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Impact of climate change on diseases in sustainable arable crop systems: CLIMDIS

by

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1. ABSTRACT

Climate change is predicted to lead to milder, wetter winters and hotter, drier summers for the UK. Crops will advance growth with current wheat cultivars flowering 2-weeks earlier and harvested three weeks earlier than traditionally. ‘Mediterranean-types’ of cereals could advance these growth stages by another 2 weeks. Elevated CO_2 concentrations will increase crop productivity, as long as diseases and pests are controlled. Crops will probably move slightly to the north, with potential new crops such as maize and sunflower grown in the south of England and many diseases will change in importance only slightly. However, the risk of newly introduced diseases establishing is increased by climate change so it is important to maintain or increase statutory crop monitoring, quarantine and surveillance and to ensure that crop genotype collections keep as much diversity as possible for future breeding programmes.

More extreme weather may make certain diseases (e.g. rusts and powdery mildews) more sporadic and encourage those that develop quickly in warm conditions. Insect vectored virus and phytoplasma diseases will increase due to greater vector activity. Many contradictory effects of climate change mean that some detailed knowledge of each pathogen’s life cycle and ideally climate-based disease-progress models are needed. We predict that rusts and powdery mildews will become more severe after mild weather in winter and early spring (assuming some dry days will allow dispersal) but less severe after particularly hot, dry weather in summer. Summer droughts may favour other pathogens that sporulate on debris due to reduced activity by molluscs and other invertebrates. A knowledge gap exists in understanding pathogen survival and the timing of spore release to infect subsequent crops as different responses to the climate by the pathogen and crop could lead to more or less infection. More research is also needed to understand impacts of climate change on soil microbes, particularly those that mitigate root diseases such as take-all. Generally warmer conditions will increase severity of autumn- and winter-infecting root and stem rots, while spring-infecting root and stem rots will advance with earlier crop growth and so not change in relative severity. However, yield losses from these diseases will also increase due to greater and earlier transpiration stress caused by heat or drought. Effects of increased CO_2 concentrations on plant pathogens also require further research. Increased CO_2 will lead to denser crop canopies, which will encourage a range of foliar diseases. Due to milder winters that will advance both crop growth and disease epidemics, T0 sprays could increase in importance. Leaf production in mid-late spring may also become so rapid that the timings of T1 and T2 sprays (relative to growth stage) will need revision in order to achieve optimal protection. Introductions of new pathogens (‘unknown unknowns’), changes in farm practices including new crops grown, complexities of climate change projections and the biotic responses to this make prediction of the future impact of climate change on plant diseases relatively uncertain. It is therefore also important to create funding mechanisms that can allow a rapid response to research new diseases. Climate change offers the opportunity to increase crop productivity and diversify cropping systems, and

emphasises the need to produce arable crops with a low carbon-footprint, while maintaining a secure and stable food supply.

ABBREVIATIONS

DON: Deoxynivalenol (mycotoxin)

EID: emerging infectious disease

IPM: integrated pest management

NAPPFAST: NCSU (North Carolina State University) APHIS (Animal and Plant Health Inspection Service) Plant Pest Forecasting System

