Arable crop disease control, climate change and food security

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Summary

Global food security is threatened by crop diseases that account for average yield losses of 16%. Climate change is exacerbating threats to food security in much of the world, emphasising the need to increase food production in northern European countries such as the UK. However, to mitigate climate change, crops must be grown so as to minimise greenhouse gas emissions (GHG); results with UK oilseed rape demonstrate how disease control in arable crops can contribute to climate change mitigation. However, work examining impacts of climate change on UK epidemics of winter oilseed rape diseases illustrates unexpected, contrasting impacts of climate change on complex plant-disease interactions. In England, phoma stem canker is expected to become more severe whilst light leaf spot is expected to become less severe. Such work can provide guidance for government and industry planning for adaptation to impacts of climate change on crops to ensure future food security.

Key words: Adaptation to climate change, climate change mitigation, crop-disease-climate interactions, food security, greenhouse gas emissions, oilseed rape diseases, sustainable agriculture

Introduction

Crop diseases directly threaten global food security because diseases cause crop losses, estimated at 16% globally despite efforts to control the diseases (Oerke, 2006), in a world where more than 1 billion people (one sixth of world population) do not have enough food to eat (Anonymous, 2009). Thus, food production must be increased by controlling crop diseases more effectively. These crop diseases, together with pests and weeds, mean that there is less food to eat due to crop losses, estimated at £144 billion per year on just four major worldwide crops; without crop protection measures the losses are estimated at £273 billion (Oerke, 2006; Table 1). It is estimated that if crop losses to diseases, pests and weeds were decreased by 1% worldwide, then an extra 25 million people could be fed with no extra use of land, water, fertilisers or chemicals (CABI report, 2009−2010; http://www.cabi.org/). By contrast, if factors such as climate change increase losses from crop diseases, more people will starve. However, strategies for adaptation to the changing environment, such as development of new fungicides or new cultivars that will be resistant to diseases in the changed environment both take 10−15 years to implement; thus decisions need to be taken now to plan for future (Barnes *et al*., 2010).

Since food security problems associated with crop diseases are exacerbated by climate change (Garrett *et al.*, 2006; Gregory *et al.*, 2009; Stern, 2007), there is a need to evaluate impacts of climate change on disease-induced losses in crop yields to guide government and industry policy and planning for adaptation to climate change.

Table 1. *Crop protection and food security worldwide, illustrated by rice, wheat, maize and potato crops. A comparison between actual estimated losses from diseases, pests and weeds for those crops and potential losses if no crop protection measures were used to control pests, diseases and weeds.*

	Actual crop losses (with crop protection)		Potential crop losses (without crop protection)	
	%	£bn[a]	%	£bn[a]
Rice	37	74	77	154
Wheat	28	31	50	56
Maize	31	18	40	23
Potato	40	21	75	40

[a] Financial estimates of losses were obtained by multiplying percentage crop losses to diseases, pests and weeds (expressed as proportions) estimated by Oerke (2006) by current worldwide values of production of these crops estimated by FAO (http://faostat.fao.org/)

Since the threats of climate change to food security are particularly severe in marginal areas (Strange & Scott, 2005; 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 to climate change mitigation from agriculture (Jackson *et al.*, 2007). To decrease the contribution of agriculture to global warming, possible options include reducing the use of fossil fuels and nitrogen fertilisers, reducing methane emissions from livestock and increasing the sequestering of carbon from the atmosphere (Glendining *et al.*, 2009). This paper reports work to study the contribution to climate change mitigation from disease control in arable crops through fungicide treatment, using UK oilseed rape as an example, and estimates the impacts of climate change on oilseed rape and losses from phoma stem canker across the UK.

