Control of arable crop pathogens; climate change mitigation, impacts and adaptation

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Abstract

In the context of threats to global food security from impacts of damaging crop diseases and of climate change, this chapter describes three aspects of the interactions between climate change and diseases that reduce arable crop yields. It considers the role of crop disease control in **climate change mitigation**, by estimating consequences for greenhouse gas (GHG) emissions of crop management strategies to control diseases, using UK oilseed rape and barley crops as examples. It concludes that good control of crop diseases, resulting in more efficient use of nitrogen fertiliser, can decrease UK GHG from crop production by c. 1.6Mt CO_2 eq. each year. It discusses **impacts of climate change** on incidence of crop diseases and their effects on crop yields, using UK oilseed rape phoma stem canker and wheat fusarium ear blight as examples. For both these diseases, it is estimated that global warming will increase the range and severity of epidemics. To make such estimates, it is emphasised that it is important to estimate impacts of climate on both crop growth and disease development. In response to such projections of impacts of climate change, it assesses strategies for **adaptation to climate change** of crop disease management to decrease arable crop losses related to climate change, for both policymakers and farmers.

Key words

Agricultural adaptation to climate change; climate change mitigation; crop diseases; food security; impacts on agriculture.

Introduction

Crop diseases directly threaten global food security because diseases cause crop losses, estimated at 16% globally despite efforts to control the diseases (Fisher *et al*., 2013; Oerke, 2006), in a world where more than 1 billion people do not have enough food (Anon., 2009). Thus, food production must be increased by controlling crop diseases more effectively. Food security problems associated with crop diseases can be exacerbated by climate change (Fitt *et al*., 2011; Garrett *et al*., 2006; Gregory *et al*., 2009). Since the threats of climate change to food security are particularly severe in marginal areas (Schmidhuber & Tubiello, 2007), there is pressure on farmers in fertile areas that may benefit from climate change, such as northern Europe (Butterworth *et al*., 2010), to produce more food to ensure global food security (Stern, 2007). Thus, it is essential to include methods to control disease problems in strategies for adaptation to impacts of climate change (Evans *et al*., 2008; Gregory *et al*., 2009). However, it is also necessary to grow crops in countries such as the UK in a manner that decreases emissions of greenhouse gases (GHG) to contribute now to climate change mitigation from agriculture (Jackson *et al*., 2007; Hughes *et al*., 2011). To decrease the contribution of agriculture to global warming, possible options include decreasing the use of fossil fuels and nitrogen fertilisers, decreasing methane emissions from livestock and increasing the sequestering of carbon from the atmosphere (Glendining *et al*., 2009; Smith *et al*., 2008).

This chapter describes three aspects of the interactions between climate change and diseases that reduce arable crop yields:

- Climate change mitigation; consequences for greenhouse gas (GHG) emissions of crop management strategies to control diseases, using UK oilseed rape and barley crops as examples.
- Impacts of climate change on incidence of crop diseases and their effects on crop yields, using UK oilseed rape phoma stem canker and wheat fusarium ear blight as examples.
- Adaptation of crop disease management strategies to decrease arable crop losses related to climate change.

Crop disease control & climate change mitigation

In 2008, agriculture accounted for 7.7% of UK GHG emissions (48 Mt CO_2-eq.; DECC 2010) and these were primarily in the non-CO_2 sector. As part of the overall 80% emissions reduction strategy, the UK Committee on Climate Change has set a target of a 70% reduction in the non-CO_2 sector by 2050 (Committee on Climate Change 2010). This has prompted debate about how best to decrease GHG whilst maintaining food production. One question in this debate is whether the use of fungicides and other treatments to control crop diseases leads to an increase or decrease in GHG emissions, with the associated environmental consequences.

Mahmuti *et al*. (2009) calculated the GHG emissions for production of 1 t of winter oilseed rape seed. The differences in yields between fungicide-treated and untreated plots were then analysed to estimate the effects of fungicides on GHG emissions per tonne of seed. This was done for data from UK winter oilseed rape experiments in harvest years 2004 to 2007 (Figure 1). The analysis takes account of GHG emissions associated with the manufacture and application of fertilisers and fungicides, and with the field operations of spraying, harvesting, drying etc. The production of 1 ha of winter oilseed rape was estimated to release emissions of 3337 kg CO_2 eq. The GHG emissions per tonne of seed produced decreased as the yield of the seed increased; the difference in GHG emissions per tonne between yields of 1 and 3 t ha^{-1} was 2225 kg CO_2 eq. t^{-1}. In the series of experiments over 4 years, mean yields were 4.33 t ha^{-1} for fungicide-treated crops and 3.84 t ha^{-1} for untreated crops. Thus the disease-induced yield loss of approximately 11.3% of the fungicide-treated winter oilseed rape yield was associated with a net increase in emissions of 98 kg CO_2 eq. t^{-1} for winter oilseed rape. Crop yields depend on many factors and vary from year to year but the same results were obtained in a wide range of comparisons. One important factor was the extent to which different cultivars of oilseed rape were susceptible or resistant to pathogens such as *P. brassicae* or *L. maculans*. Cultivar resistance provides not only the direct benefit of greater yields but also the indirect benefit of reduced GHG emissions per tonne of seed produced. However, such resistance tends to have limited effectiveness against changing virulence in the pathogen population. This raises further questions about how best to deploy resistant cultivars to obtain most benefit from them.

(Figure 1 near here)

Hughes *et al*. (2011) did similar calculations for 28 cultivars of winter and spring barley, grown at 24 UK sites. The inputs to growing winter barley (including fungicides) were estimated to release emissions of 2617 kg CO_2 eq. ha^{-1}. The corresponding emissions for spring barley were 20% less (2099 kg CO_2 eq. ha^{-1}), mainly because nitrogen inputs were smaller. These estimates are smaller than comparable estimates for oilseed rape (Mahmuti *et al.*, 2009) and wheat (Berry *et al*., 2008), mainly because average rates of fertiliser application to barley crops are smaller. Across all datasets, fungicide treatment reduced GHG emissions by 42–60 kg CO_2 eq. t^{-1} (11–16%) for winter barley and by 29–39 kg CO_2 eq. t^{-1} (8–11%) for spring barley. The reductions in GHG emissions were larger when fungicide treatment was more effective in increasing yields. In addition, the decrease in GHG emissions was generally greater for winter barley than for spring barley, because winter barley production emits more GHGs than spring barley production. There were reductions in GHG emissions across a wide range of comparisons. A sensitivity analysis confirmed that disease control continues to give reductions in GHG emissions, even if alternative, substantially greater values were used for the emission factors associated with agricultural pesticides.