OSR: oilseed rape

STICS: Simulateur mulTIdiscplinaire pour les Cultures Standard

UKCIP: UK Climate Impacts Programme

2. SUMMARY

2.1. Project aims and background

Europe is likely to experience milder wetter winters, hotter drier summers and more extreme weather events. As a result, arable cropping systems face new or increased threats from pests and diseases. It is difficult to predict impacts of climate change on crops and their diseases as many interactions are complex and non-linear. Associated with climate change, increases in atmospheric CO_2 are also likely to affect both crops and diseases. It is not all bad news. Climate change can be an opportunity and, managed correctly, crop productivity can increase with new arable crops and various tender vegetable and fruit crops potentially able to be grown outdoors on a wide scale. This project aims to inform industry and government about likely disease threats to UK arable crops in the future as a result of climate change. Although climate change is a gradual and long-term phenomenon, it is necessary to identify potential threats and, if necessary, conduct new research into them in the immediate future to optimise surveillance and disease control schemes, develop new crop protection methods and select cultivars with disease resistance. Breeding of elite cultivars with resistance to a new disease, or development of new crop protection products often takes over ten years. There is still considerable flexibility in arable crop systems to avoid or overcome any new disease problems as they arise, compared to systems such as orchards and forests, and arable farmers usually have added flexibility of being able to apply a crop protection product, or even to cut their losses and grow a different crop in the following season. Both disease-resistant crops and moderate use of crop protection products, when needed as part of Integrated Pest Management (IPM), are desirable in order to increase yields and such disease control methods actually decrease the carbon footprint of producing each tonne of crop-yield. Efficient crop production releases surplus land for alternative crops such as biofuel crops with a consequential increase in biodiversity and a reduction in green-house gas emissions associated with food production compared to low-input systems. This review considers fungal, bacterial and viral diseases of current key arable crops in the UK (wheat, oilseed rape, barley and sugar beet) and predicts likely changes to specific diseases in these groups, including new potential diseases, to inform industry and government, particularly to highlight R&D priorities. Predictions are based on the current climate projections of the UK Met office & United Kingdom Climate Impacts Programme (UKCIP), which are varied and subject to modification.

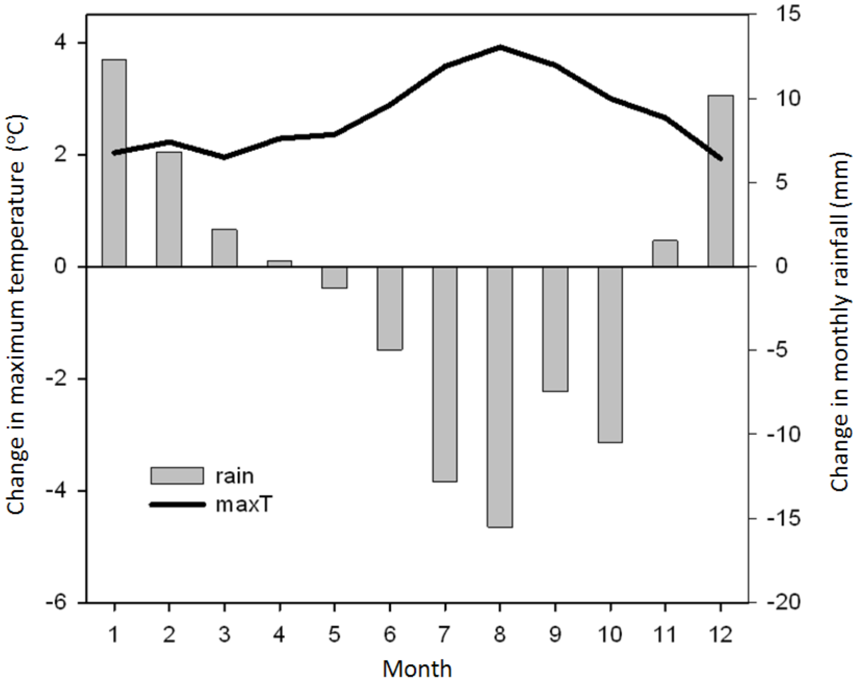
2.2. Factors influencing crop disease epidemics

Plant disease occurs when three factors combine: a susceptible host, sufficient effective pathogen inoculum and suitable environmental conditions. Farmers are able to reduce plant disease by using a range of integrated crop protection practices that affect these three factors, such as tillage to bury crop residues (on which new spores are often produced) and crop rotation to separate new crops from debris of previous crops, which both serve to reduce the amount of pathogen inoculum. Choice of cultivars that are resistant to certain pathogens affects host susceptibility, while the main environmental factor altered by the farmer's actions is application of crop protection products, such as fungicides to protect the crop at particular growth stages. Changes in disease pressure may occur due to altered sowing date but for broad-acre arable crops, the farmer has no control over the weather, which is the main environmental factor influencing arable crop diseases.

