North-south divide; contrasting impacts of climate change on crop yields in Scotland and England

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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 non-linear. To investigate these crop-disease-climate interactions, UKCIP02 scenarios predicting UK temperature and rainfall under high- and low-CO_2 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 (15%). By 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% (1.5 t/ha) 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

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1. INTRODUCTION

Worldwide climate change is affecting agricultural crops (Metz *et al.* 2007; Stern 2007) and the diseases that attack them (Garrett *et al.* 2006; Chakraborty 2005). 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). Whilst 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 (Anderson *et al.* 2004; Coakley *et al.* 1999) and there have been few attempts to produce combined crop-disease-climate models (Luo *et al.* 1995).

The increased concentrations of CO_2 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 (500,000 ha) grown 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 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.

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 £12M 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 £500M per season (Fitt *et al.* 2008). Whereas 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 colonise 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. MATERIALS 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 (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 observed weather from the baseline period 1960 to 1990. Using two CO_2 emission scenarios, low (LO) and high (HI), 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 CO_2 concentration in the UK atmosphere were 334ppm (baseline), 422ppm (2020LO), 437ppm (2020HI), 489ppm (2050LO), 593ppm (2050HI), taken from the IPCC emission scenarios. Thirty years of daily weather data were generated for 15 sites located across the UK (electronic supplementary information, 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).

(figure 1 near here)

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 (°C-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 parameters that determine the rate of crop growth in response to radiation were therefore increased by 36% 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 1987-2007 (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 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 develop 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 colonisation 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 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), Dh 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 ^{o}C on day *i:*

$$Sc_p = (0.00135 - 0.00035A) \sum_{i=Dc_p}^{D_h} T_i \qquad (1)$$

The canker severity at harvest (S) is related to the cultivar resistance (A) by the equation:

$$\frac{\Delta S}{S} = \frac{\Delta K}{K} \qquad (2)$$

where:

$$K = 0.00135 – 0.00035A \quad (3)$$

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 information, figures 3 & 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:

$$Y = 99.1 - 15.2S \quad (4)$$

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 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 information, 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 at Withington (1993) with one cultivar and 22 fungicide treatments and from 23 experiments with unsprayed/fungicide-sprayed plots harvested at Boxworth (1997-2002), Rothamsted (1997 and 2000) or High Mowthorpe (2001). 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 information, 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 CO_2 emission scenarios than for the low CO_2 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, predicted for eastern Scotland for the 2050s high CO_2 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.

(figure 2 near here)

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 the baseline, especially in England (figures 3 and 4). They suggest that the greatest losses (up to 50%, i.e. 1.5 t/ha) will be in southern England under the high CO_2 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 CO_2 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% for the 2050s under the high CO_2 scenario.

(figures 3 & 4 near here)

3.3. Regional treated and untreated oilseed rape yield predictions

The total area of oilseed rape grown in the UK in 2006 was around 500,000ha, 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). The total production was greater in England (1,430,000 t) than Scotland (113,000 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 were 264,000 t. 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% (South West) and 10% (North East); conversely, the effect of climate change in Scotland will be to increase the yield by 3%. 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. By 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%) by contrast with a predicted increase for Scotland (4%). These predictions suggest that climate change will increase total production of fungicide-treated winter oilseed rape from the baseline of 2.69 Mt to 2.90 Mt in the 2050HI scenario, with the amount produced in Scotland increasing. By contrast, they suggest that total production of untreated winter oilseed rape in England would decrease from 1.17 Mt under the baseline scenario to 1.04 Mt under the 2050HI scenario but production in Scotland would increase from 109,000 to 113,000 t.

(table 1 near here)

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 CO_2 concentration in the atmosphere which increases radiation use efficiency and yield (Brisson *et al.* 2002, 2003; Semenov 2008). There is evidence that increased concentrations of CO_2 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. Whilst 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. By 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 (Neal Evans, personal communication). Thus use of fungicides on winter oilseed rape in Scotland may no longer be economically justified.

By 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 CO_2 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 emphasise 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 fertiliser applied so that greenhouse gas emissions associated with crop production are less (Berry *et al.* 2008, Glendining *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 emphasise 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 (Glendining *et al.* 2008) and global food security (Morton 2007; Schmidhuber & Tubiello 2007).

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Figure legends

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).

