

Foresight

Infectious Diseases: preparing for the future

OFFICE OF SCIENCE AND INNOVATION

**T7.2 The Effects of Climate Change on
Infectious Diseases of Plants**

Dr Tim Chancellor,
Plant, Animal and Human Health Group, Natural Resources Institute,
University of Greenwich at Medway, Central Avenue,
Chatham Maritime, Kent ME4 4TB, UK

Dr Jerome Kubiriba,
Banana Programme, National Agricultural Research Organisation,
Kawanda, Uganda

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1 Introduction

Plant diseases have had a major impact on agricultural productivity throughout recorded history, and major outbreaks have sometimes had devastating effects on human societies. The potato famine that occurred in Ireland in the 19th century and led to the death of a million people resulted from severe epidemics of potato late blight, caused by the fungal pathogen *Phytophthora infestans*. Plant diseases can also have serious effects on natural vegetation, as seen in the outbreak of Dutch elm disease in Europe from the 1960s. In spite of our increased understanding of pathogenic microbes and how they cause epidemics in populations of plant hosts, plant diseases continue to cause serious losses in yield and income for farmers globally. The International Potato Center (<http://www.cipotato.org/>) has estimated that the total production loss of potato in developing countries due to late blight disease alone amounts to approximately US\$2.75 billion (Anonymous, 1997).

The distribution, incidence and severity of plant diseases are influenced by many interacting factors including host susceptibility, cropping systems, management strategies and environmental conditions. Climate is a prime determinant of the geographical distribution of plants, and climatic variables have a major effect on the development of plant diseases. Anthropogenic climate change will impact directly on crops and natural vegetation as well as on their interactions with plant pathogens (Rosenzweig et al., 2000). How severe these impacts will be is difficult to predict. In some cases even the likely direction of change is uncertain. It is possible that climate change will have relatively small short-term impacts in comparison with other drivers of change, such as crop intensification or major advances in disease management technologies. However, the majority of these other drivers will also be affected by some aspect of climate change. Nevertheless, it is important to attempt to identify the potential impacts of climate change in order to establish a sound basis to inform future planning processes.

Estimates of future global climate change are necessarily somewhat imprecise, with different models showing substantial variations in predicted climate patterns. It is important to remember, however, that at least for the next 40 years or so a large amount of this change is already built into the system and cannot be reversed. This is due to the long lifetime of atmospheric carbon dioxide (CO₂) and the 'thermal inertia' of the climate system. Climate change beyond this period will be influenced by future emission rates, and change models utilise a range of carbon dioxide and aerosol emission scenarios. Here, we use climate change scenarios for the 2020s and the 2080s and focus on the potential effects of climate change in the UK and in sub-Saharan Africa. For the UK, we give priority to the more economically damaging diseases of the most important agricultural crops. The approach taken for sub-Saharan Africa is to highlight likely impacts of diseases on key subsistence crops in areas that are considered to be most affected by climate change.

2 Climate change scenarios

The concentration of CO₂ in the atmosphere has increased by 30% since before the Industrial Revolution – a trend unlikely to be reversed by the year 2100. In its third assessment report, the Intergovernmental Panel on Climate Change (IPCC) estimated that, by 2100, the most probable outcomes will be an increase in global mean temperature of 1.4-5.8⁰C, significant changes in precipitation patterns and a greater frequency of extreme weather events (Houghton et al., 2001). The global projections mask substantial regional variations, so that any impacts will not be evenly felt across agroecosystems. Currently, there is no single method capable of generating reliable predictions of future climate. Forecasts are usually presented as climate scenarios derived from Global Circulation Models (GCMs) and other indicators such as the development of the El Niño Southern Oscillation (ENSO).

It is not easy to develop regional and local scenarios from GCMs, but there are now models that attempt to make predictions at these smaller spatial scales. For the purposes of this review, we will use the most recent United Kingdom Climate Impacts Programme (UKCIP) report for the UK (Hulme et al, 2002). The authors predict that temperatures will rise by 0.5-1.5⁰C by the 2020s and by 2-4⁰C by the 2080s¹. Warming will be greater in summer than in winter, and there will be an increased frequency of very hot summers, particularly by the 2080s. Total annual precipitation may be little changed, but summer rainfall is projected to fall by up to 10% and 50% by the 2020s and 2080s, respectively. Winter rainfall will increase, with greater risks of flooding. It is also possible that winds will be stronger in winter.

The size and geographical diversity of sub-Saharan Africa make climate change predictions particularly challenging. However, most of the current climate models² indicate that the overall scenario is one of rising temperatures and changes in rainfall patterns, with more prolonged and frequent drought and flooding. Mean temperatures over land areas are expected to increase by an average of around 1-2⁰C by 2020, with the largest increases occurring in southern Africa. By 2080, mean temperatures are expected to increase by c. 1.7-6⁰C in southern Africa, 1.3-4.5⁰C in eastern Africa and 1.7-5.5⁰C in western Africa. There is less agreement between the various climate models for rainfall than for temperature. However, most predict a decrease in rainfall for southern Africa of approximately 5% by 2020 and 10% by 2050. Similar decreases are also anticipated in parts of the Horn of Africa, with some areas in eastern Africa likely to receive a significant increase in rainfall (Hulme et al., 2001; Houghton et al., 2001).

In the UK, the predicted changes in climate will be more marked in the south. Impacts may be greater in natural than in agricultural systems. For example,

¹ These changes are relative to a 1961-1990 baseline

² Global Circulation Models currently used include Hadley Centre Model (HadCM3) <http://www.metoffice.com/research/hadleycentre/models/HadCM3.html> ; and Community Climate Systems Model (CCSD) <http://www.cgd.ucar.edu/csm/>.

native beech trees on thin calcareous soils are already suffering severe stress, with reduced foliation due to drier conditions in the summer (Defra, 2003). The increased need for irrigation may make it uneconomic to grow some field crops, but such changes will also depend on future developments in the agricultural support system. It will become increasingly difficult to grow seed potatoes even at more northerly latitudes, as warmer winters favour the survival of aphids and facilitate the spread of virus diseases (Bale et al., 2002). In Africa, the most severe impacts are likely to be found in rain-fed cropping systems. Crop production in these areas will be subject to increasing water stress or drought conditions. The most obvious result will be a reduction in the area suitable for growing maize, a key subsistence crop preferred by many farmers, with a concomitant increase in the area planted for the more drought-tolerant sorghums and millets.