In particular, the weather can directly affect plant diseases by influencing the location and seasonal timing of release of spores that start disease epidemics. Changes to the weather affect the coincidence of inoculum (usually spores) and sensitive crop growth stages. Weather also affects the success of infection because suitable infection conditions are needed (most fungal plant pathogens require wetness or high humidity for infection). Temperature can increase or decrease the effectiveness of specific components of host resistance and the speed of disease development (pathogen growth and reproduction). Weather also affects pathogen survival (frost kills some pathogens while hot dry weather can reduce populations of those pathogens that only live on growing green leaves). Climate change may also have indirect effects due to the inclusion in arable rotations of alternative crops that can act as hosts for certain pathogens, e.g. maize is a host to *Fusarium graminearum*, which also affects wheat. Environment and particularly climate change has been predicted to lead to an altered geographic distribution of both crop hosts and their pathogens as well as changes in host pathogen interactions and yield-loss relationships. Areas growing particular crops are likely to move slightly to the north as the climate warms while at the southern edge of their distribution, change to diseases and crop productivity may result in some crops becoming unprofitable and other crops may be introduced.

2.3. General Predictions

The climate of the UK is predicted to be milder over winter and particularly warmer in the summer but also much wetter over the winter and drier in the summer (Summary Figure 1) and there will also be more extreme weather events.

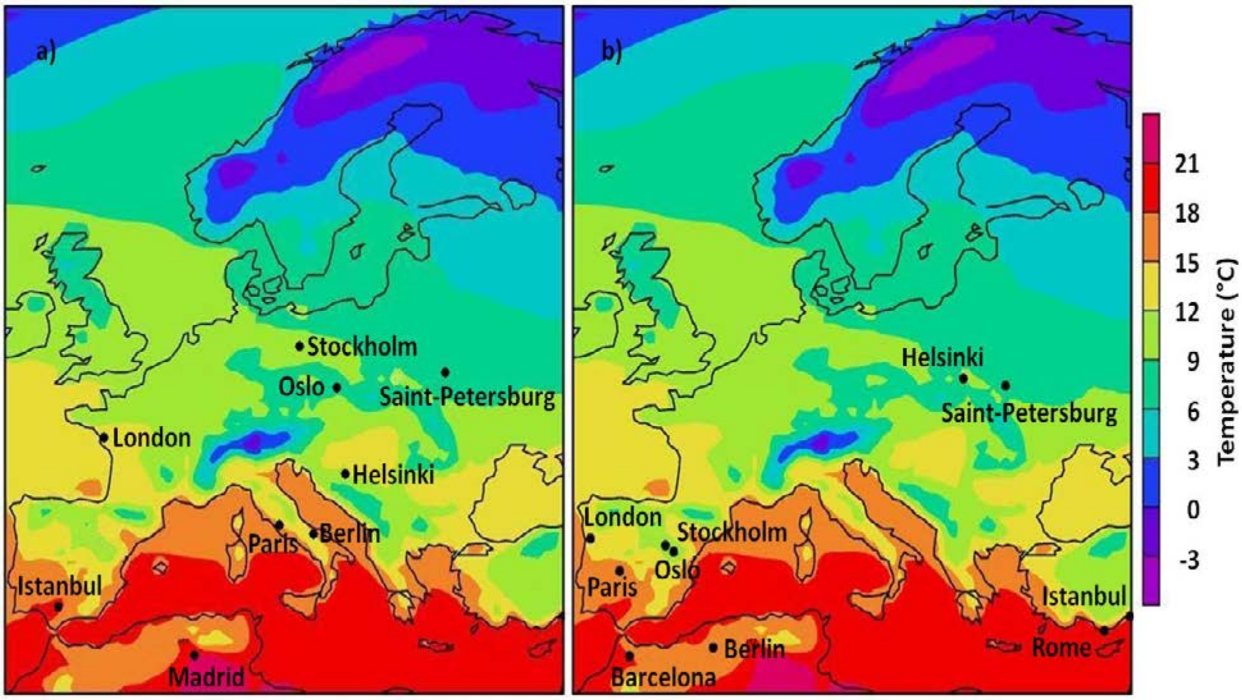


Summary Figure 1. Predicted change in temperature and rainfall forecast for Rothamsted, Hertfordshire, England, based on the HadRM3 scenario for the 2050s, modified from Semenov (2009) supplementary material.