Combining the decreases in GHG emissions associated with disease control in UK winter wheat, winter oilseed rape, winter barley and spring barley crops, Hughes *et al.* (2011) estimated that for the UK such disease control in arable crops decreased GHG by c. 1.6Mt CO_2 eq. each year from 2005 to 2009 (Figure 2), making a substantial contribution to government targets for decreasing GHG associated with agriculture.

(Figure 2 near here)

There are also more general effects to consider. Suppose arable crop yields were to decrease in future. This could happen for a number of reasons, including climate change, the arrival of new crop diseases in UK, greater susceptibility to existing diseases or reductions in the types or quantities of permitted fungicides. To maintain UK production at the same level as today, more arable land would be needed. Mahmuti *et al*. (2009) estimated that an additional 680,000 ha would be required to sustain UK agricultural production at 2007 levels, if crops were untreated rather than sprayed with fungicides. This area represents land that could otherwise be used to grow more food or biofuel crops, or as a wildlife habitat. Furthermore, since both biomass and soil organic carbon are typically released when uncultivated land is cultivated, use of such land for crops can increase GHG emissions. Taking 200 t CO_2 eq. ha^{-1} as an estimate of the GHGs emitted by converting temperate grassland into arable crop land, the conversion of 688,000 ha UK grassland to agricultural crops would release more than 100 Mt CO_2.

Generally speaking, measures that decrease crop yields (e.g. reduced use of fungicides and N fertilisers) are likely to result in an overall increase in GHG emissions, due to the necessary expansion of land under cultivation (Berry *et al.*, 2010; Burney *et al*., 2010; Carlton *et al*., 2012). On the other hand, certain soil fertility management practices associated with organic crop farming have the potential to sequester soil organic carbon (SOC) in long-term arable land (Azeez, 2009) and a reduction in inputs can decrease emissions (Lin *et al*., 2011).

Carlton *et al*. (2012) compared the annual GHG emissions from UK arable production under the conventional (current) crop production system with the emissions predicted assuming the nationwide adoption of reduced tillage, organic or integrated arable systems whilst maintaining current crop production. The ‘reduced tillage’ arable system is similar to conventional crop production except that reduced tillage methods are adopted wherever practical (not usually for crops requiring considerable soil cultivation, such as potatoes, sugar beet etc.). The 'organic' arable system assumes that there are no applications of synthetic crop protection products or synthetic fertilisers, and that crop rotations include fertility-enhancing periods. The 'integrated' crop production system integrates the high yields of conventional crop production with the SOC sequestration of organic crop production, employing fertility enhancing rotations and use of organic manure to augment soil organic carbon, but allowing use of additional synthetic fertilisers, fungicides for disease control and other crop protection products to achieve conventional crop yields.

This analysis suggests that conventional farming, plus reduced tillage cultivation where appropriate, can best contribute to the achievement of government GHG emissions targets. The reduced tillage system demonstrated a modest (< 20%) reduction in emissions in all cases, although in practice it may not be suitable for all soils and is likely to cause problems with control of diseases spread on crop debris. However, there were substantial increases in GHG emissions associated with the organic and integrated systems nationally, principally due to soil organic carbon losses from land use change. The integrated system includes a 50% fertility-enhancing rotation, which increases the total average UK arable area (currently about 6 Mha) by 2.7 Mha. The area of arable land under the organic system would be more than double the arable area under the conventional system through the combined impacts of smaller yields and the 50% fertility-enhancing rotation.

It is important to recognise that local or regional factors can greatly affect the conclusions from studies such as these. For example, soil water losses are likely to become increasingly important in the south and east of England, where climate change is predicted to lead to drier summers. Reduced tillage can reduce such losses, but can also increase the severity of disease epidemics caused by residual inoculum on crop debris. This is a small example of a general conclusion from these studies, that the interaction between climate change, GHG emissions, crop diseases and agricultural production is very complicated. In addition, all crop management systems must operate within cultural and economic constraints.

Impacts of climate change on crop diseases

There is a need to evaluate impacts of climate change on disease-induced losses in crop yield to guide government and industry policy and planning for adaptation to climate change. It is essential to identify now those current crop diseases that may increase in severity or range and those pathogens that may spread to new areas. Impacts of climate change on crop yields may be especially severe in developing countries, where food security problems are already most acute because diseases can destroy crops and cause famine for subsistence farming families who have few alternatives to their staple crops (Strange & Scott, 2005). There is an urgent need to identify potential impacts of climate change on crop diseases now because it can take 10-15 years to breed a new crop cultivar or develop a new fungicide (Fitt *et al*., 2011) and implementation of policy changes in agriculture also takes time since farmers are often reluctant to change long-established practices.

Methods to assess potential impacts of climate change on crop disease-induced losses have improved greatly over the last few years. Early attempts to assess such impacts used qualitative, rule-based reasoning that could not easily accommodate the complex host-pathogen-environment interactions involved (Coakley *et al*., 1999; Anderson *et al*., 2004). This work did not use simulated weather generated by general circulation models but relied on predictions of fixed changes in temperature and rainfall. Little of this work was based on data that was extensive enough to allow use of separate independent data sets for model development and model validation, respectively. This work did not always clearly distinguish between direct impacts and indirect impacts of climate change on crop diseases. Indirect impacts of climate change on crops are extremely difficult to assess, let alone to model. For example, increasing temperature in the UK may have contributed to the increase in the area of maize grown, which may in turn have contributed to the increase in incidence of the mycotoxin-producing *Fusarium graminearum*, since maize debris is a potent source of inoculum of this pathogen (West *et al*., 2012a).