3 Climate and plant diseases

Environmental conditions have a major influence on the survival, propagation and dispersal of plant pathogens. The effects of the climate are perhaps most obvious for fungal pathogens, which require suitable temperatures and minimum amounts of moisture to survive and reproduce and to initiate the infection process in plants. Most plant pathogens complete part of their life cycle on their host plants and the remaining part in the soil or on plant residues in the soil. Thus, temperature and moisture conditions in both air and soil are important for pathogen survival and development.

Whereas free mycelium has to be in contact with moist surfaces to survive, most types of fungal spore can endure greater extremes of temperature and a wider range of moisture conditions (Agrios, 1997). However, spores do need favourable moisture and temperature to germinate and, in the case of zoospores, free water is needed for their development and movement. For some diseases, the 'quality' of rainfall is a more important determinant of disease progress than the amount which falls. Septoria leaf blotches of cereals, for example, are spread through rain-splash – a process greatly enhanced during periods of heavy rainfall.

The effect of temperature on disease development in plants is highly dependent on the specific combination of pathogen and host. Plants and pathogens each have optimum temperatures for growth, and the degree to which they overlap varies among pathosystems. Agrios (1997) describes the effects of the root rot-causing fungus, *Giberella zae*, on wheat and maize. On wheat, which grows best at lower temperatures than corn, disease develops most rapidly at temperatures above the optima for both wheat and the pathogen. On maize, however, the situation is reversed with maximum disease development occurring at temperatures below the optima for the crop and the pathogen. This suggests that the pathogen has an advantage over the crop under temperature conditions which are unfavourable to both. Thus, in some pathosystems at least, climate change-induced stress on plants may create enhanced opportunities for disease development. Further research is needed to investigate the mechanisms responsible for these effects.

Climate interacts with other factors to impact on plant diseases. Climate and host resistance can affect the prevalence of races of fungal pathogens within geographical areas. Annual variation in populations of yellow rust of wheat, caused by the pathogen *Puccinia recondita tritici*, depend on climate and the resistance characteristics of the host varieties (Knott, 1989). Temperature rises have been shown to affect the physiology of host plants and alter their resistance to disease. In another cereal crop, oats, experiments show that temperature-sensitive resistance to stem rust in varieties with the *Pg3* and *Pg4* genes is inactivated when temperatures rise above 20°C (Martens et al., 1967). Therefore, crop yield projections under future climate change scenarios need to take account of these potential effects.

Indirect effects of climate may also be important. In particular, vector-borne diseases are strongly influenced by climatic effects on the vectors. There are established climatic thresholds for the phenological development of many arthropod vectors of plant viruses. Climate affects the fecundity and mortality of arthropod vectors and influences the number of generations in a year. In temperate climates, warm and dry conditions in early spring allow aphids such as *Myzus Persicae* to multiply rapidly and initiate damaging outbreaks of virus disease epidemics (Cammell and Knight, 1992).

Geographical distributions of plant-parasitic nematodes are influenced by host availability and soil type, but climate also plays a role (Boag et al., 1996). Climate is particularly important for economically-important migratory ectoparasitic species such as *Heterodera* and *Globodera*. Soil temperature and moisture are the key climate variables that affect nematode abundance. Soil temperature is generally considered to be the limiting factor for plant-parasitic nematodes and probably explains why certain species have not become established in areas that otherwise might be suitable (Lahtinen et al., 1988).

4 Climate change and plant diseases

4.1 Effects of climate on plant hosts

An important way in which climate change impacts on plant diseases is through its effects on plant hosts. Climate change can affect the distribution and abundance of plant species, and there is evidence from the fossil record of extinctions due to past changes in climate. Indeed, one species-level extinction has been documented in the tropics due to recent changes in the climate (Pounds et al., 1999). A recent study suggests that anthropogenic climate change is likely to have significant further impacts on species-level plant extinctions (Thomas et al., 2004). Using mid-range climate change scenarios for 2050, the authors estimated that 21-40% of Proteaceae in South Africa will become extinct, depending on the assumptions made for plant dispersal. Samples for European flora showed lower, but still significant, extinction rates of 3-16%. These estimates do not incorporate projected changes in land use, or other factors such as the suitability of soil types for plant growth. Hence, they may even be underestimates. However, not all projections are so alarmist. It is likely that the magnitude and direction of

climate change impacts on crops and natural vegetation will vary according to species and their particular growth characteristics.

Many studies have reported an increase in crop yields under elevated CO₂ conditions, and increases have been recorded in dry weight, stem and root length, leaf area and duration and other growth characteristics (Coakley, 1999). Kimball et al (2002) reviewed experimental studies showing that elevated CO₂ increased biomass production in C₃ grasses by an average of 12%. This resulted in yield gains of 10-15% for wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.), while tuber yield in potato (*Solanum tuberosum* L.) increased by 28%. These beneficial effects are reduced at higher temperatures, in part because photorespiration becomes highly inefficient at temperatures above 30°C. Higher temperatures lead to more rapid plant development, reduced grain fill and lower efficiency in resource use.

However, a recent review has cautioned that previous estimates of these increases have probably been unrealistically high (Long et al., 2004). Preliminary findings from a current field study in the USA indicate that this so-called 'fertilisation' effect of rising CO₂ may be substantially less than many of the earlier predictions (Long et al., 2005). The results suggest that the increase in photosynthesis and yield by elevated CO₂ in maize, rice soybean and wheat may be c. 50% less than projected from chamber studies.

4.2 Effects of climate on pathogens

Little research has been conducted into the effects of climate change on plant diseases compared to studies on human, and to a somewhat lesser extent, livestock diseases (Coakley et al., 1999). Much of this research has been carried out under controlled environmental conditions and has examined the effects of a single climatic variable on the pathogen and the plant host, or sometimes the interactions between the two. We now have quite detailed knowledge of the environmental conditions that favour the development of many pathogenic microbes. In general, less is known about how climatic factors interact with other variables to affect the epidemiology of plant diseases.