Increased inoculum production per infection, increased pathogen aggressivity (altered host resistance) and/or increased infection success of pathogens (particularly those with many cycles of infection per season) could increase the rate of disease epidemics and final disease severity. Enhanced survival of pathogens may occur due to less crop debris being eaten by slugs, snails and other invertebrates over the summer, or by increased winter survival due to less-severe frost. This elevated survival will make disease epidemics appear earlier in the growing season. Additionally, changes to both crop and pathogen development in response to the climate may cause inoculum (disease propagule) production and susceptible crop growth stages to coincide more (which will increase disease incidence) or less (which will decrease disease – also known as 'disease escape'). Milder winters should therefore increase survival and epidemic rate of a range of foliar pathogens and cause spring epidemics to start earlier (rusts, mildews, leaf spots, etc). In contrast, very warm, dry and long summers should reduce over-summer survival of pathogens that need living green leaves (rusts). So rusts could become very sporadic because weather may be very favourable for a few years leading to a lot of disease, but the pathogen could decline to negligible levels for a few years following one or more years when weather patterns in the summer were unfavourable. Disease predictions considering climate change are usually not easy without mathematical models because often a climate-change scenario may promote one component of a disease epidemic but reduce another component of disease development. For example, with stem canker of oilseed rape, dry summers will delay ascospore release (suggesting a delayed or reduced epidemic) but milder winters will increase pathogen growth in the plant (suggesting increased disease development). Detailed research is therefore needed to understand what the outcome of these contradictory factors is likely to be – in the case above, the increased pathogen growth in the winter and spring outweighs the effect of delayed disease onset in the autumn and so final disease severity is predicted to increase.

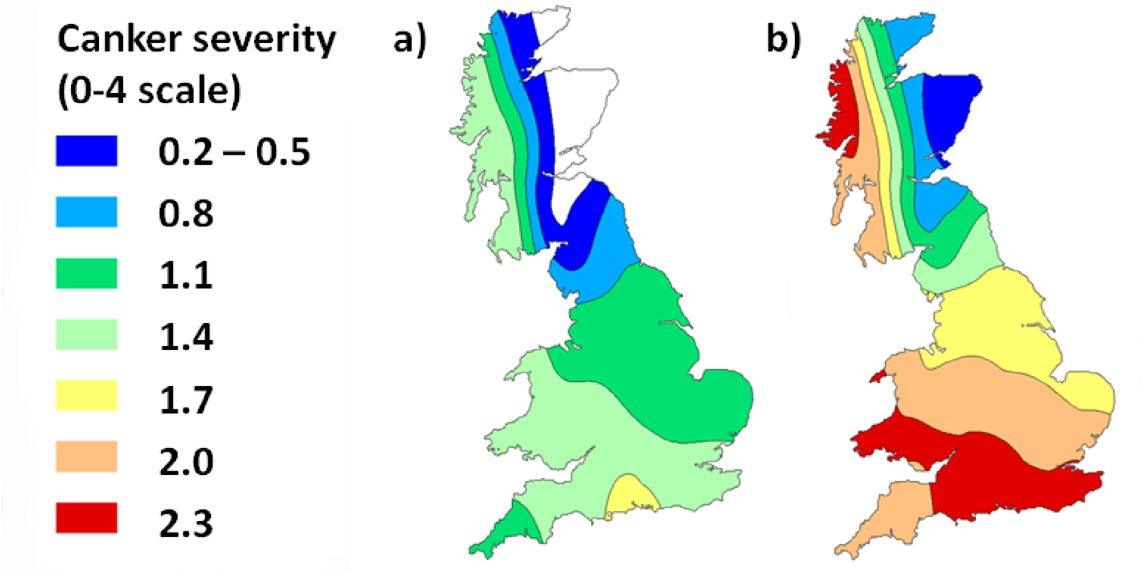
Introduction of a disease to a new location is still the main reason for new diseases occurring. Changes to climate should normally cause relatively small and gradual shifts in the range of existing diseases from the previous range. However, diseases that are newly introduced to an area usually spread faster than changes to the climate would suggest because the new pathogen is usually interacting with a host population that has developed little resistance to that pathogen. Establishment of the new disease can occur only if the crop system and climate is favourable for the pathogen to complete its life cycle (i.e. reproduce). Propagules of many new or rare pathogens frequently arrive in the UK, often in the wind or on imported plant products but they often do not establish because the climate is unfavorable. A key aspect of climate change is that it could enable a new range of introduced diseases to establish for the first time, rather than die out.