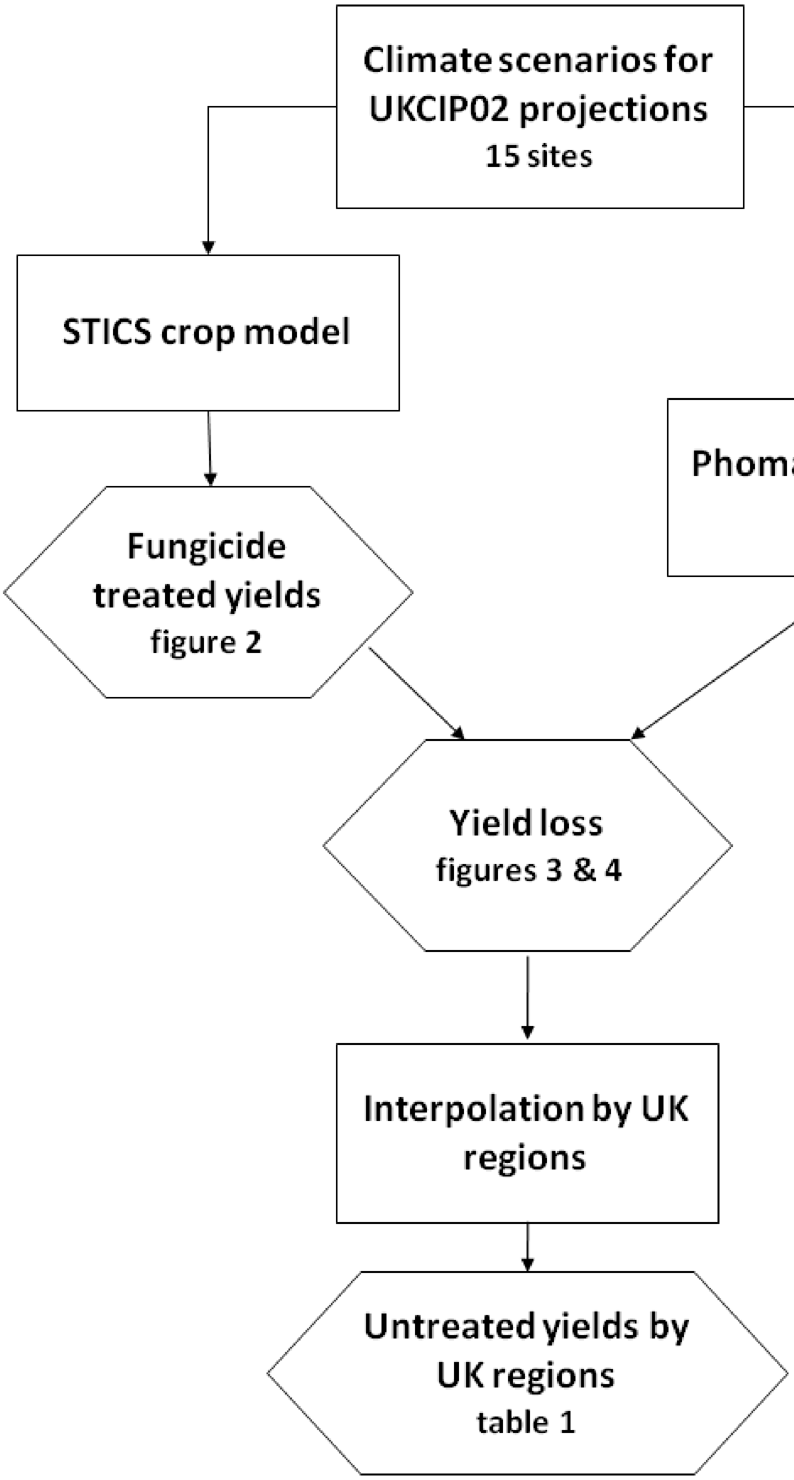
Figure 2. Predicted yield of oilseed rape (treated against diseases). Predicted yields (t ha^{-1}) of fungicide-treated winter oilseed rape for (a) baseline, (b) 2020LO, (c) 2020HI, (d) 2050LO, and (e) 2050HI climates. The maps are interpolated from yield data generated for 15 UK sites using the STICS 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.

Figure 3. Predicted yield loss from phoma stem canker for cultivars susceptible to *Leptosphaeria 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.