Recent methodological developments have created new opportunities to study such effects. Using technology such as Free Air Carbon Enrichment (FACE), field-scale experiments can be conducted in which carbon dioxide, ozone and other variables can be manipulated (Runion et al., 1994). Open air systems such as FACE have the advantage that solar radiation received by the plants, along with other variables including air temperature, wind pattern effects and humidity, are not greatly affected (McLeod and Long, 1999). It is not easy to modify air temperatures or to reduce precipitation, making some important climatic interactions difficult to study. However, innovative approaches have been developed in some recent studies; for example, the use of underground heated cables to modify temperature and rain shelters to regulate precipitation in a comparative study on the effects of simulated climate change on grassland communities (Grime *et al.*, 2000).

Although, as mentioned earlier, projections of the likely effects of CO₂ on plant growth are now being revised, the potential impact of enhanced growth on plant diseases may still be significant. These effects are likely to be most apparent for foliar diseases such as leaf spots, rusts and powdery mildews. These diseases would be favoured by larger and denser crop canopies, with increased nitrogen content, and the increased canopy humidity that would result (Manning and von Tiedemann, 1995).

In a recent, ground-breaking study, Chakraborty and Datta (2003) investigated the effects of elevated CO₂ on aggressiveness, fecundity and genotype of the fungal pathogen *Colletotrichum gloeosporioides* on the pasture legume *Stylosanthes scabra*. They reported that the aggressiveness of the pathogen, as measured by disease severity, was initially reduced under twice ambient levels of CO₂. However, after a period of ten infection cycles, pathogen aggressiveness increased on both resistant and susceptible varieties. This was attributed to the ability of the pathogen to adapt to the presumed changes that elevated CO₂ had induced in the plant host. Enhanced host plant resistance to pathogens under elevated CO₂ has been recorded in some pathosystems, where results were obtained from considerably fewer infection cycles. The study by Chakraborty and Datta indicates that such increases in resistance may not be sustained in the longer term. Another interesting finding in this study is that there is an increase in the number of spores produced per lesion area. The authors draw attention to the possibility that increased pathogen reproductive fitness under elevated CO₂ might also reduce the duration of resistance to the pathogen.

More favourable conditions during the winter lead to an increase in the amount of inoculum that can survive to initiate new infections in the following cropping season. Eversmeyer and Kramer (2000) analysed leaf rust epidemics in wheat in Kansas, USA, between 1980 and 1999 and found that yield losses were greatest in areas where the fungus successfully overwintered. This was attributed to earlier establishment of the disease, which enabled additional generations of the pathogen to occur during the rainy season. This, in turn, caused a greater severity of infection during the period of grain formation. Milder winters in the UK are expected to enhance the survival of certain pathogens, but the ultimate effect on disease development will also depend on other factors such as spring and summer temperature and rainfall.

The effects of air pollutants on plant diseases have been covered in detail in other reviews (e.g. Madden and Campbell, 1987) and will not form a prime focus of our study. In particular, considerable attention has been paid to the potential impacts of enhanced ozone (O₃) on crop growth and yield, and on plant diseases. Increased levels of O₃ may affect the susceptibility of plants to diseases, but results from experimental studies are equivocal. It has been suggested that elevated ozone may favour infection of plants by necrotrophic pathogens, primarily through causing early senescence of tissues (Bearchell et al., 2005). As a general rule, it is probable that the effect of enhanced O₃ on plant pathogens will depend primarily on the stage of pathogen development at which it is exposed to O₃. (Fuhrer, 2003).

4.3 Effects of climate on vectors

Many important plant diseases, mainly viruses and mycoplasmas, are spread by arthropod vectors. Hence, in these pathosystems, the effect of climate on vector survival, reproduction and efficiency of pathogen transmission is directly linked to disease development. Temperature thresholds have been established experimentally under controlled environmental conditions for many insects. However, these thresholds only provide a crude estimate of insect responses to changes in temperature under field conditions. For example, in attempting to explain why populations of the sweetpotato whitefly *Bemisia tabaci* in Latin America do not establish at altitudes above 1000 metres above sea level, Morales and Jones (2004) found no simple relationship with temperature. Based on empirical meteorological data, they postulated that whitefly populations could only be sustained at these elevations when the mean temperature in the hottest month was above 21°C. A climate probability model was then developed and used to predict regions prone to whitefly-borne epidemics. The rule-based model predicted that high geminivirus disease regions had a dry season of at least four months with less than 80mm of rain, and a mean temperature of the hottest month exceeding 21°C. Thus, the effect of climate on vector-borne plant diseases can be complex, and it is difficult to generalise potential future impacts due to climate change. This is supported by other examples of insect responses to climate change reviewed by Bale and co-workers (2002), who suggest that predictions need to take account of factors such as phenotypic and genotypic flexibility.

4.4 Effects of climate on trees

Little attention has been paid to the potential effects of climate change on tree diseases, but this is now beginning to change in some countries. In Canada, for example, disease monitoring is being intensified as it is believed that warmer winter temperatures and more frequent droughts will affect forestry diseases in the eastern part of the country (Hopkin et al., 2005). Projections of disease impacts due to climate change are needed for forest management plans, which need to take account of all the factors likely to affect the future growth of trees. Due to the requirement for large areas of land with suitable terrain and the need to obtain returns on investment in existing infrastructure such as saw mills, it is probable that commercial forestry will continue to operate for some time after climatic conditions become marginal for production.

5 Evidence of climate change affecting plant disease

Evidence of the effects of recent climate change on plants and plant diseases is beginning to emerge from empirical studies. In Australia, recent climate change was reported to account for 30-50% of grain yield increases of wheat (Nicholls, 1997). Most of the observed yield increase was attributed to a rise in minimum temperature. By contrast, an increase in minimum temperatures was associated with a decline in rice yields in Asia (Peng et al., 2004). Here, yields decreased by 10% for each 1°C increase in minimum night time

temperature, and there was no measurable effect of the much smaller increase in daytime temperature on yield. Again, this demonstrates that caution needs to be exercised in making generalisations about likely impacts due to changes in climate.