It is possible to use climate-matching software to map locations where key conditions needed by a pathogen are met in order to identify locations where increased surveillance is advised and mitigating control measures researched. An alternative approach is to identify locations that currently have a climate that is very similar to that projected for another location (say the UK) and to observe what crops and crop diseases occur there. However, climates currently similar to that predicted for the UK occur in very few locations because of the unique effect of our maritime situation and the gulf-stream (Summary Figure 2). Locations in south-west France (around Poitiers and Nantes) are most similar to the climate predicted for the UK in the 2050s. Septoria and brown rust are the two main wheat diseases there. In addition to wheat, maize and sunflower are also important crops of that region.



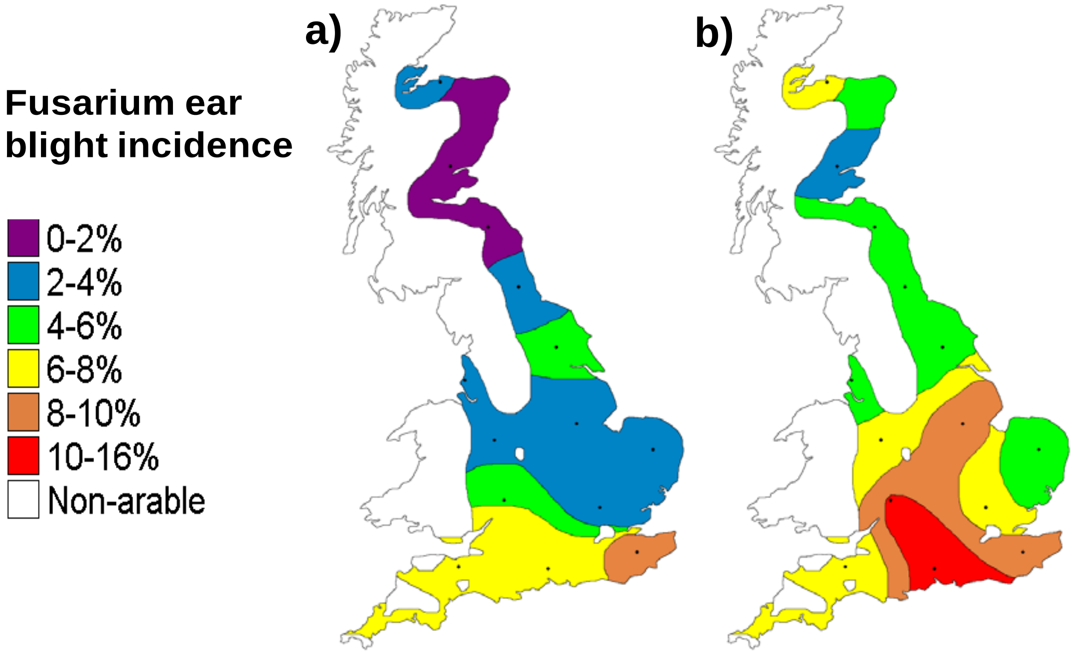
Summary Figure 2. Map showing the background mean temperature ranges of Europe (colours) for the period 1961-1990 and location of cities in places that have their predicted temperature patterns for the end of the 21st century according to two climate models; ARPEGE (a), and the HadRM3H (b) in an 'A2' global warming scenario (based on continued relatively high CO_2 emissions). Reproduced with permission from Kopf *et al.* (2008).

To help in this project's broad-ranging evaluation of possible diseases of arable crops, a detailed study of the likely response of both crop and crop-disease to the projected climate of the UK was made for phoma stem canker of oilseed rape and fusarium ear blight (specifically part of this disease complex caused by *Fusarium graminearum*) of wheat. Both studies tested predictions of a crop-growth model for oilseed rape and wheat, respectively. Climate change was found to advance flowering and harvest dates of both crops. Oilseed rape will flower approximately 3–4 weeks earlier than at present and a combination of both favorable and unfavourable effects of changed-climate on stem canker is predicted to lead to an overall increase in disease severity and a shift northwards in its range into eastern Scotland (Summary Figure 3; although not severely enough to affect yield in Scotland).