Figure 4. Predicted yield loss from phoma stem canker for cultivars resistant to *Leptosphaeria maculans*. Predicted yield loss (% of maximum yield from fungicide-treated plots) from phoma stem canker for susceptible 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.

Figure 1



Climate scenarios for UKCIP02 projections
15 sites
STICS crop model
Phoma stem canker model
Fungicide treated yields
figure 2
Yield loss
figures 3 & 4
Interpolation by UK regions
Untreated yields by UK regions
table 1

Figure 2

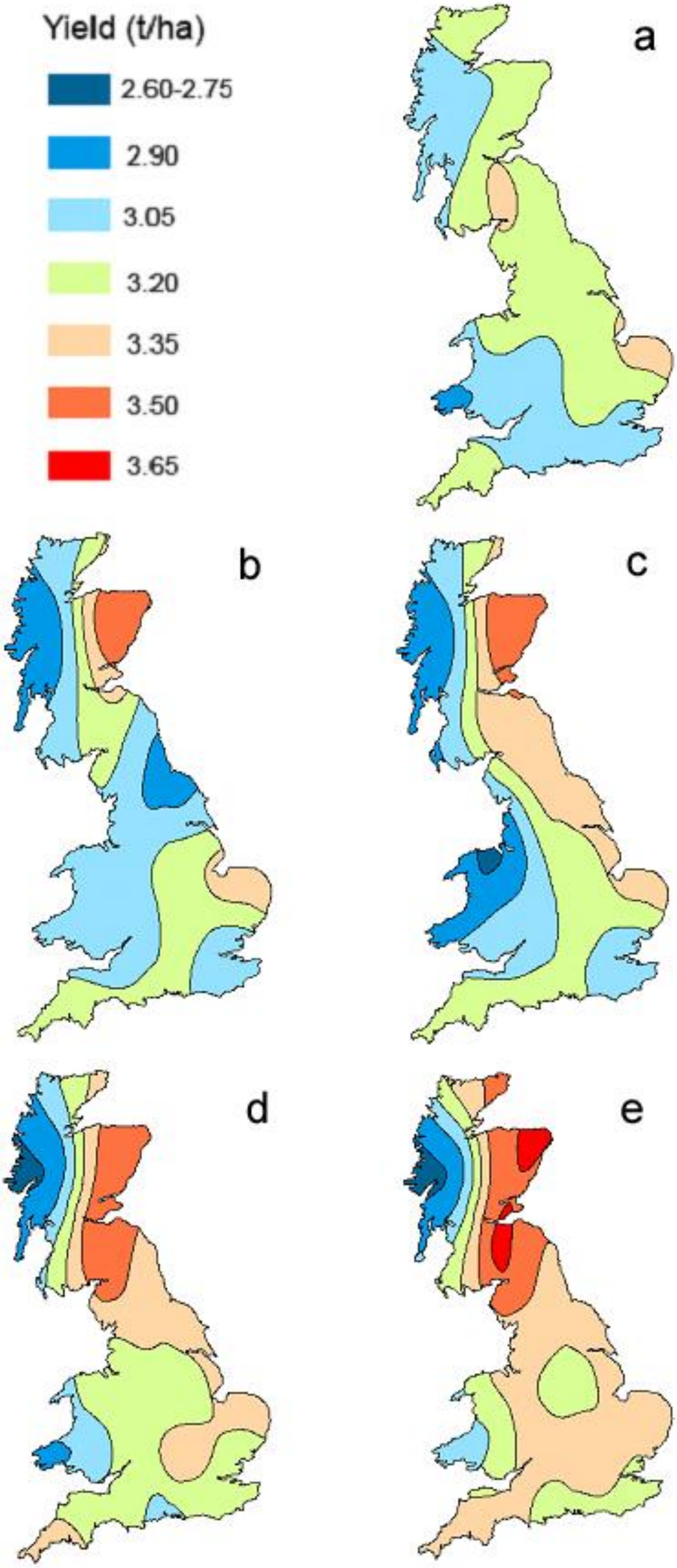


Figure 3

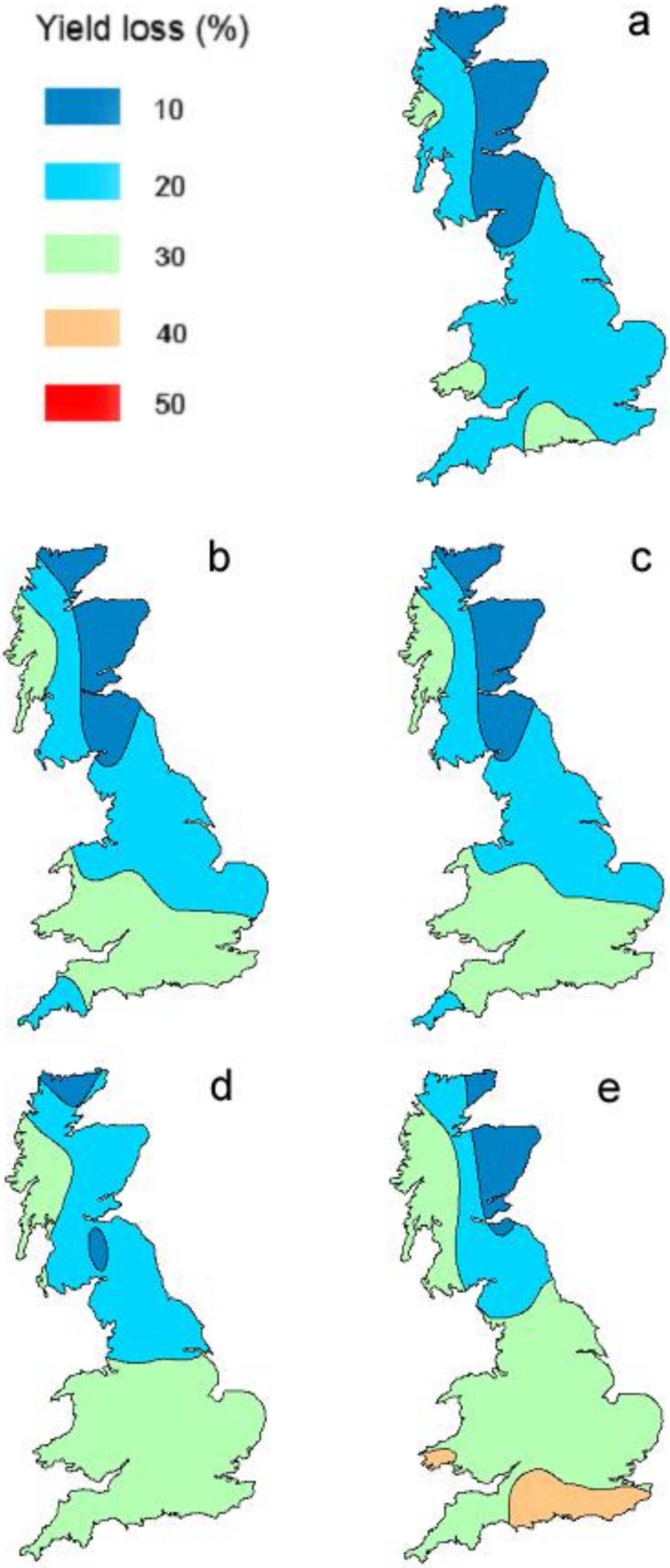


Figure 4

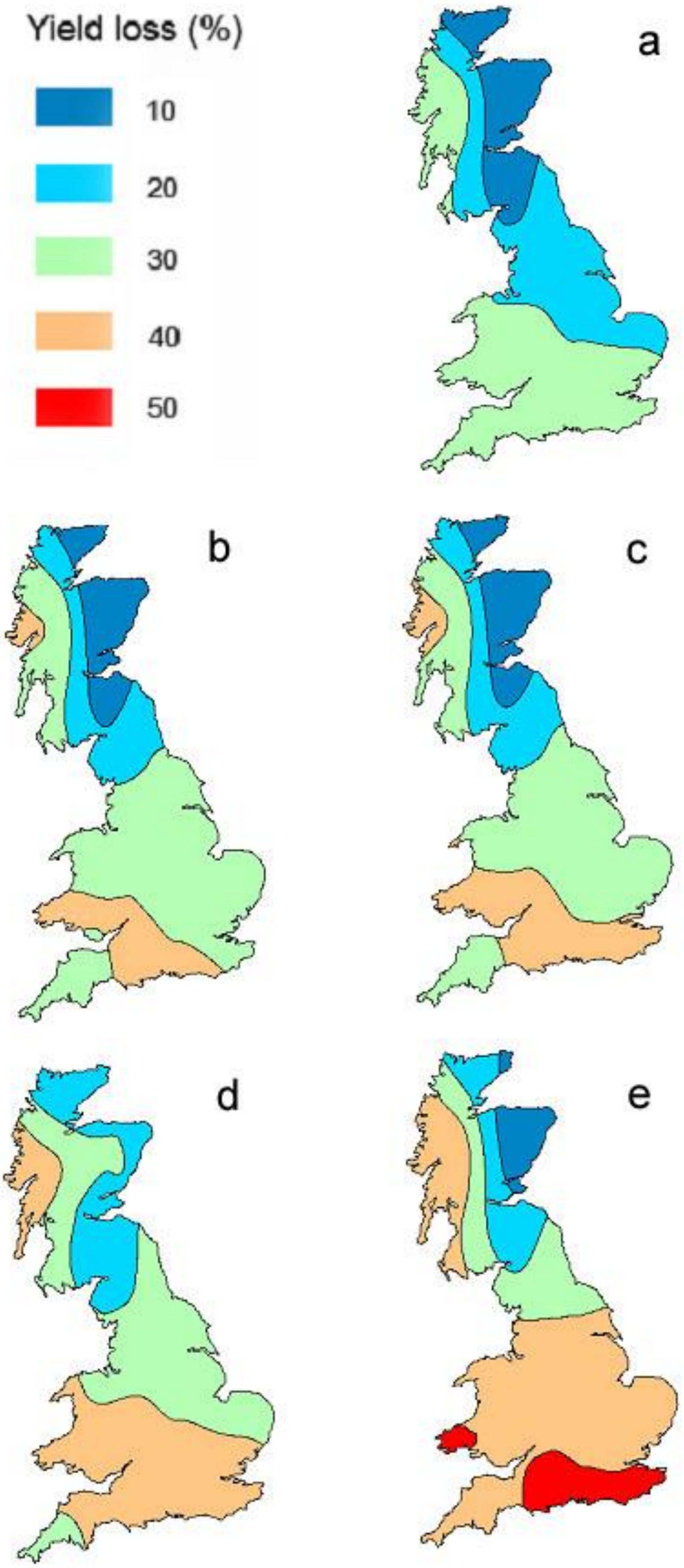