A recent study on the effects of climate change on agriculture in the USA highlighted the increased crop damage caused by a greater frequency of extreme weather events in the 1980s and 1990s (Rosenzweig et al., 2000). Warmer winters have allowed pests such as the European corn borer, *Ostrinia nubilalis* Hübner, to extend their range northward and to increase their number of generations per year. Similar phenological shifts in insects due to warming have been reported from the UK (Whittaker, 2001). Data show that, during warm summers in the UK, certain insect species have extended their range further northwards (Morecroft et al., 2002). Impacts on insect distribution and abundance have also been reported from tropical zones. In 2002, a serious outbreak of the B-biotype of *Bemisia tabaci* occurred on tomato and beans in the Cauca Valley in Colombia, which led to severe begomovirus disease epidemics (Morales and Jones, 2004). The affected area is considered to be marginal for whiteflies, but the unusual prolongation of the dry season in 2002 created favourable conditions for a disease outbreak.

Recent climate change has also had direct impacts on plant pathogens in temperate areas. In the USA, the northward spread of soybean sudden death syndrome is thought to have been associated with increased rainfall and higher temperatures. The disease, which is caused by a soil-borne fungus, was largely restricted to the Mississippi River Delta area in the 1970s. By the end of the 1990s it had reached as far north as Ontario (Rosenzweig et al., 2000). It is also thought that the emergence of wheat scab in the Great Plains region may be associated with rising temperatures during the past decade (Rosenzweig et al., 2001).

It has recently been established that there is a causal link between anthropogenically-induced atmospheric pollution and a major disease of wheat in the UK. An unexpected association was identified between levels of atmospheric sulphur dioxide (SO₂) and the relative abundance of two fungal pathogens of wheat, that cause septoria leaf blotch diseases. Using archived wheat samples from a long-term experiment which began in 1843 at Rothamsted, a 160-year time series of the abundance of *Mycosphaerella graminicola* and *Phaeosphaeria nodorum* was generated (Bearchell et al., 2005). DNA extracts from leaf and stem material were analysed using quantitative real-time polymerase chain reaction (PCR) assays. A close relationship was found between changes in the ratio of the two pathogens and changes in atmospheric SO₂ emissions in the UK during the 160-year period of the study.

The significance of the association between changes in pathogen ratio and increases in SO₂ emissions is strengthened by the correlation between UK SO₂ emissions and changes in the ratio of stable sulphur isotopes in grain and straw from the Rothamsted experiment. The greatest period of change in the pathogen ratio occurred during the 1980s when the abundance of the

previously dominant *P. nodorum* declined, and *M. graminicola* became more prevalent. The change in the pathogen ratio was also correlated with certain other examples of agronomic or environmental factors, such as harvesting technique and winter temperature, but these associations were weaker and considered less likely to reflect a causal relationship. There remains a possibility that decreases in peak concentrations of ozone (O₃) may also have contributed to the change.

Evidence is also beginning to emerge which suggests that the impacts of climate changes are being felt on plant diseases in natural ecosystems. Bisgrove and Hadley (2002) have highlighted the particular threat posed by *Phytophthora* diseases to native vegetation. Increased winter temperatures and longer periods of waterlogging will create favourable conditions for the development of root rots and blights. Prolonged dry periods during the summer will increase root stress and predispose plants to enhanced levels of disease. These authors suggested that water shortages in the summer and increased flooding in the winter are already leading to more rapid loss of trees and shrubs to *Armillaria*, *Phytophthora* and other pathogens.

6 Prospects for the future

6.1 Other drivers of change

Future climate change is one of many so-called 'drivers of change' likely to affect the incidence and severity of plant diseases in the future. In a recent review, Anderson et al. (2004) assessed the potential contribution of several drivers of change to the successful establishment of emerging infectious diseases (EIDs). They concluded that the primary cause of the majority of plant EIDs is the anthropogenic introduction of parasites. This has resulted from the rapid growth in international trade in recent decades, which has led to a series of new disease introductions. Furthermore, given current projections of continuing increases in the volume of global trade and the amount of international air travel, it is highly likely that the number of introduced diseases will also rise (Daszak and Cunningham, 2003).

The study by Anderson et al. (2004) also suggests that severe weather events are making an important contribution to the emergence of plant diseases in new locations. There is an important interaction here, with the introduction of alien plant pathogens through trade in live plants, seeds and plant products. There is a greater likelihood that invasive diseases will become established as climate change will also allow some plants and pathogens to survive outside their historic ranges (Harvell et al., 2002). In Britain, a new framework has been established by the Department of Food and Rural Affairs to evaluate the potential for any non-native organism, whether intentionally or unintentionally introduced, to enter, establish, spread and cause significant impacts in all or part of the UK (Baker, 2005). This framework would allow future climate scenarios to be reflected in future pest risk assessments for specific organisms (Holt, 2005).

6.2 UK

Potential impacts of climate change in the 2020s and 2080s for some economically important diseases of cereals, oilseed rape and potatoes in the UK are shown in Table 1. The list of diseases is intended to be illustrative and is by no means comprehensive; the absence of suitable data does not allow a comprehensive table to be constructed. Incidence and severity data have been taken from exhaustive field surveys conducted in commercially-grown crops in recent years. The fullest data are available from the wheat disease survey, which covers the period between 1989 and 1998 (Hardwick et al., 2001).

Table 1 shows that some stem and leaf pathogens of wheat and barley are likely to become less important by the 2020s and that this trend may continue into the 2080s. In the case of yellow rust of wheat, caused by *Puccinia striiformis*, several factors are likely to contribute to reduced incidence of the disease. Higher summer temperatures and longer dry periods will reduce disease levels in the crop, and warmer winters will reduce survival of inoculum into the following season.