Summary Figure 3. Impacts of climate change on severity of phoma stem canker (*Leptosphaeria maculans*) at harvest of winter oilseed rape crops (mean of resistant and susceptible cultivars) for (a) baseline 1961–1990, (b) 2050s climates (mean of low and high emission scenarios); stem canker severity on a 0–4 scale (0, no disease; 4, plant dead); areas where crops are currently unaffected by the stem canker disease are marked white. Maps adapted from Butterworth *et al.* (2010).

Wheat flowering will be around 2 weeks earlier by the 2050s (4 weeks earlier if we switch to using 'Mediteranean-type' cultivars) and harvest will be 3 weeks earlier (or 5 weeks). Despite a shorter grain-filling period, yields in the absence of disease should be at least as good, if not greater than now because of the positive effect of greater CO_2 concentrations. Consideration of these altered growth stages is important because without it we would conclude that the incidence of fusarium ear blight will reduce substantially due to a decrease in occurrence of suitable wet conditions for infection occurring in early-mid June (the current flowering date over much of the UK arable area, slightly later in northern parts). However the predicted advanced flowering date means that suitable infection conditions will be only slightly less frequent than at present (see rainfall trend in Summary Figure 1). In the case of *F. graminearum*, warmer spring weather will increase spore production and additional spore release from maize debris is likely to lead to an overall increase in fusarium ear blight on wheat (Summary Figure 4). This is an example of an indirect effect of climate change on a crop disease.



Summary Figure 4. Maps showing the projected average fusarium ear blight incidence (% plants affected) generated by a fusarium ear blight model and based on advanced anthesis dates for two weather scenarios; baseline (a) and 2050s high emission scenario (b). The baseline scenario is based on weather from 1960–1990. The maps were produced by spatial interpolation between the 14 sites (adapted from Madgwick *et al*. 2011).

2.4. Effects of climate change on fungal crop diseases

Considering our findings from the two diseases studied in detail (phoma stem canker and fusarium ear blight), we furthermore conducted a broad-ranging review, categorising diseases into different ecotypes based on their survival, dispersal, epidemic type and plant tissue infected. As an exemplar for the first ecotype, we investigated the rain-splashed, polycyclic (many infection cycles per season) foliar fungal disease, septoria leaf blotch (*Mycosphaerella graminicola*) as this is currently the most important wheat disease in the UK. Septoria leaf blotch epidemics are started by air-dispersed ascospores (sexually-produced spores) in late summer and autumn but this is followed by many cycles of rain-splashed conidia (asexually-produced spores) and usually a second batch of ascospores in the spring. In summary of the literature, the disease is favored by dry summers, which increase inoculum survival, mild winters, which allow more infection and disease cycles and wet springs which promote rain-splashed dispersal and infection onto the most important leaf layers.

Moderately increased disease is likely for the following diseases that are similar ecotypes to septoria leaf blotch (*Mycosphaerella graminicola*). These are: leaf blotch or scald (*Rhynchosporium secalis*) and ramularia leaf spot (*Ramularia collo-cygni*) of barley; tan spot (*Pyrenophora tritici-repentis*) of wheat, and alternaria dark pod spot of oilseed rape (*Alternaria brassicae*). Most of these diseases are predicted to increase in severity due to more epidemic cycles, greater plant biomass, denser canopies, and wetter conditions for most of the vegetative crop growth period. Some, however, may reduce slightly if longer intercrop periods promote disease escape due to ascospore release ahead of emergence of the following crop. In other cases, drier summer conditions may reduce the breakdown of crop debris (reduced activity of detritivorous invertebrates) and therefore increase inoculum availability, which may also be better synchronised with crop emergence. Two exceptions in this group are *Pyrenopeziza brassicae*, which causes light leaf spot of OSR and is favoured by cool temperatures so a slight decrease has been predicted. The second is cercospora leaf spot of beet (*Cercospora beticola*), which unlike the others diseases in this group, causes most leaf infection in the summer months, which are predicted to be drier while the disease is encouraged by hot and wet or humid weather. Current research gaps for this ecotype are primarily in understanding over-summer survival and timing of spore release to infect the following crop.