However, direct impacts of changes in weather patterns as a result of climate change can be modelled more easily. General circulation models were used as a basis for projections of an increase in the range of *Phytophthora cinnamomi* disease on oak trees in France (Bergot *et al*., 2004). Intergovernmental Panel on Climate Change (IPCC) global high and low CO_2 emission scenarios (Nakicenovic 2000) were used as a basis UKCIP02 climate change projections for the 2020s and 2050s, using regional climate models, by comparison with a baseline period (1960-1990) (Hulme *et al*., 2002). UKCIP02 provides predicted changes in monthly climate variables on a 50km grid. The LARS-WG weather generator used UKCIP02 projections to produce yearly site-specific daily weather for the 2020s and 2050s (Semenov, 2007). Simulated daily weather for 70 years was used to project an increase in the range and severity of phoma stem canker on UK oilseed rape (Evans *et al*., 2008). Later work has been able to use new IPPC climate change scenarios; for work on projections of fusarium ear blight in China, the A1B climate change scenario was used (Zhang *et al*., 2014). It is important to assess the impacts of climate change on both crop growth and the disease epidemiology; to ignore one of them can produce inaccurate projections (Butterworth *et al*., 2010; Madgwick *et al*., 2011).

There are a number of steps required to assess such impacts (Figure 3; Madgwick *et al*., 2011). Firstly, there is a need to assemble a good set of observed crop growth, disease incidence/severity and weather data. Generally, at least 10 years of data from a range of sites in the region of interest is required. These data can then be divided into two parts. Two thirds of the data can be used for model construction and the remainder used to provide an independent data set for model validation; it is important that both data sets span the range of sites and years. In the case of fusarium ear blight, the data required were the date of anthesis (since the crop is susceptible only at this growth stage; Xu *et al*., 2002, 2009), incidence of fusarium ear blight, temperature and rainfall.

(Figure 3 near here)

Having assembled the data, it is then necessary to produce weather-based crop growth and disease incidence/severity models. Such models need to be simple and should not include parameters for which simulated weather associated with different climate change scenarios cannot be generated. There may be an existing crop growth model that can be calibrated for the region of interest; for example the SIRIUS wheat growth model (Jamieson *et al*., 1998) was used for work on fusarium ear blight (Madgwick *et al*., 2011) and the STICS oilseed rape growth model (Brisson *et al*., 2003) was used for work on phoma stem canker (Butterworth *et al*., 2010); the STICS model was developed in France but the radiation use efficiency parameter was modified so that the model fitted oilseed rape yields in the UK. It is frequently the case that weather-based disease models developed elsewhere do not fit the region of interest and new region-specific models have to be developed (Madgwick *et al*., 2011; Zhang *et al*., 2014). When these weather-based crop growth and disease incidence/severity models have been developed, it is necessary to validate them with independent data.

In parallel, it is necessary to produce simulated weather data for the region and climate change scenario of interest. In UK work with phoma stem canker of oilseed rape and fusarium ear blight of wheat, these weather data were provided by the LARS-WG stochastic weather generator (Semenov, 2007), whereas in the Chinese work with fusarium ear blight (Zhang *et al*., 2014) they were provided by PRECIS (Jones *et al*., 2004). These simulated weather data can then be inputted into the crop and disease models to estimate the impacts of climate change on the disease at sites in the specific region for the selected climate change scenario (Evans *et al*., 2008; Madgwick *et al*., 2011; Zhang *et al*., 2014). Whilst the outputs of such assessments of impacts of climate change on crop diseases are generated for specific sites, they can be converted into maps by spatial interpolation between those sites (Figure 4). Thus it was projected that the climate change will increase incidence of wheat fusarium ear blight and severity of phoma stem canker in the UK, especially in Southern England (Evans *et al*., 2008; Madgwick *et al*., 2011).

(Figure 4 near here)

By using yield loss formulae relating yield loss (t/ha) to incidence or severity of a specific disease, these data then can be used to estimate the losses associated with diseases under different climate change scenarios. For example, Butterworth *et al*. (2010) combined the STICS oilseed rape crop growth model with simulated weather to project that yields of oilseed rape in which diseases are controlled will increase in the 2020s and 2050s under both high and low CO_2 emission scenarios, especially in Scotland but also in some regions of England (Table 1). By contrast, when phoma stem canker was not controlled, there was a projected decrease in yield, especially in southern England. Subsequently, further work included light leaf spot disease, which is generally most severe in Scotland, by comparison with phoma stem canker, which is generally most severe in southern England. When crop prices were added, it was possible to estimate impacts of climate on values of crop disease losses in different regions of England and Scotland (Tables 2 & 3; Evans *et al*., 2010). Such projections can help to guide forward financial planning, although they involve various assumptions about changes in prices with time. Such assumptions must be clearly stated.

(Tables 1, 2 & 3 near here)

Whilst these projections apply to specific diseases, it is also possible to classify diseases into groups according to specific aspects of their pathogen life cycle in relation to climate change projections (West *et al*., 2012b). It is important to realise that there are uncertainties in such projections, associated with uncertainties in the projected weather, crop growth or disease models. Nevertheless, such projections are widely appreciated by politicians who have to make long-term policy decisions based on the best available projections. There has never been a time when guidance on climate change and crop diseases is more clearly appreciated to guide strategies for adaptation to climate change.

Adaptation of crop disease control to climate change

Various adaptation strategies are available to minimise or negate predicted climate change related increases in yield loss from phoma stem canker in UK winter oilseed rape production (Barnes *et al*., 2010). A number of forecasts for crop yield, national production and subsequent economic values are presented, providing estimates of impacts on both yield and value for different types of adaptation. Under future climate change scenarios, there will be increasing pressure to maintain or increase crop yields. Losses can be minimised in the short term (up to 2020) with an autonomous adaptation strategy, which essentially requires some farmer-led changes towards best management practices. However, the predicted impacts of climate change can be negated and, in most cases, improved upon, with planned adaptation strategies. This requires increased funding from both public and private sectors and more directed efforts at adaptation from the producer. Most literature on adaptation to climate change has been conceptual with little quantification of impacts. Quantifying the impacts of adaptation is essential to provide clearer information to guide policy and industry approaches to mitigate future climate change risk.

As indicated, adaptation can be autonomous (i.e. without a conscious strategy) or planned and implemented by the public sector. Farmers may adopt autonomous adaptation to optimise their return on investment (Fig. 5). This adaptation may include includes less frequent use of oilseed rape crops in rotations to reduce the incidence of phoma stem canker and increase yield. Similarly, cultivar choice and the timing of sowing seeds can be optimised to increase yield. Furthermore, improved timing and frequency of fungicide applications will help to increase crop yields in the short term. However, planned adaptation may be beneficial to mitigate impacts of climate change on disease-related yield losses. Investment from the private sector should make more effective fungicides for use on oilseed rape available by the 2020s. Moreover, public and private investment, to exploit recent development in our understanding of both host and pathogen genomics, should produce new cultivars with more durable disease resistance. Both advances are expected to increase crop yield and contribute to global food security. The impacts of these two adaptation strategies were modelled to guide government policy and strategic industrial decision making (Barnes *et al*., 2010).

