3

Climate Change and Arable Crop Disease Control: Mitigation and Adaptation

B.D.L. FITT[1], N. EVANS[1], P. GLADDERS[2], D.J. HUGHES[1,3],
J.W. MADGWICK[1], M.J. JEGER[3], J.A. TOWNSEND[1], J.A. TURNER[4] and
J.S. WEST[1]

[1] *Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*
[2] *ADAS Boxworth, Battlegate Road, Boxworth, Cambridge CB23 4NN, UK*
[3] *Imperial College at Silwood Park, Ascot, Berkshire SL5 7PY, UK*
[4] *Food and Environment Research Agency, Sand Hutton, York YO41 1LZ, UK*

Abstract

Global food security is threatened by crop diseases that account for average yield losses of 16%. Climate change is exacerbating the threats to food security in many areas of the world, emphasising the need to improve crop yields to increase food production in northern European countries such as the UK. However, to **mitigate** climate change, the crops must be grown in such a way as to minimise greenhouse gas emissions (GHG) and optimise inputs associated with their production. As examples, it is estimated that UK production of winter oilseed rape and winter barley is associated, respectively, with GHG of 3300 and 2617 kg CO_2 eq. ha^{-1} of crop, with >70% of the GHG associated with the use of nitrogen fertiliser. Furthermore, it is estimated that control of diseases by use of fungicides in UK oilseed rape and barley is associated, respectively, with decreases in GHG of 100 and 50 kg CO_2 eq. t^{-1} of seed. These results demonstrate how disease control in arable crops can make a contribution to both climate change mitigation and sustainable arable crop production. Climate change will affect both growth of agricultural crops and diseases that attack them but there has been little work to study its combined effects on crop-disease interactions to guide strategies for **adaptation** to climate change. For example, it may take 10-15 years to develop a new fungicide and it is important to identify future target diseases now. As examples, the impact of climate change on UK epidemics of phoma stem canker and light leaf spot on winter oilseed rape and fusarium ear blight on winter wheat is investigated by combining weather-based disease models, crop growth models and simulated weather for different climate change scenarios. It is predicted that climate change will increase the risk of oilseed rape phoma stem canker and wheat fusarium ear blight epidemics but decrease the risk of light leaf spot epidemics by the 2050s. Such predictions illustrate unexpected, contrasting impacts of climate change on complex plant-disease interactions in agricultural and natural ecosystems. They can provide guidance for government and industry planning for adaptation to effects of climate change on crops to ensure future food security.

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

Modern Fungicides and Antifungal Compounds VI

where more than 1 billion people do not have enough food (Anonymous, 2009). Thus, food production must be increased by controlling crop diseases more effectively. Food security problems are most serious in developing countries, where diseases can destroy crops and cause famine for subsistence farming families (Strange and Scott, 2005). 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.

Since the threats of climate change to food security are particularly severe in marginal areas (Schmidhuber and 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 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). 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 and barley crops as examples, and estimates the impact of climate change on oilseed rape and losses from phoma stem canker and wheat anthesis date and fusarium ear blight 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 produced per tonne of winter oilseed rape seed produced were estimated at 834 kg CO2 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 CO2 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 CO2 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 CO2 eq. t^{-1} for HGCA trials (Figure 1), 169 kg CO2 eq. t^{-1} for Rothamsted and 82 kg CO2 eq. t^{-1} for ADAS experiments (Figure 2).

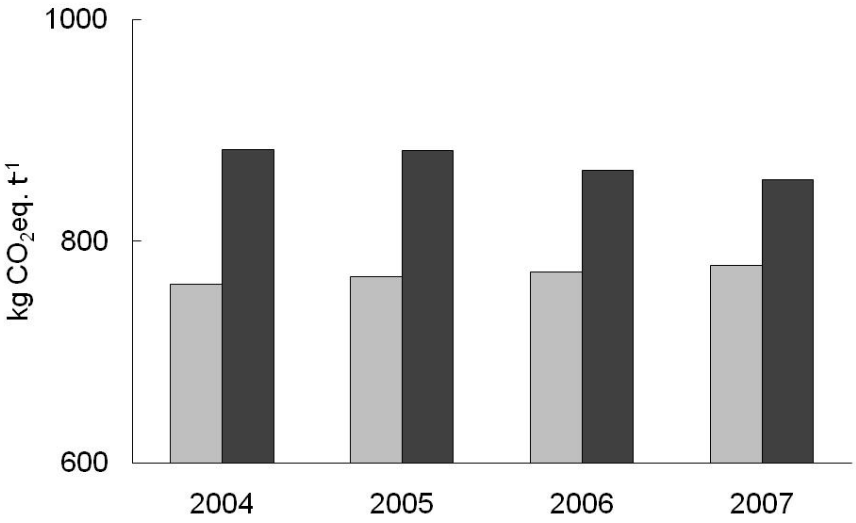

Figure 1: Differences in greenhouse gas (GHG) emissions per tonne of yield between winter oilseed rape crops (means of 24-39 cultivars at 4-7 different sites) treated with fungicides to control phoma stem canker and light leaf spot diseases (⬜) and untreated crops (■) in the HGCA trials), at sites differing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

