Tebeest, D. O., Teng, P. S. & Fabellar, N. G. 1995 Simulation studies on risk analysis of rice leaf blast epidemics associated with global climate change in several Asian countries. *J. Biogeogr.* **22**, 673–678. (doi:10.2307/2845969)
- Metz, B., Davidson, O. R., Bosch, P. R., Dave, R. & Meyer, L. A. 2007 *Climate change 2007: mitigation of climate change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. New York, NY: Cambridge University Press.
- Morton, J. F. 2007 The impact of climate change on small-holder and subsistence agriculture. *Proc. Natl Acad. Sci. USA* **104**, 19680–19685. (doi:10.1073/pnas.0701855104)
- Nakicenovic, N. 2000 Greenhouse gas emissions scenarios. *Technol. Forecast. Soc.* **65**, 149–166. (doi:10.1016/S0040-1625(00)00094-9)
- Schmidhuber, J. & Tubiello, F. N. 2007 Global food security under climate change. *Proc. Natl Acad. Sci. USA* **104**, 19703–19708. (doi:10.1073/pnas.0701976104)
- Semenov, M. A. 2007 Development of high-resolution UKCIP02-based climate change scenarios in the UK. *Agric. For. Meteorol.* **144**, 127–138. (doi:10.1016/j.agrfor.2007.02.003)
- Semenov, M. A. 2009 Impacts of climate change on wheat in England and Wales. *J. R. Soc. Interface* **6**, 343–350. (doi:10.1098/rsif.2008.0285)
- Stern, N. 2007 *The economics of climate change: the Stern review*. Cambridge, UK: Cambridge University Press.
- West, J. S., Kharbanda, P. D., Barbetti, M. J. & Fitt, B. D. L. 2001 Epidemiology and management of *Leptosphaeria maculans* (phoma stem canker) on oilseed rape in Australia, Canada and Europe. *Plant Pathol.* **50**, 10–27. (doi:10.1046/j.1365-3059.2001.00546.x)
- Zhou, Y., Fitt, B. D. L., Welham, S. J., Gladders, P., Sansford, C. E. & West, J. S. 1999 Effects of severity and timing of stem canker (*Leptosphaeria maculans*) symptoms on yield of winter oilseed rape (*Brassica napus*) in the UK. *Eur. J. Plant Pathol.* **105**, 715–728. (doi:10.1023/A:1008761219493)