Table 1 Economically important diseases of major field crops in the United Kingdom and the potential impacts of future climate change

<i>Pathogen type</i>	<i>Mode of transmission</i>	<i>Crops affected</i>	<i>Incidence and severity</i>	<i>Effects of climate</i>	<i>Likely impacts of climate change in 2020s and 2080s</i>	<i>References</i>
FUNGAL						
<u>Root and stem base:</u>						
Take-all , caused by <i>Gaeumannomyces graminis</i>	Soil-borne	Wheat, barley, oats and rye	Incidence ¹ : 27.3% Severity ¹ : category 1 (17.5%), 2 (5%), 3 (3.4%), 4 (1.4%)	Incidence of the disease greatest in the north and west of the UK.	Uncertain. Effects of increasing soil temperature?	-
Eyespot , caused by <i>Tapesia yallundae</i> and <i>T. acuformis</i>	Soil-borne (survives on infected stubble) but spread through rain-splashed conidia.	Wheat, barley, oats and rye	Incidence ¹ : 87.8% Severity ¹ : slight (17.1%), moderate (10.8%), severe (0.3%)	Recent increase in incidence and severity of the disease may be linked to milder autumns and winters, and wetter periods in late spring.	Uncertain. Likely to be mainly influenced by rainfall distribution patterns.	1
<u>Stem and leaf:</u>						
Septoria leaf blotch , caused by <i>Mycosphaerella graminicola</i>	Rain-splash or airborne spore dispersal	Wheat	Incidence ¹ 69% Severity on 2 nd leaf ¹ : 2.6%	Requires cool, moist conditions for disease development and rainfall to initiate secondary infections.	Importance likely to decrease as early as 2020s. Higher summer temperatures will suppress disease levels.	
Rynchosporium leaf blotch , caused by <i>Rynchosporium secalis</i>	Airborne spore dispersal, but local spread via water droplets is important. Also seed-borne.	Barley, rye	The most severe foliar disease on barley for seven consecutive years to 2003-04 in national survey (>90% incidence) ²	Disease spread is favored by damp, cool conditions and little spread occurs at temperatures above 20°C.	Importance likely to decrease as early as 2020s. Higher summer temperatures will suppress disease levels.	

Net blotch , caused by <i>Pyrenophora teres</i>	Conidia and ascospores spread in rain-splash and air currents.	Barley	Consistently present at moderate incidence levels in national survey. ²	Disease spread is favored by wet or very humid conditions during the summer.	Importance likely to decrease as early as 2020s. Higher summer temperatures will suppress disease levels.	-
Powdery mildew , caused by <i>Blumeria graminis f. sp. hordei</i>	Airborne dispersal of spores (conidia)	Wheat, barley and other cereals N.B. Specialised forms exist on each crop	Incidence ¹ : 53% Severity on 2 nd leaf ¹ : 0.5% On barley, mildew also consistently present at moderate incidence levels	Disease development is favored by warm and dry weather.	Hotter and drier summers are likely to enhance disease incidence, but temperatures at the top end of the range may depress disease levels by 2080s.	-
Yellow rust , caused by <i>Puccinia striiformis</i>	Airborne dispersal of uredospores	Wheat, barley and rye	Incidence ¹ :8.3% Severity on 2 nd leaf ¹ :0.1 %	Requires free water for infection and disease favored by cool, wet summers. High temperatures and extended dry periods would reduce disease levels and carryover of inoculum to next crop.	Hotter and drier summers are likely to reduce the importance of this disease.	-
Brown rust , caused by <i>Puccinia recondita</i>	Airborne dispersal of uredospores	Wheat and rye	Incidence ¹ : 17.9% Severity on 2 nd leaf ¹ : 0.3%	More prevalent in the drier eastern and south-eastern regions of the UK.	Uncertain.	-
Late blight , caused by <i>Phytophthora infestans</i>	Airborne dispersal of spores	Potato	High incidence in 1998 to 2000, when present in 13% of crops. The incidence of foliar infection was particularly severe in 1998.	Disease development is facilitated by moist and cool conditions during crop growth.	Hotter and drier summers are likely to reduce the importance of this disease, although earlier disease onset may act in the opposite direction.	3, 4

Phoma stem canker , caused by <i>Leptosphaeria maculans</i> (anamorphic stage <i>Phoma lingam</i>)	Airborne dispersal of ascospores	Oilseed rape	Incidence generally lowest in the cooler north of the UK. In 2003-04 a total of 26.6% of stems were affected in the summer, compared with 69.7% in 2002-03.	Complex relationship between temperature and rainfall at different stages of plant development. The most damaging early infections are favored by wet conditions.	Higher temperatures and extended dry periods in the summer are likely to reduce disease levels. However, climatic conditions during early plant growth also important and projections are difficult.	6
Light leaf spot , caused by <i>Pyrenopeziza brassicae</i> (anamorphic stage <i>Cylindrosporium concentricum</i>)	Airborne dispersal of ascospores, with secondary infections through rain-splashed conidia	Oilseed rape	Highest disease incidence generally recorded in northern regions. Low pod incidence of 3% in 2003-04 (10.7% in 2002-03).	Requires cool, damp conditions for disease development and rainfall to initiate secondary infection.	The disease is likely to become less important, particularly by the 2080s	5
VIRAL						
Barley yellow dwarf virus	Vector-borne. Persistent transmission by aphids; primarily <i>Rhopalosiphum padi</i> and <i>Sitobion avenae</i>	Wheat, barley and oats.	Incidence: 19.3% Severity: Category 1 (14.1%), 2 (2.8%), 3 (2.0%), 4 (0.5%)	Mild winters and warm springs favour the survival and early development of aphid vectors. However, hot dry summers increase aphid mortality.	Uncertain. Milder winters will favour disease development. By 2080s, assuming highest projections for increases in temperature, disease incidence may decrease.	7

Note: Disease incidence and severity data have been calculated from data provided in national disease surveys available at:

<http://www.cropmonitor.co.uk/commercialsurvey>

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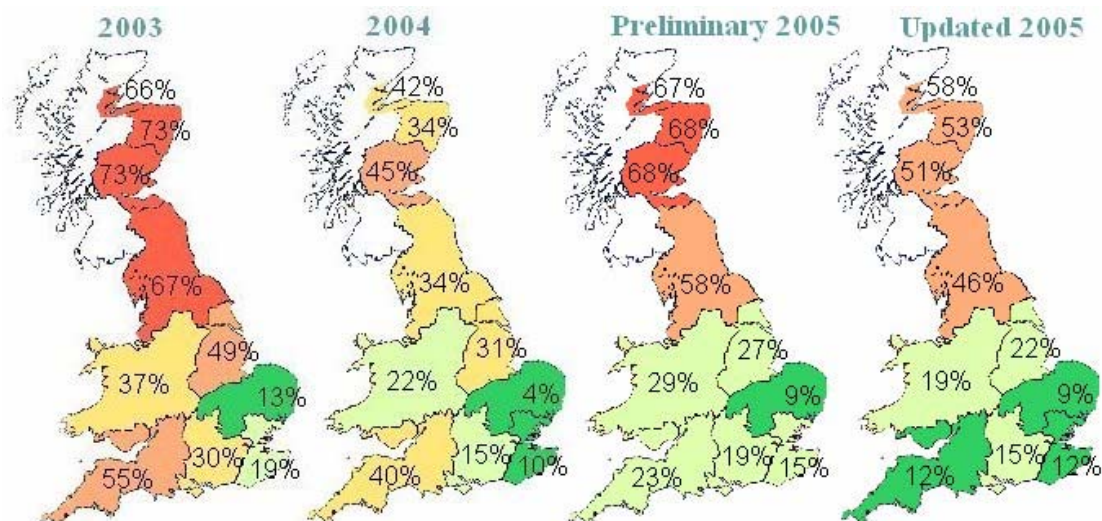
For pathogens spread by rain-splash as well as airborne dispersal, the situation is rather more complex. Most of the major fungal pathogens of cereals thrive in cool, damp or humid conditions so higher summer temperatures will help to depress disease levels. The historical wheat disease survey showed a strong correlation between reduced number of rainy days and severity of both septoria leaf blotches and eyespot, caused respectively by *Tapesia yallundae* and *T. acuformis* (Hardwick et al., 2001). As noted above, the spread of spores through rain-splash is more efficient during periods of heavy rainfall. Hence, future disease levels will depend on the intensity of rainfall as well as its temporal distribution. However, the survey results for septoria leaf blotch diseases and eyespot do suggest that these diseases may reduce in importance under future climate change scenarios. The overall picture for many fungal diseases appears, therefore, to be one of declining importance. Even powdery mildew, caused by *Blumeria graminis*, may become less of a problem. Although the development of this disease is favoured by warm weather, pustule development is retarded at temperatures above 25°C.

The difficulties in predicting likely outcomes for individual diseases under future climate change scenarios are well illustrated by the case of late blight of potato. Different approaches to forecasting the impacts of climate change on plant diseases can result in widely differing conclusions. Coakley et al. (1999) drew attention to the use of two modelling approaches, which led to contrasting results for *P. infestans*. In one study, historical disease monitoring data sets from Germany were used to develop empirical climate-disease models for a range of host-pathogen combinations, including potato late blight (Jahn et al., 1996). The conclusion was that the incidence of the disease would reduce to only 16% of its level at the time of the study. By contrast, results from a population model developed for potato plant growth and late blight outbreaks in Finland indicated that tuber yield gains would be largely counterbalanced by earlier outbreaks of the disease (Kaukoranta, 1996). Hence, the key issue would appear to be whether less favourable conditions for disease development during the growing season are offset by earlier disease onset.

At present, there is a clear geographical division in the two most important fungal diseases of oilseed rape, *Brassica napus*. Light leaf spot disease, caused by *Pyrenopeziza brassicae*, is prevalent in the cooler and wetter northern and western regions of the UK (Welham et al., 2004 and Figure 1). By contrast, the incidence of phoma stem canker, caused by *Leptosphaeria maculans*, is particularly high in the warmer and drier southern and eastern regions. Warming is likely to reduce the incidence of light leaf spot. By the 2080s it may become a relatively minor disease (N. Evans, personal communication). The impact of future warming on phoma stem canker is more difficult to predict. Stem infections are associated with leaf scars, with the most severe cankers being formed from infections which arise before the period of rapid stem extension (West et al. 2001). Hence, conditions during the summer and early autumn are critical for disease development. Higher temperatures and drier conditions would delay the development of pseudothecia and the subsequent release of ascospores. Warmer winters,

however, would create more favourable conditions for disease development, and canker onset would be hastened. Thus, whilst predictions are somewhat hazardous, it might be expected that less favourable conditions during the critical, early stages of plant growth would act to reduce disease incidence.

Figure 1: Mean incidence of light leaf spot on winter oilseed rape in Great Britain in 2003-2005. Data are derived from regional forecasts and show the percentage of crops with more than 25% affected plants.



Source: <http://www3.res.bbsrc.ac.uk/leafspot/hist/index.html>

Note: The preliminary annual regional forecast for light leaf spot is made around September and is based on disease incidence on pods in the previous season, deviation from 30 year mean summer temperature data and 30 year mean rainfall data. The forecast is later updated to include deviation of actual winter rainfall data from the 30 year mean.

Certain vector-borne virus diseases are likely to increase in importance under future climate change scenarios. This is largely due to the prospect that aphid survival and early population development are likely to be favoured by increased winter and spring temperatures in the UK. One study, utilising historical data from the Rothamsted Insect Survey, suggests that, for each 1°C increase in mean winter temperature, the migratory phenology is advanced by 4-19 days for both holocyclic³ and anholocyclic species (Zhou et al., 1995). Increased winter survival and spring migration of the anholocyclic species will place winter-sown cereals at greater risk of BYDV infection at a time when they are susceptible to greater yield loss. Climate warming may mean that it will become increasingly difficult to produce virus-free stocks of potato seed tubers in Scotland, where the seed industry is currently concentrated. This is supported by experience from the USA, where an analysis of historical records of outbreaks of potato leaf roll in North America from 1930 to 1991 suggests that there is a link with years of drought (Bagnall, 1991). Higher aphid densities in the summer are also likely to increase direct

³ Overwinters as diapausing eggs

yield losses to crops, although this effect may be counteracted by more efficient natural enemy action (Cammell and Knight, 1992).

Whitefly problems in the UK are presently restricted largely to glasshouse cultivation. However, with current climate change scenarios, southern regions will become suitable for the reproduction and survival of exotic species. The greatest concern is that the highly damaging *Bemisia tabaci* will become established and pose a threat to a wide range of horticultural crops.

It is likely that, by the 2080s, the current geographical range of some plant-parasitic nematodes will have extended significantly and that other species will emerge as important crop pests. A survey of the distribution of the most abundant plant-parasitic nematode in the UK, *Longidorus caespiticola*, was conducted throughout most of the British Isles (Boag et al., 1991). The results showed that the distribution of *L. caespiticola* was largely determined by the location of the 14°C isotherm. The authors predict that a 1°C rise in temperature would allow *L. caespiticola* to become established as far north as the 13°C isotherm. This would mean that its range would extend to cover the whole of England and much of the fertile agricultural land in Scotland.