Table 1. Effects of climate change on the yield of treated oilseed rape (Tr) and untreated oilseed rape (Unt) after phoma stem canker losses, calculated by region. The untreated oilseed rape was calculated as the mean of susceptible and resistant cultivars. The area grown per region (2006) and the predicted 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 CO_2 emission), 2020HI (high CO_2 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.

		Baseline yield (t/ha)		Yield (% of baseline yield)							
				2020LO		2020HI		2050LO		2050HI	
Region [a]	Area of oilseed rape grown (ha) [b]	Treated (Tr)	Untreated (Unt)	Tr	Unt	Tr	Unt	Tr	Unt	Tr	Unt
North East	22787	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 & Humberside	61068	3.12	2.64	95.0	90.7	102.8	97.3	102.4	93.8	103.1	89.3
East Midlands	113479	3.11	2.59	100.7	95.2	100.4	94.0	101.1	91.1	102.7	86.9
West Midlands	34419	3.00	2.37	99.6	94.2	83.4	78.2	103.5	94.0	107.6	91.4
Eastern	103488	3.16	2.58	100.0	94.5	99.7	93.1	103.0	92.8	104.7	88.3
London and South East	79063	3.01	2.34	100.8	95.4	100.9	94.4	103.7	93.0	106.9	89.1
South West	44858	3.05	2.41	100.3	95.1	100.5	94.2	103.1	93.7	106.7	90.7
England total	462764	3.09	2.52	99.3	94.1	99.5	93.4	102.6	92.9	104.8	88.9
Scotland	35780	3.15	3.06	104.8	103.2	107.1	105.0	109.7	96.9	111.5	103.6
UK total	498544	3.12	2.77	101.8	98.7	103.0	99.3	105.9	94.9	107.9	96.4

[a] Government regions can be found at http://www.statistics.gov.uk/geography/downloads/uk_gor_cty.pdf
[b] Area of winter oilseed rape grown in each region in harvest year 2006 (www.defra.gov.uk)