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REVIEW

Climate change, plant diseases and food security: an overview

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Global food production must increase by 50% to meet the projected demand of the world's population by 2050. Meeting this difficult challenge will be made even harder if climate change melts portions of the Himalayan glaciers to affect 25% of world cereal production in Asia by influencing water availability. Pest and disease management has played its role in doubling food production in the last 40 years, but pathogens still claim 10–16% of the global harvest. We consider the effect of climate change on the many complex biological interactions affecting pests and pathogen impacts and how they might be manipulated to mitigate these effects. Integrated solutions and international co-ordination in their implementation are considered essential. Providing a background on key constraints to food security, this overview uses fusarium head blight as a case study to illustrate key influences of climate change on production and quality of wheat, outlines key links between plant diseases, climate change and food security, and highlights key disease management issues to be addressed in improving food security in a changing climate.

Keywords: climate change, food safety, fusarium head blight, global food security, mycotoxin, plant disease

Introduction

The earth's climate has always changed in response to changes in the cryosphere, hydrosphere, biosphere and other atmospheric and interacting factors. It is widely accepted that human activities are now increasingly influencing changes in global climate (Pachauri & Reisinger, 2007). Since 1750, global emissions of radiatively active gases, including CO_2, have increased rapidly, a trend that is likely to accelerate if increase in global emissions cannot be curbed effectively. Man-made increases in CO_2 emissions have come from industry, particularly as a result of the use of carbon-based fuels. Over the last 100 years, the global mean temperature has increased by 0·74°C and atmospheric CO_2 concentration has increased from 280 p.p.m. in 1750 to 368 p.p.m. in 2000 (Watson, 2001). Temperature is projected to increase by 3·4°C and CO_2 concentration to increase to 1250 p.p.m. by ~2095 under the A2 scenario, accompanied by much greater variability in climate and more extreme weather-related events (Pachauri & Reisinger, 2007). Underlying these trends is much spatial and temporal heterogeneity, with projections of climate change impacts differing among various regions on the globe. Some of this is clear in the outputs from models that take into account geographic criteria such as land mass distribution, topography, ocean currents and water masses, and known meteorological features such as air streams. Nevertheless, historic data show seasonal and regional variation not accounted for in model processes (e.g. Barnett *et al.*, 2006) that have major implications for practical processes such as crop sowing, harvest or pest and pathogen infection and therefore all the activities that derive from these effects.

Defining uncertainty is important in all areas of climate change research, not only in assumptions for stochastic or deterministic models, but also in biological processes where knowledge or understanding is lacking. However, uncertainties are arguably greater when the implications of climate change on food security are considered. Food security can be defined as "when all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO, 2003) or "fair prices, choice, access through open and competitive markets, continuous improvements in food safety, transition to healthier diets, and a more environmentally sustainable food chain" (Anonymous, 2008a), although a simpler definition could be 'the risk of adequate food not being available'. It is a combination of multiple food availability, food access and food utilization issues. Each of these is influenced by many factors, such as economic recession, currency fluctuations, water pollution, politi-

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cal unrest, HIV-AIDS, war, trade agreements and climate change, compounding the uncertainties in each. Issues such as education, poverty, poor market access, food price increase, unemployment and property rights are also cited as causes of food insecurity (Scholes & Biggs, 2004). These have resulted in many food security 'hotspots' around the world, particularly where multiple factors coincide (Fig. 1). Sub-Saharan African countries feature high in this list.

To understand how best to control plant diseases to improve food security in the context of climate change, plant protection professionals must work with societal change, defining its key processes and influencers to effect change. More specifically, there is a key role to play in improving food security. Plant pests and diseases could potentially deprive humanity of up to 82% of the attainable yield in the case of cotton and over 50% for other major crops (Oerke, 2006) and, combined with postharvest spoilage and deterioration in quality, these losses become critical, especially for resource-poor regions. Actual average losses for rice in the period 2001–2003 totalled 37·4%, comprising 15·1% to pests, 10·8% to pathogens and 1·4% to viruses, with the remaining 10·2% accounted for by weeds (Oerke, 2006). Each year an estimated 10–16% of global harvest (Strange & Scott, 2005; Oerke, 2006) is lost to plant diseases. In financial terms, disease losses cost US$220 billion. There are additional postharvest losses of 6–12%; these are particularly high in developing tropical countries lacking infrastructure (Agrios, 2005) and consequently are difficult to estimate. As attested by the infamous 19th century Irish potato famine (Fry, 2008) or the Bengal famine (Padmanabhan, 1973), devastations from plant diseases can be far reaching and alter the course of society and political history.