Crop disease control contributes to climate change mitigation

The GHG emissions for production of 1 t of winter oilseed rape seed were calculated (Mahmuti *et al.*, 2009). Differences in yields between fungicide-treated and untreated plots in experiments throughout the UK were analysed to estimate effects of fungicides to control disease on the emissions per tonne of seed. This was done for data from HGCA trials (harvest years 2004 to 2007) and those done by Rothamsted and ADAS for the years 2005 to 2007. The GHG emissions per tonne of winter oilseed rape seed produced were estimated at 834 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 t^{-1} between yields of 1 and 3 t ha^{-1} was 2225 kg CO_2 eq. t^{-1}. There were 627 units of yield data in the HGCA Recommended List trials during the period 2004−2007 in England and Scotland, with mean yield 4.33 t ha^{-1} for fungicide-treated and 3.84 t ha^{-1} for untreated crops. 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 produced without fungicide treatments by comparison to fungicide-treated crops. The annual mean differences in emissions were 101 kg CO_2 eq. t^{-1} for HGCA trials (Fig. 1), 169 kg CO_2 eq. t^{-1} for Rothamsted and 82 kg CO_2 eq. t^{-1} for ADAS experiments (Fig. 2)

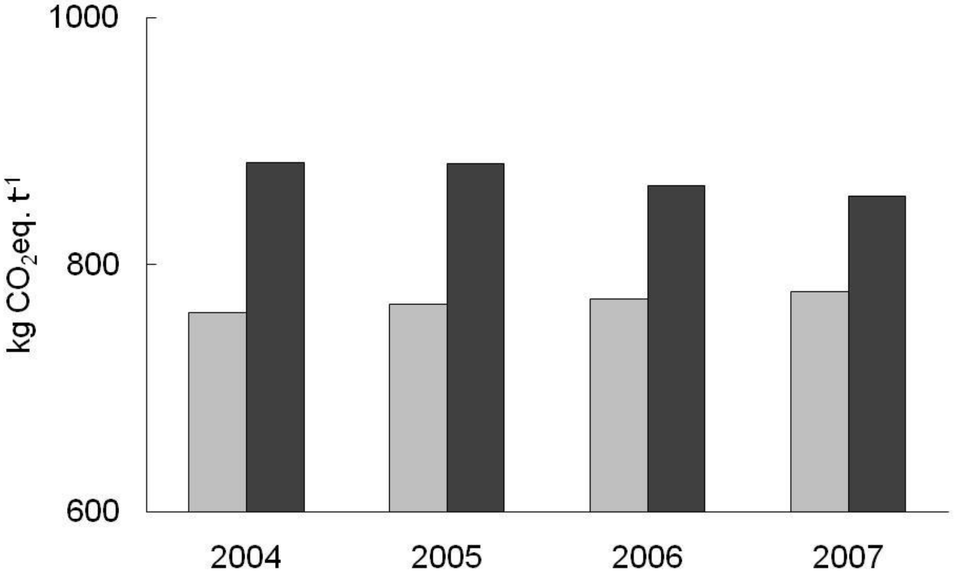

Fig. 1. Differences in greenhouse gas (GHG) emissions per tonne of yield between winter oilseed rape crops (means of 24−39 cultivars at 4−7 different sites) treated with fungicides to control phoma stem canker and light leaf spot diseases (■) and untreated crops (■) in the HGCA trials), at sites differing 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).