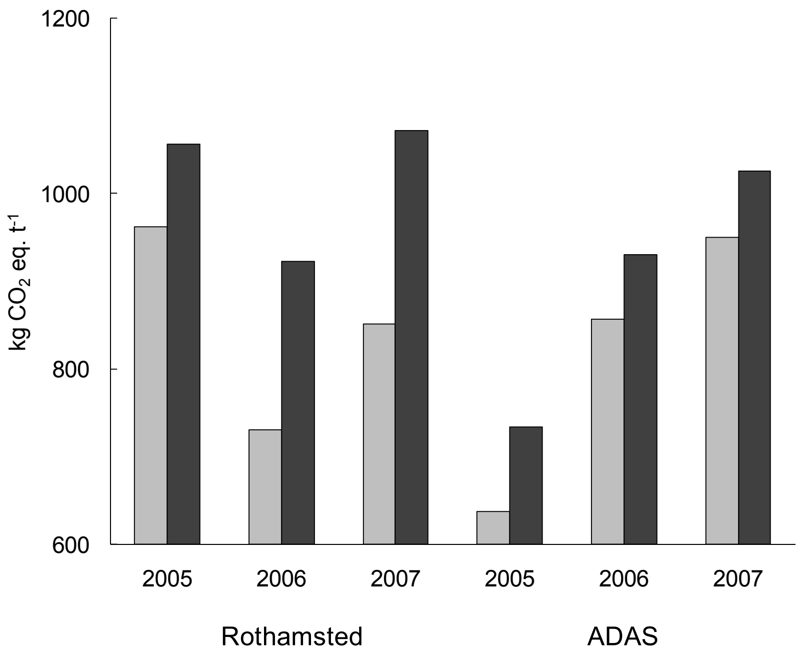

Figure 2: Differences in greenhouse gas (GHG) emissions per tonne of yield between winter oilseed rape crops treated with fungicides to control phoma stem canker and light leaf spot diseases (⬜) and untreated crops (■). Results are for field experiments done at Rothamsted (2005-2007) and by ADAS at Teversham (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).

Effects of fungicide treatment on GHG emissions t^{-1} 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 as part of a BBSRC LINK project and some ADAS trials done for Bayer CropScience. In the HGCA dataset, fungicide treatment increased the 8-year mean yield for winter barley by 1.38 t ha^{-1} (19%) and for spring barley by 0.91 t ha^{-1} (14%). Yield always responded to fungicide treatment, with increases of 0.98 - 2.04 t ha^{-1} for winter barley and 0.60 - 1.14 t ha^{-1} for spring barley. In the LINK dataset, fungicide treatment increased the 3-year mean yield for winter barley by 1.03 t ha^{-1} (14%) and the 4-year mean for spring barley by 0.57 t ha^{-1} (9%). In the ADAS dataset, fungicide treatment increased the 7-year mean yield for all winter barley experiments by 1.41 t ha^{-1} (19%).

Average yield across all 2,400 plots (treated and untreated) in the HGCA data for winter barley was 7.8 t ha^{-1} and for spring barley was 7.0 t ha^{-1}. In terms of the grain yield, 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 of producing 1 t of winter or spring barley for each UK data set (HGCA, LINK, ADAS). 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 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 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 these experiments.

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 yield loss predictions were also mapped onto these areas. 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 1). 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 fungicide-treated yield was greatest in eastern England/Scotland (3.15 t/ha). 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.

Table 1: Effects of climate change on the yield of treated oilseed rape (OSR) (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 OSR (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

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.

The baseline yield indicates that the annual value of the total oilseed rape output for the UK, calculated at a price of £195.60 t^{-1}, was over £302M (Table 2), if phoma stem canker and light leaf spot were controlled with fungicides. This value is predicted to increase under all climate change scenarios, with highest 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 £13M more than the baseline scenario in England and £2.5M more in Scotland. Average annual losses caused by phoma stem canker and light leaf spot were estimated at £74M under the baseline scenario (Table 3) and climate change is predicted to increase these losses, with further losses of £6-8M in England and £0.6-0.9M in Scotland by the 2020s. By the 2050s, losses in England are predicted to increase by £16M in the low emissions scenario and by £28M in the high emissions scenario. This is in contrast to Scotland, for which losses are predicted to increase by £2.2M for the 2050HI scenario and by £3.1M for the 2050LO emissions scenario. The UK total losses are predicted to increase by £30M in the 2050s. The price in autumn 2010 is now nearer £300 t^{-1}, so these values are underestimates.

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

Further work has investigated how impacts of climate change on wheat anthesis date will influence fusarium ear blight in the UK. 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 and Paul, 2009; Xu and 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 suggest that industry and government strategies for adaptation to climate change should prioritize improved control of fusarium ear blight to ensure future food security.

Discussion

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 considerably greater than those associated with disease control in winter wheat (Berry *et al.*, 2008) or winter or spring barley. 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 and 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 and 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 HGH 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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