The 'fertilization effect' of increasing CO_2 increases crop biomass and grain yield (Ainsworth & Long, 2005), raising the possibility of increased food production. However, emerging evidence of reduced grain yield from high-temperature and water limitations (Anwar *et al*., 2007; Torriani *et al*., 2007) make a wholesale increase in crop productivity unlikely. Also, the impacts of plant diseases, mostly ignored in assessments of global food security under climate change, minimize or reverse any benefit from the CO_2 fertilization effect (Fernandes *et al*., 2004; Butterworth *et al*., 2010). Nevertheless, grain production has doubled over the last 40 years as a consequence of changes in plant protection and other agricultural technology, including a 15–20-fold increase in pesticide use worldwide. Despite this, the overall proportion of crop losses has increased during this period and excessive use of insecticides has increased pest outbreaks and losses in some crops and areas (Oerke, 2006). As world agriculture responds to challenges of securing sufficient, safe and nutritious food for the ever-expanding human population under changing climate, no doubt pesticide usage will increase even more. Identifying key constraints to food security, primarily from a production perspective, this overview highlights how improving plant disease management can enhance global food security. Using a case study, it outlines key influences of climate change on fusarium head blight (FHB) and its effects on production and quality of wheat, which impacts food security. Finally, it highlights key disease management issues to be addressed in improving food security in a changing climate.

Constraints to food security

The FAO estimated that 1·02 billion people went hungry in 2009, the highest ever level of world hunger, mainly as

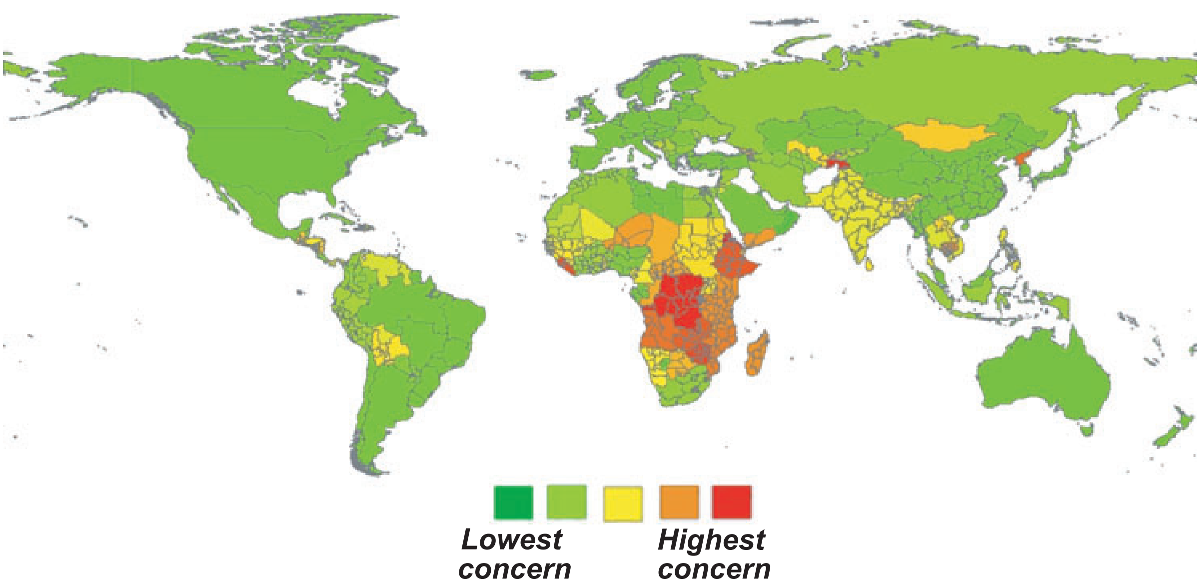

Figure 1 Identification of food insecurity hotspots based on hunger, food aid and dependence on agricultural gross domestic production statistics from FAOStat and WRI; 2001–2003. [Global Environmental Change and Food Systems (GECAFS), personal communication].

a result of declining investment in agriculture (Anonymous, 2010). It has been estimated that land degradation, urban expansion and conversion of crops and croplands for non-food production will reduce the total global cropping area by 8–20% by 2050 (Nellemann *et al.*, 2009). This fact, combined with water scarcity, is already posing a formidable challenge to increase food production by 50% to meet the projected demand of the world's population by 2050. Conditions will be even more difficult if climate change results in melting of portions of the Himalayan glaciers, disturbs the monsoon pattern and increases flooding/drought in Asia, as this will affect 25% of the world's cereal production through increased uncertainty over the availability of water for irrigation and more frequent floods affecting lives and livelihoods.