(Figure 5 near here)

The yield of winter oilseed rape infected by the phoma stem canker pathogen *Leptosphaeria maculans* was assessed (Fig. 6). Yields were predicted to decrease during the period from the 2020s to the 2050s because occurrence of *L. maculans* is projected to increase under climate scenarios with low or high CO_2 emissions (Butterworth *et al*., 2010).

However, autonomous adaptation involving adopting the best management practices will result in increased yields, even in the short term. Even greater yields are possible in the short term if planned adaptation strategies are also adopted. Adoption of a planned adaptation strategy would benefit the industry in the whole of the UK benefits, although yield increases would be greater in England than in Scotland by the 2050s.

(Figure 6 near here)

The economic benefit of different adaptation strategies was calculated, based on the predicted yield responses (Fig. 6, Barnes *et al*., 2010). The value of the crop was based on an average price for the period from 2002 to 2008. Future values were discounted using UK Treasury recommended discount factors of 3.5% and 3% for 2020 and 2050, respectively. Without adaptation, the value of the crop was expected to decrease from 2020 to 2050. For England and, to a lesser extent, for Scotland, the economic benefit of planned adaptation would be particularly good in the short term. The benefits of adopting a planned adaptation strategy would therefore greatly outweigh the expenditure on research and knowledge transfer by 2020. Interestingly, crop value would still increase until 2050 when autonomous adaptation is implemented, whereas the financial benefits decrease in the case of planned adaptation although this decrease is less than in the absence of adaptation. Discounting may therefore affect the value more when planned adaptation is used. Over the whole period, however, planned adaptation performs better than autonomous adaptation.

Experimental work confirms that an increase in temperature, which is projected under all climate change scenarios, will increase phoma stem canker severity (Huang *et al.*, 2006). An important contributor to the increased susceptibility of oilseed rape cultivars to *L. maculans* at increased temperature is the temperature sensitivity of certain resistance (*R*) genes (e.g. *Rlm6*, Huang *et al.*, 2006). The propensity of certain genes for resistance against *L. maculans* to become ineffective at elevated temperatures can place a burden on breeders to develop disease resistance in cultivars that is both environmentally stable and durable. Certainly, the use of genetic backgrounds with quantitative resistance will be an important component of breeding programmes (Brun *et al*., 2010).

Conclusions

These results show that disease control in arable crops can contribute to both climate change mitigation and global food security. They suggest that disease control should be included in policy options for decreasing GHG emissions from agriculture (Smith *et al*., 2008). Thus, controlling diseases in UK winter oilseed rape and barley gives benefits in terms of decreased GHG per tonne of crop produced and increased yield to contribute to food production in northern Europe in response to climate change threats to global food security (Stern, 2007). These decreases in GHG are especially associated with more efficient use of nitrogen fertiliser applied to the crop (Glendining *et al*., 2009). Furthermore, the climate change mitigation benefits associated with disease control in UK winter oilseed rape are relatively greater than those associated with disease control in winter wheat (Berry *et al*., 2008) or winter or spring barley Hughes *et al*., 2011). It is also likely that there will be climate change mitigation benefits from disease control in other arable crops in different regions of the world.

These results with diseases of UK oilseed rape demonstrate how climate change can increase losses from crop diseases. For UK winter oilseed rape, the increase in losses is associated with the increase in range and severity of phoma stem canker with global warming (Butterworth *et al*., 2010; Evans *et al*., 2008). Predicted losses from canker are substantial even though they may be offset by decreasing losses from light leaf spot. This work illustrates how, worldwide, increased disease losses may be associated with increases in severity of existing diseases or spread of diseases to new areas to threaten crop production (Garrett *et al.,* 2006; Gregory *et al.*, 2009). Thus, there is a risk that the 16% of crop production lost to diseases (Oerke, 2006) may increase, with serious consequences for the 1 billion people who do not have enough to eat (Anon., 2009; Strange & Scott, 2005), unless appropriate strategies for adaptation to this effect of climate change are put in place. To guide government and industry strategies for adaptation to climate change, there is an urgent need for reliable predictions of impacts of climate change on different diseases, obtained by combining impacts on crop growth and on disease epidemics with predicted future weather patterns (Barnes *et al.,* 2010). Since it may take 10-15 years to develop a new fungicide or incorporate resistance to a crop pathogen from a novel source of resistance, it is important to identify future target diseases now.

In a world where climate change is exacerbating the food security problems for communities farming in marginal environments (Schmidhuber & Tubiello, 2007), it is essential to develop better strategies for controlling crop diseases as a contribution to global food security. There is an urgent need to decrease current global average crop losses to diseases from 16% (Oerke, 2006), especially since disease losses are often much greater in crops grown by subsistence farmers in marginal areas. It is environmentally preferable to increase food production by decreasing losses to diseases rather than by expanding the area cultivated with crops, which will lead to destruction of rainforests and other natural ecosystems and increases in GHG emissions. Disease resistance breeding, fungicides and cultural methods can all contribute to strategies to decrease disease losses but they need to be carefully integrated into disease management strategies appropriate for the relevant farming system. There is a need to optimise disease control to maximise crop production in northern Europe both as a contribution to global food security in the face of climate change (Stern, 2007) and to maintain the yields and profitability of European farms and thus provide food security for their farming families.

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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[c].

Region [a]	Area oilseed rape (ha) [b]	Baseline yield (t/ha)		Yield (% of baseline yield)							
				2020LO		2020HI		2050LO		2050HI	
		Tr	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
Yorks & 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 & 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)
[c] Based on Butterworth *et al*. (2010), with corrected data for Scotland and UK total

Table 2 Effects of climate change on the output of winter oilseed rape (treated with fungicide), calculated by region. The area grown per region (2006) and the predicted regional output are given for the baseline (1960-1990), 2020LO (low CO_2 emissions), 2020HI (high emissions), 2050LO and 2050HI climate scenarios and presented in thousands of pounds (£000s). The yield figures were calculated after interpolating the results from the oilseed rape yield predictions according to UK government region and then multiplied by an average price of £195.60 t^{-1}.