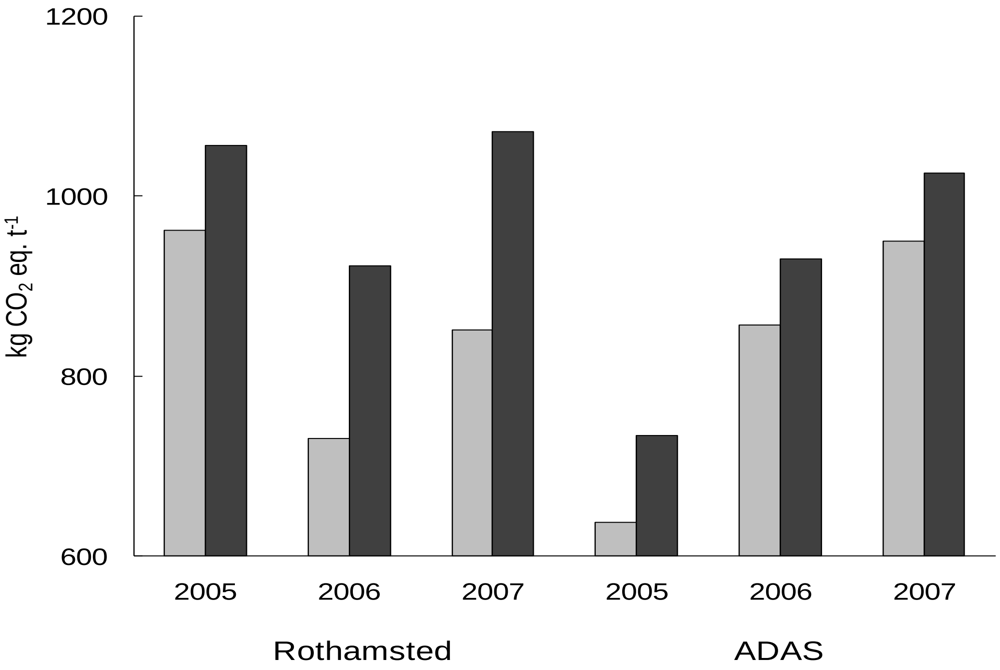

Fig. 2. Differences in greenhouse gas (GHG) emissions per tonne of yield between winter oilseed rape crops treated with fungicides to control phoma stem canker and light leaf spot diseases (■) and untreated crops (■). Results are for field experiments done at Rothamsted (2005−2007) and by ADAS at Teversham (2005) and Boxworth (2006−2007), at sites differing in epidemic severity. Rothamsted experiments tested 19 different cultivars in 2005 and 20 cultivars in 2006 and 2007, in all cases with three replicates of each untreated and treated plot (six plots per cultivar). ADAS experiments tested 20 cultivars with three replicates of each treated and untreated cultivar (6 plots) for 2005 and four replicates (8 plots) for 2006−2007. Adapted from Mahmuti *et al.* (2009).

Similarly, effects of fungicide treatment on GHG emissions t^{-1} of winter or spring barley grain were also calculated in kg CO_2 eq. t^{-1} using data from HGCA trials, experiments in England and Scotland (BBSRC LINK project) and ADAS trials for Bayer CropScience (Hughes *et al.*, 2011). In the HGCA trials, fungicide treatment increased the 8-year mean yield by 1.38 t ha^{-1} (19%) for winter barley and by 0.91 t ha^{-1} (14%) for spring barley. Yield responses to fungicide treatment were 0.98 - 2.04 t ha^{-1} for winter barley and 0.60 - 1.14 t ha^{-1} for spring barley. In the LINK experiments, fungicide treatment increased the 3-year mean yield by 1.03 t ha^{-1} (14%) for winter barley and the 4-year mean by 0.57 t ha^{-1} (9%) for spring barley. In the ADAS experiments, fungicide treatment increased the 7-year mean yield by 1.41 t ha^{-1} (19%) for all winter barley experiments.

Average yields across all 2,400 plots (fungicide-treated and untreated) in the HGCA trials were 7.8 t ha^{-1} for winter barley and 7.0 t ha^{-1} for spring barley. The total GHG emissions were 355 kg CO_2 eq. t^{-1} for winter barley and 318 kg CO_2 eq. t^{-1} for spring barley. Fungicide treatment reduced average GHG emissions associated with producing 1 t of winter or spring barley in HGCA, LINK and ADAS experiments. For winter barley, fungicide treatment reduced GHG emissions by 42 - 60 kg CO_2 eq. t^{-1} (11−16%) and for spring barley, fungicide treatment reduced GHG emissions by 29 - 39 kg CO_2 eq. t^{-1} (8−11%). Disease control in winter oilseed rape decreased GHG emissions (Mahmuti *et al.*, 2009) more than disease control in winter or spring barley or winter wheat (60kg CO_2 eq.t^{-1}, Berry *et al.*, 2008). However, these calculations all underestimate the climate change mitigation benefits of disease control since the fungicide treatments did not completely control diseases and disease epidemics can be much more severe than those in the experiments.