Total food production alone does not define food security since food must be both safe and of appropriate nutritive value. Furthermore, food has social values inseparable from the production, distribution and use value chain. Food must be accessible, affordable and available in the quantities and form of choice. This is dependent on production, distribution and trading infrastructure and mechanisms. All these factors may be affected by climate change, and some are affected both directly and indirectly through pest- and pathogen-mediated changes that occur because of climate change. A good example of these effects is illustrated in the case study of FHB, where changes in the pathogen complex affect crop yield, quality and safety, with consequent effects on trade and end-users, and therefore value and food security. Another example is the potato aphid–vector–parasite complex. Increased temperatures, particularly in early season, enable virus-bearing aphids to colonize seed potatoes earlier in northern Europe, thus contaminating the stocks and reducing their value for potato production (Robert *et al.*, 2000). Aphids are predated by various other insects such as wasps and ladybirds, but whether predators will increase at similar rates to constrain the problem is not known. Furthermore, aphids are predominantly clonal in cooler northern latitudes and insecticide resistance can be monitored in these clones. Warmer climates favour sexual populations with increased variability and thereby resistance spread, which may exacerbate problems to growers (Malloch *et al.*, 2006). Aphids themselves are dependent on specific microbes in their tissues, such as bacteria in their gut, which affect not only many fitness traits, but also their resistance to parasitoids and fungal pathogens (Ferrari *et al.*, 2004), representing yet more trophic interaction complexes potentially differentially affected by climate change. How climate change may influence diseases of major field crops (Luck *et al.*, 2011) and tropical and plantation crops (Ghini *et al.*, 2011) are considered elsewhere.

Soil is a highly complex ecosystem comprising numerous biological processes, each affected differentially by climate variables (Pritchard, 2011). We consider only some of the net consequences of these that will be expressed through direct effects on plant growth and effects on the crop environment. The latter comprise effects of the crop itself through effects on root and canopy architecture (Pangga *et al.*, 2011) and effects on other organisms such as weeds, pathogens, beneficial and non-pathogenic components of microbial complexes (Newton *et al.*, 2010b). For example, in minimum tillage situations, pathogens such as sharp eyespot *Ceratobasidium* (*Rhizoctonia*) *cerealis* can decline in severity, probably because of enhancement of natural antagonists and competitors (Yarham & Norton, 1981; Burnett & Hughes, 2004). However, such changes are highly dependent on the particular soil conditions and few generalizations attributable to climate change can be made.

Water limitation is key to food security and is normally the rate-limiting factor for plant growth at lower latitudes, whereas irradiation is the key rate-limiting factor at many higher latitudes (Churkina & Running, 1998; Baldocchi & Valentini, 2004). There is no overall trend for amount of precipitation change, but there is clear historical evidence of changed distribution patterns both regionally and seasonally (e.g. Barnett *et al.*, 2006). These changes will produce cropping changes which will have implications for food availability, directly or indirectly, through, for example, consequent changes in pathogen and pest incidence and severity.

Another important aspect of water is its quality, e.g. whether it is affected by pollution or salination. Use of excessive amounts of irrigation can cause salination problems for crop growth directly or through sea water ingress. This has direct effects on crop production, but also many indirect effects through effects on pest, pathogen and interactions with beneficial microbes, since many abiotic stress mechanisms are also biotic stress response mechanisms, particularly abscisic acid, jasmonate, ethylene and calcium regulation (Fujita *et al.*, 2006). Pathogen spores from water- or salt-stressed plants, for example, can have increased infectivity (Wyness & Ayres, 1985). Furthermore, cold and drought stress and stress-relief can affect disease resistance expression (Newton & Young, 1996; Goodman & Newton, 2005). Thus, effects on such interactions should be considered in terms of not only the crop as a substrate for the pest, pathogen or other microbe, but also the efficacy of defence mechanisms. Many nutrients affect disease development and will be influenced indirectly by climate change (Walters & Bingham, 2007), but particular deficiencies, in potassium for example, may compromise defence pathways such as the jasmonate pathway, to be compromised, resulting in differential effects on expression of resistance towards necrotrophic pathogens (J. Davies, Scottish Crop Research Institute, Dundee, UK, unpublished data).