	Value of oilseed rape crop (£000s) [b]				
Region [a]	Baseline	2020LO	2020HI	2050LO	2050HI
North East	14,098	13,168	14,536	14,646	14,812
North West	2,097	2,024	1,861	2,115	2,169
Yorkshire & Humberside	37,220	35,342	38,251	38,126	38,358
East Midlands	69,007	69,480	69,277	69,744	70,874
West Midlands	20,194	20,121	16,839	20,900	21,726
Eastern	63,885	63,854	63,661	65,792	66,907
London and South East	46,508	46,867	46,939	48,216	49,700
South West	26,742	26,831	26,873	27,570	28,538
England total	279,749	277,688	278,237	287,110	293,085
Scotland	22,038	23,086	23,600	24,182	24,567
UK total	301,787	300,774	301,837	311,292	317,652

[a] Government regions can be found at http://www.statistics.gov.uk/geography/downloads/uk_gor_cty.pdf

[b] This table is based on a table in Evans *et al.* (2010), with corrected data for Scotland and UK total.

Table 3 Effects of climate change on losses from phoma stem canker and light leaf spot (for cultivars with average resistance) in winter oilseed rape crops not treated with fungicide. Values are given for the baseline (1960-1990), 2020LO (low CO_2 emissions), 2020HI (high emissions), 2050LO and 2050HI climate scenarios and presented in thousands of pounds (£000s). Figures were calculated after interpolating results from stem canker and light leaf spot yield loss predictions according to UK government region and then multiplied by an average price of £195.60 t^{-1}.

	Value of losses caused by phoma stem canker and light leaf spot (£000s)[b]				
Region [a]	Baseline	2020LO	2020HI	2050LO	2050HI
North East	3,431	3,526	3,934	4,208	4,630
North West	520	533	501	602	676
Yorks & Humberside	7,804	8,118	9,074	9,661	10,874
East Midlands	15,116	16,869	17,567	18,871	21,748
West Midlands	5,038	5,539	4,716	6,244	7,308
Eastern	14,481	16,179	16,582	18,454	21,359
London & South East	12,388	13,540	13,874	15,381	17,882
South West	7,910	8,198	8,337	8,996	10,191
England total	66,690	72,502	74,584	82,417	94,668
Scotland	7,109	7,663	7,901	10,240	9,067
UK total	73,890	80,165	82,485	92,657	103,735

[a] Government regions can be found at http://www.statistics.gov.uk/geography/downloads/uk_gor_cty.pdf

[b] The stem canker and light leaf spot loss predictions depend on the crop yield predictions in Table 2 of Evans *et al*. (2010). This table is based on a table in Evans *et al.* (2010), with corrected data for Scotland and UK total.

Figure legends

Figure 1 Differences in greenhouse gas (GHG) emissions per tonne of yield between winter oilseed rape crops (means of 24-39 cultivars at 4-7 different sites) treated with fungicides to control phoma stem canker and light leaf spot diseases (■) and untreated crops (■) in HGCA field experiments), at sites differing in epidemic severity. The numbers of sites where the data were available for both treated and untreated crops were 5 (2004), 7 (2005), 6 (2006) and 4 (2007). The numbers of cultivars used in different years were 26 (2004), 39 (2005), 24 (2006) and 29 (2007). Adapted from Mahmuti *et al*., 2009.

Figure 2. Estimated decrease in GHG emissions (Mt CO2 eq.) through use of fungicides to control diseases and increase yields in winter wheat (■), winter oil seed rape (■) winter barley (■) and spring barley (□) for the United Kingdom in harvest years 2005–2009. Total decreases in GHG emissions are 15% (2005), 14% (2006), 15% (2007), 14% (2008) and 13% (2009) of the estimated total GHG emissions (Mt CO_2 eq.) if these four crops were grown without fungicide treatment. Adapted from Hughes *et al.* (2011).

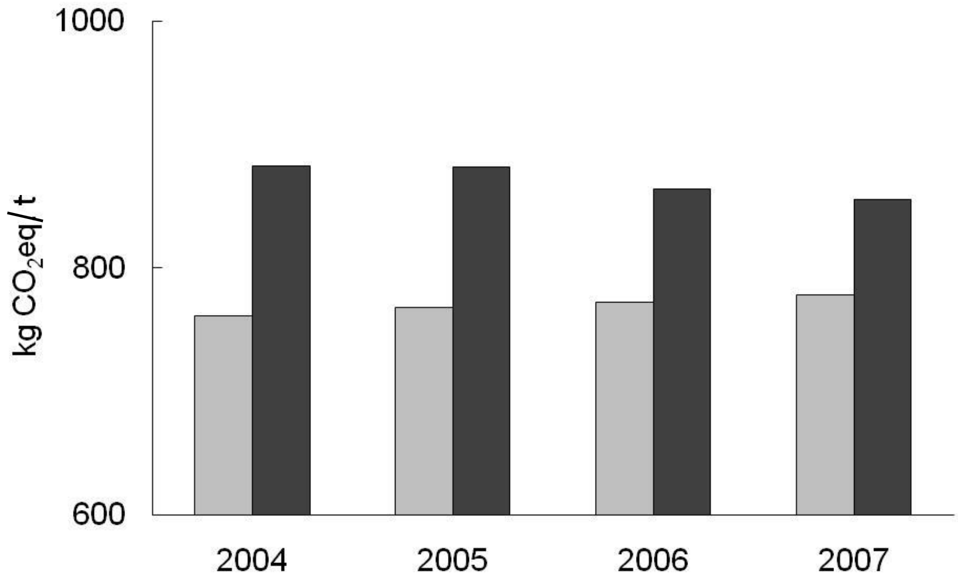
Figure 3. An illustration of how the different models were combined to produce projections of date of winter wheat anthesis (growth stage 65) and fusarium ear blight (FEB) incidence (% plants affected) for different climate change scenarios. (1) Observed data for weather (daily minimum and maximum temperature (ºC), total rainfall (mm) and solar radiation (MJ day^{-1})), date of anthesis and fusarium ear blight incidence were collated from a number of sources for different regions of the UK for the years 1994-2008. (2) The dates of anthesis predicted using the wheat growth model SIRIUS were validated by comparing predicted anthesis dates for winter wheat cv. Consort, generated by SIRIUS using observed weather data, with observed anthesis dates for the same sites for the period 1997-2004. (3) A fusarium ear blight model was developed from data for fusarium ear blight incidence from sites within 80km of Rothamsted and observed weather for Rothamsted for the period 1994-2008; the model related fusarium ear blight incidence to average May temperature and rainfall in the second week of June (time of observed anthesis dates for Rothamsted). (4) Predictions of average percentage of plants affected by fusarium ear blight were validated by comparing predictions made using observed weather to observed fusarium ear blight incidence data for the period 1994-2008 for different regions of the UK (northeast, southwest and east England) which were plotted as north (northeast) and south (southwest and east) England on the validation graph. (5) Weather data were generated using LARS-WG for each of the 14 sites for each climate scenario; baseline (based on the statistical variability (or patterns) in observed weather variables in the period 1960-1990) and high CO_2 and low CO_2 emissions scenarios for the 2020s and 2050s (2020LO, 2020HI, 2050LO and 2050HI). (6) The dates of anthesis for cv. Consort were projected for each site for each climate scenario using SIRIUS, allowing maps to be generated to show the effect of climate change on date of anthesis. (7) Using the weather generated by LARS-WG and average date of anthesis projected using SIRIUS for each of the sites for each of the five climate scenarios, the fusarium ear blight model was used to project fusarium ear blight incidence for each site for each of the five climate scenarios. Adapted from Madgwick *et al.* (2011).