Average UK yields of winter and spring barley in 2009 of 6.39 t ha^{-1} and 5.53 t ha^{-1}, respectively (Defra (ww2.defra.gov.uk)) are, respectively, 2.04 t ha^{-1}and 2.30 t ha^{-1} less than average yields of fungicide treated plots in the HGCA trials for 2009 (8.43 t ha^{-1}and 7.83 t ha^{-1}, respectively). Assuming that the potential percentage yield losses from disease in UK winter barley and spring barley are those observed in the HGCA trials in each year from 2005 to 2009, the average decrease in GHG emissions through fungicide treatment in these 5 years was 89 kg CO_2 eq. t^{-1} (17%) for winter barley and 55 kg CO_2 eq. t^{-1} (12%) for spring barley. Combining the decreases for the 2009 UK barley crop (6.8 Mt) of 0.17 Mt CO_2 for winter barley and 0.13 Mt CO_2 for spring barley with those for oilseed rape (Mahmuti *et al*., 2009) and wheat (Berry *et al*., 2008), fungicide treatment is estimated to have reduced GHG emissions by 1.64 Mt CO_2 for four major UK arable crops (winter barley, spring barley, winter wheat, and winter oilseed rape) in 2009. Similar figures were estimated for 2005−2008.

Crop diseases and adaptation to climate change

UKCIP02 scenarios predicting UK temperature/rainfall under high- and low-CO_2 emission scenarios for the 2020s and 2050s were combined with a crop simulation model for yield of fungicide-treated winter oilseed rape and a weather-based regression model for severity of phoma stem canker epidemics to investigate crop-disease-climate interactions (Butterworth *et al*., 2010). The oilseed rape model predicted effects of climate change on yields for 14 UK sites for different climate change scenarios and results were mapped onto oilseed rape growing areas. Phoma stem canker and light leaf spot yield loss predictions were also mapped onto these areas. In England, the main feature is that phoma stem canker losses are expected to increase whilst less importantly light leaf spot losses are expected to decrease. Fungicide-treated yield and yield loss data were combined to estimate untreated yields for each region for each scenario.

Total area of oilseed rape grown in the UK in 2006 was 500,000ha, with most grown in the east (Table 2). Predictions suggest that climate change will increase the yield of winter oilseed rape crops treated with fungicide to control diseases (Butterworth *et al.,* 2010). Baseline (1960−1990) fungicide-treated yield was greatest in eastern England/Scotland (3.15 t ha^{-1}). The prediction is that in the 2020s and 2050s the greatest yields will be in eastern Scotland and north-east England, with increases in yield greater for the high CO_2 than for low CO_2 emissions scenarios and greater for the 2050s than for the 2020s. The total production was greater in England (1,430,000 t) than Scotland (113,000 t). The yield losses from phoma stem canker 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 in all regions of England by 5% (South West) to 10% (North East); conversely, the effect of climate change in Scotland will be to increase the yield by 3% (Evans *et al*., 2010). 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 is similar for both scenarios. By contrast, in Scotland there will be a further predicted increase in yield (5%). 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 crops from the baseline of 2.69 Mt to 2.90 Mt in the 2050HI scenario, with the amount produced in

Scotland increasing. However, they suggest that total production of untreated winter oilseed rape in England will decrease from 1.17 Mt (baseline) to 1.04 Mt (2050HI). Such predictions illustrate unexpected, contrasting impacts of climate change on complex plant-disease interactions in agricultural and natural ecosystems.

Table 2. *Effects of climate change on the yield of fungicide-treated oilseed rape (OSR) (Tr) and untreated oilseed rape (Unt) after phoma stem canker losses, calculated by region. The untreated oilseed rape yields were calculated as the means of values for 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 OSR (ha)[b]	Baseline yield (t ha^{-1})		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

In the work of Butterworth *et al.* (2010) and Evans *et al.* (2010), an oilseed rape price of £195.60 t^{-1} was used. Since the price is currently more than £400 t^{-1} (www.hgca.com, 31 December 2010), the original estimates have been doubled accordingly. Thus, the baseline yield indicates that the annual value of the total oilseed rape output for the UK was over £604M, if phoma stem canker and light leaf spot were controlled with fungicides. This value is predicted to increase under all climate change scenarios, with the greatest proportional increases under high CO_2 emissions and in Scotland rather than England, so that under the 2050HI emissions scenario, the value of the crop will be £26M more than the baseline scenario in England and £5M more in Scotland. Average annual losses caused by phoma stem canker and light leaf spot were estimated at £148M under the baseline scenario and climate change is predicted to increase these losses, with further losses of £12−16M in England and £1.2−1.8M in Scotland by the 2020s. By the 2050s, losses in England are predicted to increase by £32M in the low emissions scenario and by £56M in the high emissions scenario. This is in contrast to Scotland, for which losses are predicted to increase by £4.4M for the 2050s high emissions scenario and by £6.2M for the 2050s low emissions scenario. The UK total losses are predicted to increase by £60M in the 2050s.