Nutrient use efficiency, particularly for nitrogen, is another plant growth-related trait that has high genetic variability (Chardon *et al.*, 2010), a large environmental interaction (e.g. Hirel *et al.*, 2001), is a modern breeding target and has direct effects on pathogen fecundity (Baligar *et al.*, 2001). Pathogens respond differentially to nutrient availability (Walters & Bingham, 2007) and it is not clear how the further complication of climate change will affect this. For example, will the yield loss be the same for a necrotroph and a biotroph under two different available nitrogen levels, and will this relationship remain the same with increased CO_2 and temperature? Will a drought or heat stress affect both in the same way? Furthermore, any such relationships may be specific to particular crops, environments or agronomic regimes.

Traits needed by plants to adapt to pathogen threats following climate change generally come in the categories of resilience and durable resistance. However, whilst in natural ecological communities we might expect these to be acquired by normal natural selection processes, in agricultural systems different traits may be prioritized as crops are grown in intra- rather than inter-genotypic competition and thus have lost functional diversity (Newton *et al.*, 2009). In such monocultures, the use of major genes for resistance to pathogens is likely to lead to strong selection on pathogen populations to overcome them (Pangga *et al.*, 2011), whereas in heterogeneous communities it may lead to stability (e.g. Huang *et al.*, 1994). Therefore, strategies for establishing greater resilience in agricultural crops should introduce more genetic variability, both within and between cultivars, thereby mimicking the broader genetic basis of resistance to both abiotic and biotic stresses found in such communities. Thus, adaptation of crops focusing on polygenic resistance, preferably with evidence of a broad spectrum of target pests and pathogens and robust expression under a wide range of temperature and CO_2 conditions, may offer durable protection. Ideally, crop resistance needs to remain effective under extreme abiotic stresses and stress-relief periods, but examples of such durable resistance are rare.

Compared with wild plants, crops have had their developmental cycle changed to enhance yield, for example by producing larger fruiting bodies or larger grain sizes, making the assimilate-remobilization phase more vulnerable to pest and pathogen attack (Newton *et al.*, 2010a). This can result in loss of yield-loss tolerance (maintenance of yield despite presence of disease), a concept much neglected as a breeding target (Bingham & Newton, 2009). This phase is also likely to coincide with down-regulation of defence pathways since these are costly to the plant; under natural conditions they no longer need to be active when senescence and seed dissemination have started. However, we should ideally be breeding for and managing 'ecological tolerance', since managing levels of pathogens that cause little yield loss is likely to be a far more robust control strategy than trying to eliminate all pathogens (Newton *et al.*, 2010b).

The choice of crops grown is determined by many factors, of which climate is only one, albeit one that constrains options available for other factors. Other factors, such as tradition, end-user demand and policy linked to payments, may push these climate boundaries through plant breeding and production strategies, such as protecting crops under glass, polythene or fleece. However, other policy drivers, such as carbon accounting and economics (particularly labour, infrastructure and fuel costs), determine the flexibility of these boundaries. Given the likelihood of a more variable climate with more frequent extreme weather events (Pachauri & Reisinger, 2007), there is likely to be a trend towards limiting crop geoclimatic distributions to the low-risk areas away from the high-risk areas. Besides a tendency to move away from the extremities of crop distributions, crop distributions will shift geographically. However, these will not simply reflect increasing temperature, because other factors such as adequate water and soil type must also be available.

Pest and pathogen threats are determined by complex changes in crops and agricultural practice that may result from climate change. Since many pests and pathogens are opportunists that occupy any trophic niche not adequately protected by a resistance mechanism or crop protection operation, prediction of future threats involves identifying where and when such niches will occur. To avoid such niches occurring, pre-emptive adaptation could involve breeding for appropriate resistance and deploying it in appropriate ways to safeguard its longevity. It also involves ensuring that when such niches occur, they are (i) detected rapidly, (ii) pest and pathogen inoculum is limited in their vicinity, (iii) niches are spread thinly and (iv) there are barriers that limit spread. Essentially, this describes functional diversity at a range of scales (Newton *et al.*, 2009). However, since functional diversity is complex at all scales, adaptation strategies to climate change must also be.