Figure 4 Maps showing the projected average fusarium ear blight incidence (% plants affected) generated by the fusarium ear blight model using the estimated average anthesis dates for three climate change scenarios; (a) baseline, (b) 2050LO and (c) 2050HI. The baseline scenario is based on the patterns in observed weather from 1960-1990, and the other scenarios are high CO2 (HI) and low CO2 (LO) emissions scenarios for the 2050s. The maps were produced by spatial interpolation between 14 sites of weather stations distributed across the arable area of the UK.

Figure 5. Seasonal development of winter oilseed rape in the UK in relation to farmer-led autonomous adaptation strategies (modified according to Barnes et al., 2010). Seeds are sown in late

summer, rosettes develop in late autumn and stem extension occurs in late winter, followed by flowering in the spring and harvest in the summer. Farmer-led adaptation strategies include crop rotation, cultivar choice (based on HGCA recommended lists) and sowing date to optimize yield. Farmers also optimize the timing and frequency of fungicide sprays based on forecasting (www.rothamsted.ac.uk/phoma-leaf-spot-forecast).

Figure 6. Impacts of different adaptation strategies on total production (a) and present value (b) of winter oilseed rape under different climate change scenarios. Impacts of autonomous (Auto), planned (Plan) or no adaptation (None) were determined. Crops grown in England and Wales (Eng) or Scotland (Sco) were considered. High (HI) or low (LO) CO_2 emission scenarios were compared (modified according to Barnes et al., 2010).



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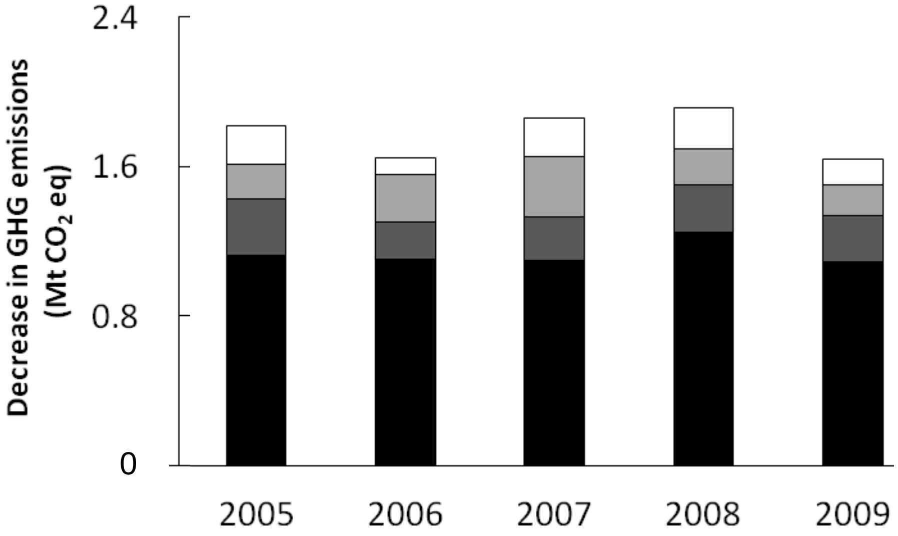