For the ecotype including dry/air-dispersed biotrophic (have to live on a living green plant) foliar fungal pathogens, such as brown rust (*Puccinia triticina*) of wheat and powdery mildew (*Blumeria graminis*), it is likely that epidemics will continue since crop growth stages will advance to earlier in the year. However, epidemics may be more sporadic particularly following droughts in the previous summer, because inoculum will decrease if grasses and cereal volunteers suffer drought conditions in the summer. Epidemics become severe when dry clear weather in spring allows sporulation and dispersal and these days are typically followed by dew films at night, which allow infection. This weather combination is not likely to change in frequency very much. By late spring in the UK, dew periods overnight are shorter but temperatures warmer and so different temperature preferences for infection by different rust species (and powdery mildew) mean that epidemics of at least one or other will be sustained well into the grain filling period (brown rust is favoured by warmer conditions compared to yellow rust). Generally better winter survival will lead to earlier epidemics and possibly more spring sunshine hours and more plant biomass will also increase sporulation, particularly of yellow rust. It is therefore likely that there will be a moderate increase in these diseases on average but with large differences from year to year due to the effect of droughts on over-summer survival. Black stem rust (*Puccinia graminis* f. sp. *tritici*) may occur late in the season and has potential to develop to significant severities if the Ug99 race, which tolerates lower temperatures, becomes widespread in southern Europe. Currently this race has spread within Africa and the Middle East and has recently reached South Africa.

Rusts and powdery mildews of barley should follow a similar pattern to that predicted for the corresponding wheat diseases. The earlier maturation of barley will mean that growth stages up to flowering will, on average, experience milder, wetter weather, while flowering, grain-filling and harvest should be in progressively drier, warmer conditions than at present. There is scope for summer droughts to reduce the impact of these pathogens in the following growing season. Similarly, crown rust (*Puccinia coronata*) of oats is likely to become more severe following mild winters and warm spring weather.

For the ecotype including various ear/flower infecting fungi, there is very little change expected except for fusarium ear blight, caused by *F. graminearum*, which can increase due to the effect of more maize (another host) cultivation. There is a need to maintain quarantine to prevent karnal bunt (*Tilletia indica*) from establishing here.

We divided the ecotype of monocyclic (single cycle of infection per growing season) root and stem fungal diseases into those with autumn spore release, those with spring spore release and those that are soil-borne. Conclusions for the autumn-releasing pathogens were based on conclusions for phoma stem canker (*Leptosphaeria maculans*). Severe epidemics of this group of diseases are favoured by mild, wet autumn, winter and spring weather. High evapo-transpiration stress in the summer before harvest may also exacerbate the yield-loss per unit of disease as the upper parts of the plant will lose water faster than it can be supplied through diseased root and stem tissue, leading to plant stress and earlier senescence. An analogous cereal disease is eyespot (*Oculimacula acuformis* and *Oculimacula yallundae; Helgardia acuformis* and *Helgardia herpotrichoides*).

Monocyclic diseases caused by pathogens that release spores in spring are likely to remain sporadic. Less change in effect of disease is likely for spring-infecting pathogens as their spore release is likely to advance along with crop growth stage and harvest will also advance. The potential for disease to develop severely depends on temperature preferences of individual species. Closer rotations and inclusion of other hosts (beans, peas and various vegetables) also increases risk for pathogens with many hosts such as *Sclerotinia sclerotiorum* (sclerotinia stem rot). For *S. sclerotiorum*, spore release should advance after milder winters to stay synchronised with flowering; hence there is little change in weather-related risk predicted.

For soil-borne pathogens, such as *Verticillium longisporum* of oilseed rape and take-all (*Gaeumannomyces graminis var. tritici*) of wheat, disease development and yield loss is also exacerbated by dry and hot conditions in late spring/early summer. Closer rotations will encourage this type of disease and warmer spring-summer weather should increase risk. Foot rot of cereals, caused by *Cochliobolus sativus,* is also likely to increase as this pathogen is favoured by warmer conditions than traditionally experienced in the UK. However, antagonism and competition by other soil-inhabiting microbes is important for control of these diseases but a knowledge gap exists in understanding the impact of climate change on soil microbes generally. Little climate-related change is expected for root-invading foliar pathogens such as cephalosporium leaf stripe (*Hymenella cerealis*).