Case study: fusarium head blight, climate change and the wheat value chain

Plant diseases are a major impediment to the production and quality of important food stuffs, and diseases such as wheat FHB affect quality and food safety. In addition to reducing yield, they are of particular concern because of their direct impacts on human and animal health. Mycotoxins and pesticide residues in food are among the top food safety concerns associated with a changing climate in Europe (Miraglia *et al.*, 2009). This section explores the influence of projected climate change on FHB and how this may impact on components of a wheat value chain comprising production, processing and marketing.

Wheat is the most important source of carbohydrate (Curtis *et al.*, 2002) providing, on average, one-fifth of the total calorific input of the world's population and half the total dietary calories in regions such as North Africa, Turkey and Central Asia (Reynolds *et al.*, 2008). Wheat is processed into many end products to provide for sophisticated consumers and grain quality increasingly influences international grain trading (Blakeney *et al.*, 2009). For instance, the Australian Prime Hard grade of wheat cultivars is used in making pan bread, hearth bread and white salted noodles; soft grade cultivars are used for biscuit, cake and pastry making; and durum wheat is used for pasta and couscous. In Scotland, over 800 000 tonnes of soft grade wheat is grown for alcohol production (Anonymous, 2008b). About half the global wheat area of >200 million hectares is in less developed countries where there have been steady increases in productivity from genetic improvements in yield potential, resistance to diseases, adaptation to abiotic stresses and better agronomic practices. Further improvement in wheat productivity will be determined by the balance between increasing demand from an expanding human population and preference for wheat-based food as a result of increasing standards of living and the loss of agricultural land caused by urbanization, scarcity of water resources, unpredictable climate and debates on genetically modified food crops. Nevertheless, productivity of wheat must be increased to meet global challenges of food security. Clawing back attainable yield and quality by improved control of plant diseases must be an important component of research and development efforts to produce more from less.

In recent decades, FHB has re-emerged as a disease of global significance, causing yield loss and price discounts as a result of reduced grain quality, costing an estimated $2·7 billion in the northern great plains and central USA from 1998 to 2000 (reviewed by Goswami & Kistler, 2004). The production of trichothecene mycotoxin and oestrogenic zearalenone in infected host tissue, responsible for a loss of grain quality, is harmful to humans and animals, although fungal infection alone can reduce grain quality too. Trichothecenes have been associated with chronic and fatal toxicoses of humans and animals (Desjardins, 2006).

On-farm production

A number of *Fusarium* and *Microdochium* species can cause FHB, but *Fusarium graminearum* (teleomorph *Gibberella zeae*) and *Fusarium culmorum* (no known teleomorph) are the most important worldwide (Xu & Nicholson, 2009), whilst *Fusarium pseudograminearum*, *Fusarium acuminatum* and some other species are important in some countries and regions (Akinsanmi *et al.*, 2004). The same pathogens also cause crown rot (CR) that affects crown, basal stem and root tissue in most cereal-producing countries, and epidemiology, toxigenicity and disease cycles of CR and FHB are linked. However, mycotoxin contamination of grains from FHB is considerably greater than that from CR (Chakraborty *et al.*, 2006). The pathogen survives as a saprophyte in infected tissue of wheat, maize and other grass species to produce ascospores (except *F. culmorum*) and/or macroconidia which are dispersed by wind, rain and insects to infect wheat at anthesis (see Goswami & Kistler, 2004 for a summary). The retention of stubbles through the widespread adoption of zero minimum or conservation tillage has resulted in considerable increase in pathogen inoculum, leading to increased severity of FHB and CR. Weather is the most significant factor in determining incidence, severity and the relative importance of the two diseases. Yield loss from CR is severe when there is a post-anthesis drought, when the restriction of the flow of water to the spike tissue by the pathogen causes 'white heads' with shrivelled or no grains (Chakraborty *et al.*, 2006; Luck *et al.*, 2011). FHB, on the other hand, is favoured by warm and wet weather at anthesis and causes partial or complete blighting of the head, reduced yield and quality (shrivelled kernels), reduced test weight and bread-making quality and the production of one or more mycotoxins. The quantitative relationships between weather, cropping practices and mycotoxin concentrations (Champeil *et al.*, 2004) form the basis of mycotoxin forecasts such as DONCAST (Schaafsma & Hooker, 2007). In general, the potential for high concentrations of mycotoxin in grains generally increases with the number of rainy days and days with relative humidity >75%, but decreases with temperature <12 or >32°C (Schaafsma & Hooker, 2007).