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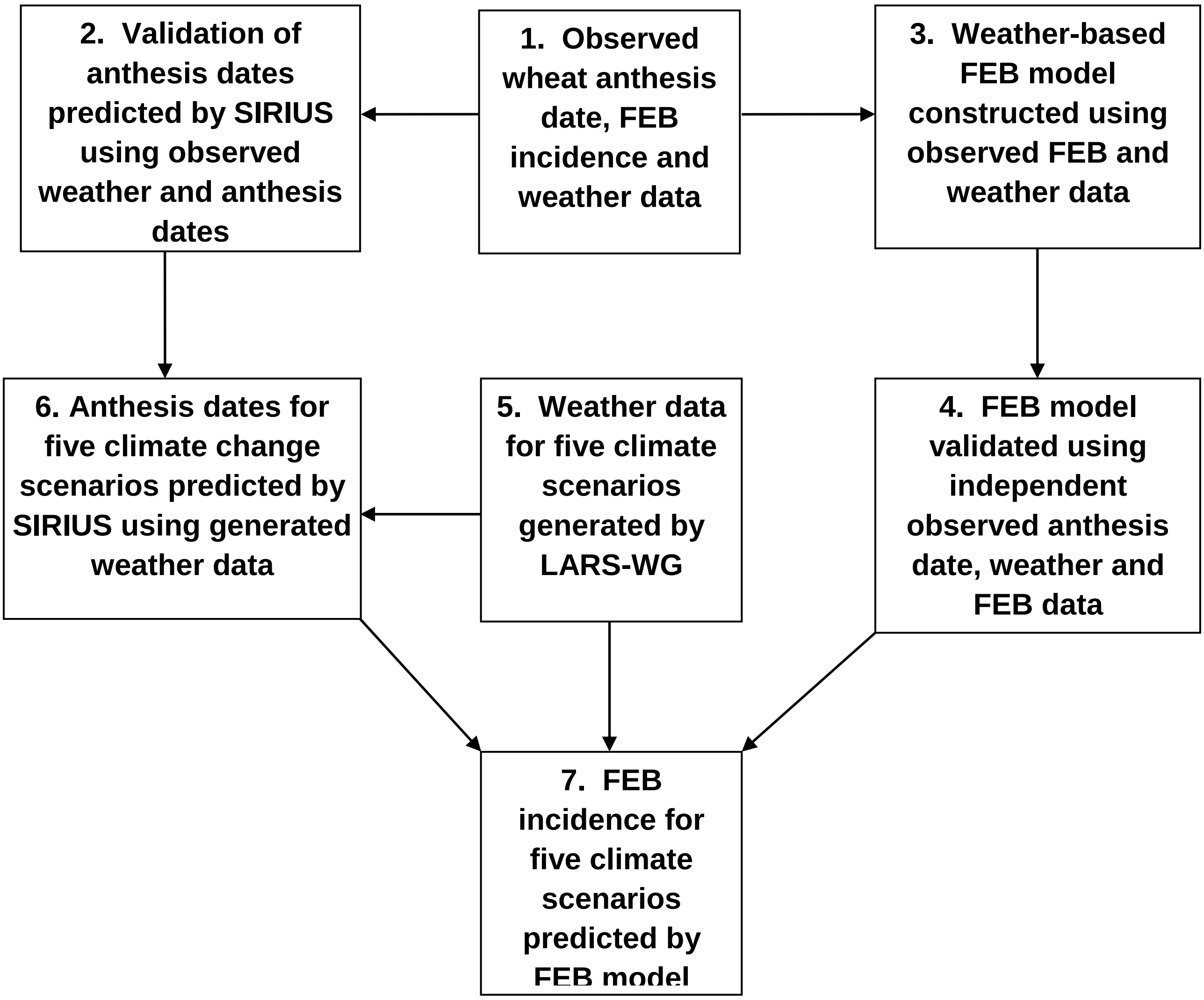

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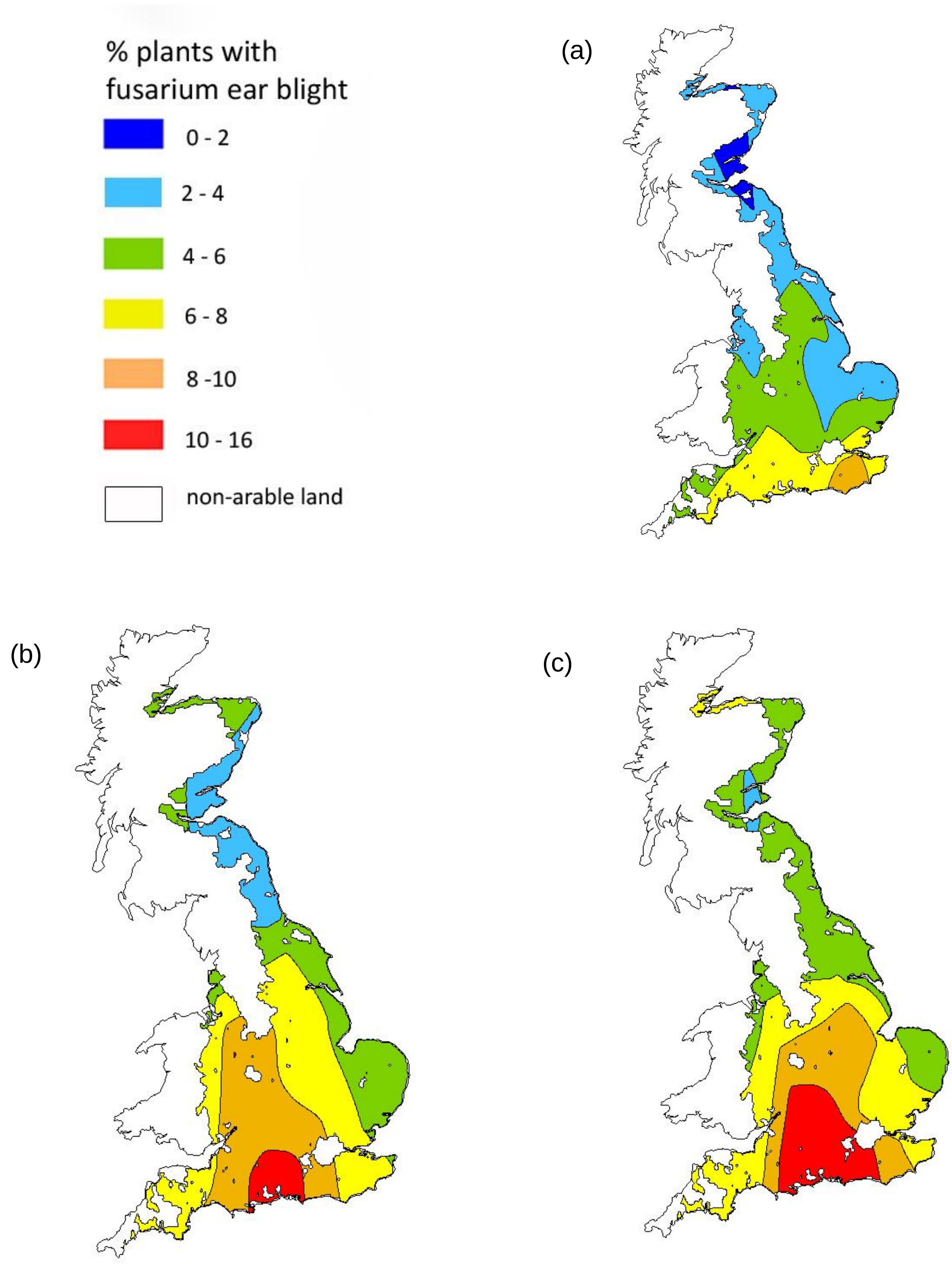