2.5. Effects of climate change on viruses, bacteria and phytoplasmas

Generally longer periods of migration and feeding activity of vectors and potential for new insect vectors, caused by warmer conditions and longer growing seasons will favour many insect-vectored virus diseases on a wide range of crops. An increased incidence of aphid-vectored viruses is predicted to occur due to either increased winter survival of aphids or their earlier spring migration. Already, mild winters have been associated with an increase in BYDV in cereals and virus diseases of sugar beet. In the southern edge of geographic crop areas, warmer soils will affect soil-borne viruses as vectors will potentially be able to infect crops at earlier growth stages and will have greater impact on development and yield. Symptoms and yield-loss may also be exacerbated by heat and drought. Bacterial diseases are likely to remain rare in arable crops but phytoplasmas, which are usually insect vectored, will follow the same trend as that predicted for insect-vectored virus diseases – becoming more severe.

2.6. Conclusions and implications for disease control options

Many diseases will on average change in importance only slightly because regions of production of particular crops will tend to move northwards. However, more extreme or variable weather may make certain diseases (e.g. rusts and powdery mildew) more sporadic. The sporadic nature of epidemics of these obligate foliar pathogens is likely to be due to greater winter survival in mild winters, which will enhance epidemics, while dramatic reductions in pathogen populations will follow severe summer droughts, which will kill ‘green bridge’ volunteers and wild grasses. Epidemics of these obligate pathogens will therefore depend on combinations of favourable and unfavourable summer and winter weather over more than one season.

Summer droughts will not affect those pathogens that sporulate on dead plant tissue, i.e. that survive saprophytically (living on the nutrients in the dead host material), and these may even be enhanced by reduced destruction of crop residues (by molluscs and other invertebrates) in dry summer weather, leading to increased inoculum production in the autumn. Generally a knowledge gap exists in understanding pathogen survival and the timing of release of spores to infect subsequent crops as different responses to the climate by the pathogen and crop could lead to more or less infection (less or more disease-escape).

Where crops remain in their original crop areas or particularly at the southern parts of their distribution, generally warmer conditions will exacerbate diseases such as stem and root rots (stem canker of OSR, eyespot and take-all of wheat) due to increased thermal time. Insect vectored virus and phytoplasma diseases will also become more important due to greater vector activity. Additionally, increased transpiration stress, heat or drought stress will speed-up symptom development and increase yield losses per unit of disease for many stem and root rots and some foliar diseases.

Increased CO_2 concentrations will lead to denser crop canopies, which will encourage a range of foliar diseases (rusts, powdery and downy mildews, and leaf blotch or spots). Increased CO_2 will also have various positive and negative direct effects on plant pathogens (systems studied so far have tended to show higher fecundity but longer latent periods) and further research could investigate combined effects of climate change and enhanced CO_2 on plant diseases.

Due to changes in crop canopy densities and milder winters that will advance both crop growth and disease epidemics, T0 sprays could increase in importance. Leaf production in mid-late spring may also become so rapid that the timings of T1 and T2 sprays (relative to growth stage) will need revision in order to achieve optimal protection. New crops such as maize could increase the incidence of wheat pathogens such as *Fusarium graminearum*. Sunflower may be introduced to southernmost England and this new crop may escape crop-specific diseases at first but will still be prone to generalists such as *Botrytis cinerea* and *Sclerotinia sclerotiorum*, the latter of which has capacity to return large numbers of sclerotia to the soil from each infected flower-head or stem. A knowledge gap exists in understanding the impact of climate change on soil microbes and particularly the effects of increased winter rainfall and decreased summer rainfall on them. Introductions of new pathogens, changes in farm practices including new crops grown, complexities of climate change projections (jet-stream changes may make it colder!), and the biotic responses to this, makes prediction of the future impact of climate change on plant diseases relatively uncertain. It is therefore also important to create funding mechanisms that can allow a rapid response to research new diseases and to maintain crop monitoring, quarantine and surveillance activities.