Further work with another monocyclic crop disease (one disease cycle per cropping season) has investigated how impacts of climate change on wheat anthesis date will influence fusarium ear blight in the UK (Madgwick *et al*., 2011). The timing of wheat anthesis affects severity of wheat fusarium ear blight (head blight, scab) because the wheat is susceptible to infection only at anthesis, when there is rainfall (Xu *et al.*, 2007). In the UK, the disease is caused by several pathogens, including *Fusarium graminearum* and *F. culmorum* of which some chemotypes produce mycotoxins (www.hgca.com; Madden & Paul, 2009; Xu & Nicholson, 2009). A wheat growth model was used for predictions of anthesis dates, and a weather-based model was developed for use in predictions of incidence of fusarium ear blight in the UK. Daily weather data, generated for 14 sites in arable areas of the UK for the baseline scenario and for high and low CO_2 emissions in the 2020s and 2050s, were used to predict wheat anthesis dates and fusarium ear blight incidence for each site for each scenario. It was predicted that, with climate change, wheat anthesis dates will be earlier and fusarium ear blight epidemics will be more severe, especially in southern England, by the 2050s. These predictions of increases in the severity of crop diseases suggest that industry and government strategies for adaptation to climate change should prioritize improved control of oilseed rape phoma stem canker and wheat fusarium ear blight to ensure future food security.

Discussion

These results with diseases of UK crops demonstrate how climate change can increase losses from some crop diseases. For UK winter oilseed rape, the increase in losses is associated with the increase in range (northwards to Scotland) and severity (especially in southern England) of phoma stem canker associated the projected increase in temperature during the cropping season (Butterworth *et al*., 2010; Evans *et al*., 2008). This work demonstrates how climate change may increase worldwide disease losses through increases in severity of existing diseases in a region 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 globally to diseases (Oerke, 2006) may increase, with serious consequences for the 1 billion people who do not have enough to eat (Anonymous, 2009; Strange & Scott, 2005), unless appropriate strategies for adaptation to this impact of climate change are implemented (Lobell *et al*., 2008). To guide government and industry strategies for adaptation to climate change, there is an urgent need for more reliable disease models that can be used to improve 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). Crop surveys have provided a valuable source of long-term data for use in developing such models. Since it may take 10−15 years to develop a new fungicide or incorporate into commercial crop cultivars resistance to a pathogen from a novel source of resistance, it is important to identify future target diseases now.

These results demonstrate that disease control in arable crops can contribute now to targets for climate change mitigation by decreasing GHG emissions. They suggest that disease control through improved disease resistance and more accurate fungicide timing should be included in policy options for decreasing GHG emissions from agriculture (Smith *et al*., 2008). Thus, controlling diseases in UK winter oilseed rape (Mahmuti *et al*., 2009) and barley (Hughes *et al*., 2011) gives benefits not only in terms of decreased GHG per tonne of crop produced but also in increased yield to increase food production in northern Europe in response to climate change threats to food security in other regions (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 considerably greater than those associated with disease control in winter wheat (Berry *et al*., 2008) or winter or spring barley (Hughes *et al*., 2011). When added together, disease control in UK arable crops can make a substantial contribution to government targets for decreasing GHG emissions from agriculture (Hughes *et al*., 2011). Thus, 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, especially where inorganic or organic nitrogen fertilisers are used to increase yields..

In a world where climate change is exacerbating the food security problems for communities farming in marginal environments (Schmidhuber & Tubiello, 2007; Lobell *et al.,* 2008), it is essential to improve 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 (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 resulting 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 to sustain the yields and profitability of European farms and to contribute to global food security in response to climate change (Stern, 2007).

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