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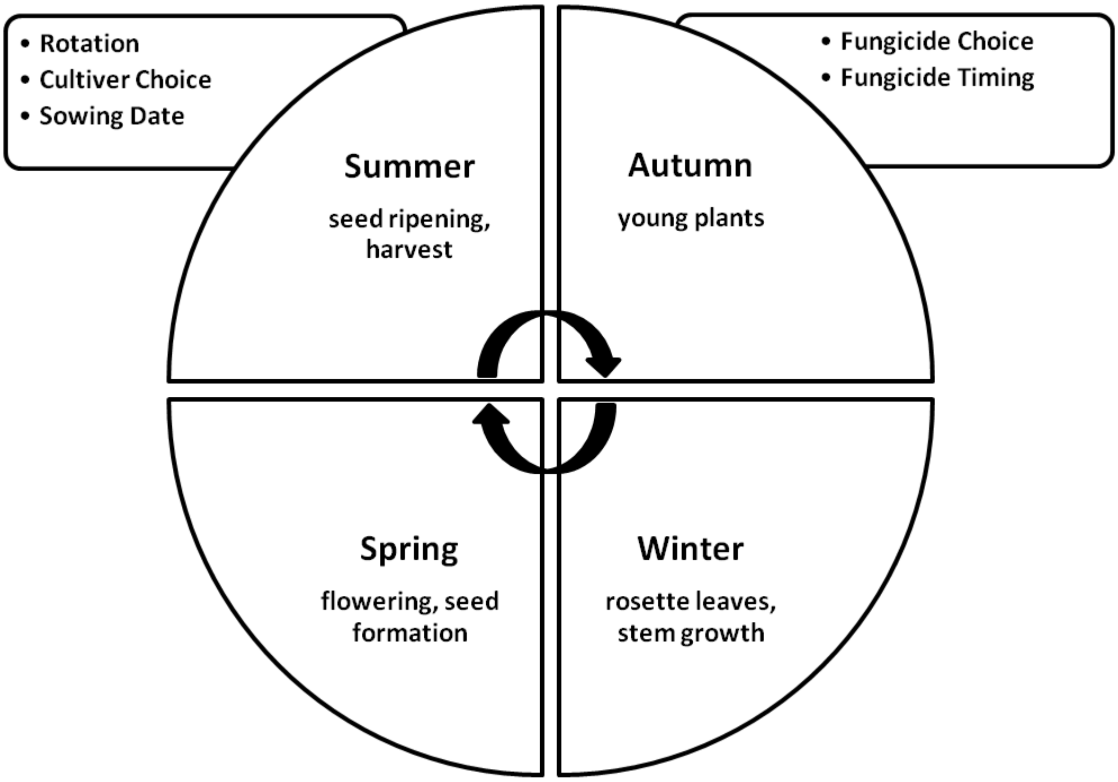

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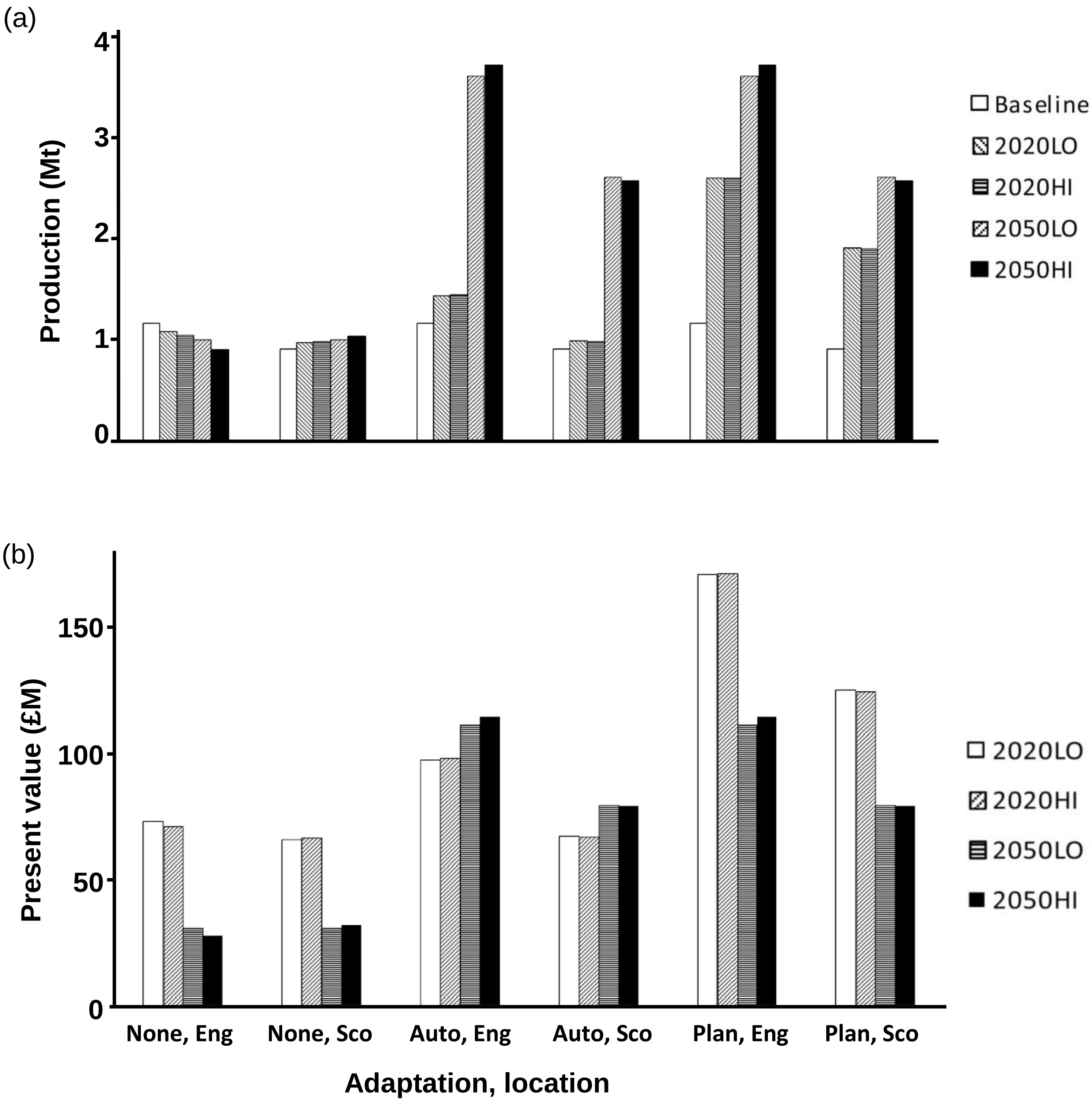

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