Changes in both physical climate and atmospheric composition influence severity of FHB. The most significant influences occur during the production phase, but impacts can affect the entire wheat value chain. In barley the consequence of reduced grain quality caused by FHB has been disastrous for the malting and brewing industries (Schwartz, 2003). Some climate related changes are already influencing wheat production. *Fusarium culmorum* and *Microdochium nivale* have been the prevalent species in cooler temperate climates of Europe, but in the last decade *F. graminearum* has become the dominant species causing FHB in the Netherlands (Waalwijk *et al.*, 2003), England and Wales (Jennings *et al.*, 2004) and northern Germany (Miedaner *et al.*, 2008), because its higher temperature optimum favours its dominance in the disease complex. Since *M. nivale* is non-toxigenic and *F. culmorum* generally produces less mycotoxin than *F. graminearum*, mycotoxin concentrations may consequently increase. In Canada, a 3ADON chemotype of *F. graminearum* with increased toxigenic and ecological fitness had replaced the 15ADON chemotype indicating genetic differentiation along environmental gradients (Ward *et al.*, 2008). Two recent reviews have considered these and other changes in FHB pathogen populations with potential concomitant changes in mycotoxin contamination (Xu & Nicholson, 2009; Paterson & Lima, 2010) and discussion about climate change and mycotoxins appears in Paterson & Lima (2010) and Magan *et al.* (2011).

Using linked models for FHB, wheat and climate change, Fernandes *et al.* (2004) projected the risk of FHB in selected areas of Brazil, Uruguay and Argentina to show that the risk index was greater under climate-change scenarios than at any time during the last 30 years for all except one area. The greatest risk from FHB came from the predicted increase in the number of rainy days coinciding with critical wheat growth stages during the September–November period. Using a similar linked-modelling approach, Madgwick *et al.* (2010) predicted that by the 2050s the risk of FHB epidemics and the number of crops where mycotoxin levels would exceed the limit set by the EU will increase across the whole of the UK. These projections are based on changes in physical weather and do not consider direct effects of atmospheric composition, such as increasing CO_2 or O_3 concentrations (Tiedemann & Firsching, 2000).

Increasing atmospheric CO_2 concentration will directly increase the amounts of FHB and CR inoculum. There is increased production of *Fusarium* biomass per unit wheat tissue at elevated CO_2, which will significantly increase transfer of inoculum between successive growing seasons; partially resistant wheat varieties able to reduce *Fusarium* biomass under ambient CO_2 will fail to do so at elevated CO_2 (Melloy *et al.*, 2010). This work also showed that the sapsotrophic fitness of the pathogen remained unchanged at elevated CO_2 and did not suffer any decrease in its ecological fitness. Furthermore, increasing crop biomass by an average 17% by elevated CO_2 (Ainsworth & Long, 2005) will further increase the amount of pathogen inoculum in stubble and crop residues. Other empirical research published in the literature, although not all on FHB, also points to important changes in host, pathogen and host–pathogen interactions influencing disease severity (Manning & Tiedemann, 1995; Chakraborty *et al.*, 2008).

Post-production storage and processing

Under climate change grain quality may deteriorate as a direct effect of increasing temperature and CO_2 that reduces protein and micronutrient content in grain, which can influence mould growth and mycotoxin production, further affecting quality during storage and transport. Changes in rainfall pattern and intensity greatly influence grain quality, but meaningful projections are difficult because of uncertainty in rainfall prediction. The level of moisture in grains, quality of grain storage facilities and temperature are the most important factors determining grain quality after harvest. Deterioration in grain quality in storage and transport includes loss of viability and processing quality, fungal growth and mycotoxin production. Grain moisture content for storage and shipping is set at 12%, and is largely determined by moisture content at harvest. If moisture content is greater than an acceptable level, harvesting can be delayed to allow the moisture level to decrease or post-harvest blending, swathing, aeration or drying can be applied to reduce moisture level. There is additional cost associated with each of these interventions and with delayed harvesting both grain quality and yield are lost with every passing day.