With regard to the emergence of new nematode pests, there is concern about several economically-important species of root-knot nematodes, *Meloidogyne* spp. At present, *M. javanica*, *M. incognita* and *M. arenaria* are present in sheltered cultivation systems, but do not occur in the field in the UK. These nematodes could become established if soil temperatures in the top 10cm layer did not fall below 10°C. Furthermore, the native *M. hapla* and some other non-indigenous *Meloidogyne* spp might become more damaging if average soil temperatures during the winter increase in line with current predictions (S. Gowen, personal communication). However, there is a more positive dimension to this scenario. Increased soil temperatures may result in improved control of horticultural pests such as the vine weevil by predatory nematodes (Bisgrove and Hadley, 2002).

Several tree species will be at greater risk from *Phytophthora* diseases which thrive during warm and moist winters. Diseases such as holly leaf blight, caused by *Phytophthora ilicis*, and *Phytophthora* root rot of yew, caused by *Phytophthora cinnamoni*, will be favoured by warmer and wetter conditions (Bisgrove and Hadley, 2002). *Phytophthora cinnamoni* is likely to be more severe throughout its current geographical range, and to spread into eastern and northern areas where it is not currently present.

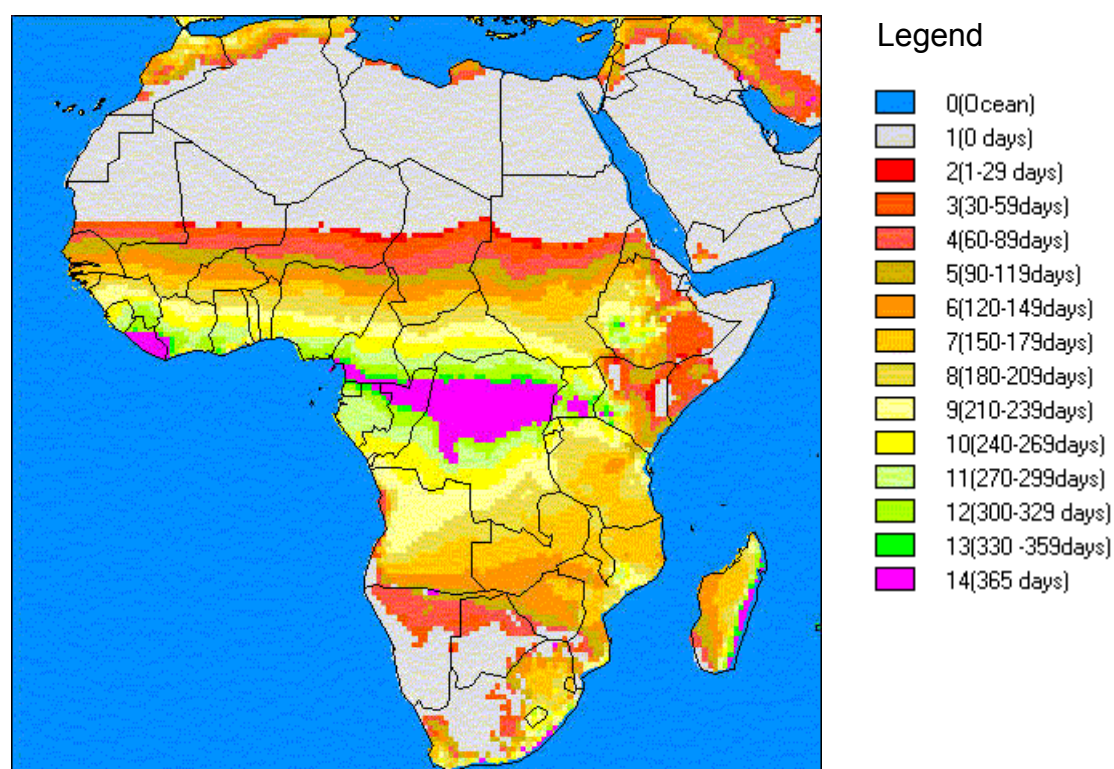
6.3 Sub-Saharan Africa

In sub-Saharan Africa, some crops are currently grown under conditions close to their maximum temperature tolerance (Houghton, 2004). Where this is combined with significant water stress, crop yields, which are already low, will be increasingly difficult to maintain. Thus, the most serious effects of climate change on agricultural production in sub-Saharan Africa are likely to occur in arid and semi-arid regions (Figure 2). For this reason, we consider potential effects on some key plant diseases in these marginal agricultural systems (Table 2). The diseases shown were identified as the most economically

important in the agroecological zones indicated in Table 2 (Geddes, 1990). Most of the crops affected are subsistence crops and are, therefore, important for food security. Some, such as groundnut, may also be sold for cash, and this can provide a vital source of income for poor families.

Figure 2: Agro-ecological classification for Africa based on the length of available growing period (LGP), defined as the number of days during the year when rain-fed soil moisture supply is greater than half potential evapotranspiration (PET). Arid areas have an LPG of less than 75 days; semi-arid areas lie in the range 75-180 days.

Source: <http://lead.virtualcenter.org/en/dec/toolbox/Refer/africa.htm>



A large proportion of damaging plant diseases in these marginal ecosystems are caused by viruses, the majority of which are vector-borne (Thresh, 2005). Cowpea mosaic and groundnut rosette diseases are transmitted by aphids, as is sweetpotato feathery mottle virus, which combines with the whitefly-borne sweetpotato chlorotic stunt virus (SPCSV) to cause the sweetpotato sweetpotato virus disease complex. Cassava mosaic disease and SPCSV are transmitted by whiteflies, *B. tabaci*, and the disease is also propagated through infected planting material. Maize streak disease is transmitted by leafhoppers, *Cicadulina* spp. Currently, the abundance of each of these disease vectors is associated with higher than average temperature and rainfall. It might be expected that future temperature increases would favour greater vector abundance, but this may not occur in areas where rainfall declines. Reduced rainfall would have a greater impact on aphids and leafhoppers than on whiteflies. Thus, the picture is complicated and will also be influenced by other factors. Increased vector abundance may be offset by a decreased rate of pathogen development, particularly under the

temperature increase projections at the upper end of the scale for the 2080s scenario. It is also likely that ongoing resistance breeding programmes will lead to the development of improved resistant or tolerant varieties. This would also work to reduce virus disease levels.

Most of the other important crop diseases in arid and semi-arid ecosystems are caused by fungi, and two of the most damaging fungal diseases are shown in Table 2. Southern leaf blight, caused by *Helminthosporium maydis* and northern leaf blight, caused by *H. turcicum*, can be highly destructive on both maize and sorghum. These diseases require moist and humid conditions for optimum development (Shurtleff, 1980), and it is likely that the distribution of the diseases will change according to future rainfall distribution patterns. Sorghum head smut, caused by *Sporisorium holci-sorghii*, is a soil-borne pathogen which is likely to be favoured by hotter and drier conditions. These will lead to more rapid pathogen development and a generally more conducive environment for pathogen survival and increase. In areas where maize is replaced by sorghum, some of which are already marginal for maize cultivation, sorghum head smut is likely to become a more serious constraint to crop production.

Table 2 Economically important diseases of the major field crops in the sub-Saharan Africa likely to be affected by future climate change in arid and semi-arid environments.

Pathogen type	Mode of transmission	Crops affected	Distribution (Agroecological zones) (Geddes, 1990)	Effects of climate	Likely impacts of climate change in 2020s and 2080s
Fungal					
Leaf blight – Southern leaf blight (Helminthosporium maydis) Northern leaf blight (H. turcicum)	-Airborne dispersal of spores -Seed borne	Maize, Sorghum, Wheat, Sugar cane	Semi-arid East and South; Forest Savanna transition	-Optimum disease development occurs at temperatures of 20-32 ^o C and conidia germinate at 8-27 ^o C. -High humidity is favourable for disease development, whereas extended periods of hot weather arrest disease spread. (Shurtleff, 1980)	Uncertain. Importance may be reduced in regions with prolonged droughts.
Sorghum head smut (Sporisorium holci-sorghii)	Soil borne - teliospores	Sorghum, Maize, Sudan grass, Beard grass (Geddes, 1990)	Semi-arid East and South	-High rainfall and relative humidity at flowering favourable for disease development. -Damp soils are conducive to disease spread and high soil temperatures suppress the pathogen. (Wrather, 2005)	- By 2080s, the climate is likely to result in increased pathogen development and survival. - This may be counterbalanced if increased sources of disease resistance are available, but lack of resources to invest in resistance breeding programmes. (R. Hillocks, personal communication)

Viral					
Maize streak virus (MSV)	Several leafhoppers (LH)(Cicadulina mbila -major vector)	Maize and many other grasses	Sudan savanna, Semi-arid East and South,	<ul style="list-style-type: none"> -Prevalence of MSV is closely associated with LH populations -C.mbila survive and reproduce readily at 20-30⁰C (Hadidi et al., 1998) -Low temperatures are associated with increased leafhopper development time, longevity and reduced fecundity. -In agroecological zones with bimodal rainfall pattern and two cropping seasons, MSV is more severe in the second season and irrigated fields are more severely affected. 	Higher vector abundance is likely in areas where rainfall is not limiting. This is likely to result in increased incidence of MSV. In more marginal areas for maize cultivation, the crop is likely to be displaced by more drought-resistant crops such as sorghum.
Cassava mosaic virus	Whitefly (Bemisia tabaci)	Cassava	Sudan savanna, Semi-arid East and South,	<ul style="list-style-type: none"> -Increased vector abundance with higher temperatures and rainfall. -Highest whitefly activity was found at 27-32⁰C (Thurston, 1998) 	<p>Increased disease incidence is likely due to:</p> <ul style="list-style-type: none"> -Increased vector abundance, more effective vector dispersal and, possibly, increased genetic diversity. -The increased movement of infected cuttings may also enhance disease spread. <p>Increased disease levels may be modified by:</p> <ul style="list-style-type: none"> -Decreased rate of pathogen development -Improved host resistance <p>(J.M. Thresh, personal communication)</p>

Sweetpotato virus complex Feathery mottle virus (SPFMV) and chlorotic stunt virus (SPCSV)	Aphids (for SPFMV). Whitefly Bemisia tabaci (for SPCSV)	Sweetpotato and other Ipomea sp	Uganda and L. Victoria zone, Mountains, Sudan Savanna	-Increased vector abundance with higher temperatures -Sweetpotato whitefly egg development is optimum at 27°C and low temperatures increase egg mortality	Likely outcomes are broadly similar to those indicated for cassava mosaic disease (above) (J. Legg, personal communication)
Cowpea mosaic	Aphid-borne	Cowpeas	Sahel, Semi-arid East and South	- Developmental period of instars is extended at low temperatures but mortality increases when temperatures reach a critical threshold.	Uncertain. Importance may be reduced in regions with prolonged droughts.
Groundnut rosette	Aphid-borne Aphis craccivora	Groundnuts	Sahel, Sudan savanna, Semi-arid East and South,	-Vector population increases with increase in rainfall and temperature (Hadidi et al., 1998)	Uncertain. Importance may be reduced in regions with prolonged droughts.

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7 Conclusions

Future climate change is likely to affect the incidence and severity of some plant diseases in both the UK and Africa, but the absence of reliable epidemiological information makes predictions hazardous. What we can say with more confidence is that the geographical distribution of some plant hosts and disease pathogens will alter as a result of future changes in climate and, especially in Africa, this effect is likely to be strongest in areas of significant water stress.

Improvements in crop management practices, particularly advances in breeding for disease resistance, may counteract enhanced susceptibility to disease in some crops. However, this is less likely to occur in subsistence crops such as sorghum, where little investment is currently being made in crop improvement programmes. In the UK, where many of the most economically-important diseases are caused by fungi, the use of fungicides is likely to continue as a primary means of control into the foreseeable future. For example, it has been estimated that fungicide use for late blight control in potato will increase by 15-25% over the coming decades (Fry and Goodwin, 1997).

In the future, there is a clear need to improve the availability and quality of data for plant disease forecasting. One way is through crop models, which provide a useful means of analysing a wide range of crop interactions subject to the influence of climate change, including the effects of plant diseases (Strand, 2000). Constraints imposed by plant diseases have not been explicitly incorporated into most crop models to date. But there should be greater opportunity to consider them as new modelling techniques are developed (Chakraborty et al., 2000).

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