Deoxynivalenol (DON) production is a common problem in stored wheat harvested under the current climate and samples from many parts of the world including Africa (Miller, 2008; Muthomi *et al.*, 2008), North America (Gocho *et al.*, 1987) and South America (Dalcero *et al.*, 1997), China (Li *et al.*, 2002) and Europe (MacDonald *et al.*, 2004; Paterson & Lima, 2010) contain high concentrations of this mycotoxin. Conditions during storage can increase DON concentration several fold within a few weeks if contaminated grains are stored with high moisture levels (Birzele *et al.*, 2000), but grains stored at a moisture activity of $\leq 0{\cdot}70\ a_w$ (approximately 10–11% moisture content) will not generally spoil or produce mycotoxins. Competition between contaminant species also seems important, and DON production by *F. culmorum* can be reduced by the presence of *Alternaria tenuissima*, *Cladosporium herbarum* or *Pythium verrucosum* on wheat grain but stimulated by the presence of *M. nivale* (Paterson & Lima, 2010). Resource-poor farmers with poor on-farm or in-house storage conditions can further increase mycotoxin content and risk to human health (Wagacha & Muthomi, 2008). However, high concentrations of DON and other mycotoxins are a global problem of weather-damaged grains or grains harvested with high moisture content (Blaney *et al.*, 1987). Storage of wheat grains under high moisture conditions can also lead to aflatoxin contamination (Blaney *et al.*, 1987; Saleemullah *et al.*, 2006; Anwar *et al.*, 2008), with severe consequences for human and animal health.

DON persists through most processing stages in the brewing and malting industries (Schwartz, 2003; Desjardins, 2006) and extrusion-based food and other industries (Scudamore *et al.*, 2008) so that it is found in consumer products from breakfast cereals (Roscoe *et al.*, 2008) to beer (Harcz *et al.*, 2007). The mycotoxin passes to humans when these products are consumed (Harcz *et al.*, 2007). When contaminated grains are fed to animals, DON is found in animal products (Goyarts *et al.*, 2007; Yunus *et al.*, 2010) including milk and meat (Fink-Gremmels, 2008), and then consumed by humans. Urinary excretion of DON correlates with cereal intake in humans. In the Netherlands, 80% of 1-year-old children exceeded the maximum tolerable daily intake of 1 $\mu g\ kg^{-1}$ body weight established by the Joint FAO/WHO Expert Committee on Food Additives, and 20% had twice the recommended maximum intake (Anonymous, 2009). DON limits are also exceeded in parts of Latin America and concentrations are close to the limit in several other countries (Miller, 2008). In addition to food intake, farm operations such as grain threshing present a high risk to farmers associated with inhalation of the fungus and mycotoxins (Anonymous, 2009).

The impact of FHB is complex due to its influence on wheat yield and quality, with subsequent effects on food safety, and how climate change will modify these influences is difficult to project because of a paucity of knowledge. Although the severity and toxigenicity is projected to increase under climate change (combination of rainfall and temperature at anthesis) with an altered distribution of FHB (Madgwick *et al.*, 2010), the information is not enough to make generalization such as ''increasing climate variability will produce more frequent epidemics of FHB'' (Miller, 2008). The prevalence and/or severity of FHB is not expected to increase in areas with projected reduction or change in distribution of rainfall. However, irrespective of FHB, wheat quality may deteriorate under increasing temperature, even in dry areas such as in South Australia (Luo *et al.*, 2009), with implications for food security.

Changing consumer preference

Mycotoxins are more of a problem in the developing than the developed world because of a combination of subsistence farming, poor postharvest handling and storage, and unregulated local markets. The situation may worsen under climate change (Shephard, 2008). What is clear is that preference for wheat-based food is increasing with affluence and with this there is increasing exposure to mycotoxins such as DON. Cereal production in China, for instance, has increased fivefold since 1961 and the ratio of rice to wheat and maize has changed from 1·2:1 to 0·8:1 (Miller, 2008). Currently, FHB poses a serious threat to wheat production in China, causing significant losses in production and quality, and increased exposure to DON (Li *et al.*, 2002; Meky *et al.*, 2003; Xu & Nicholson, 2009).

Increasing concern about food safety and a renewed interest in personal health, animal welfare and environmental sustainability resulted in a rapid growth in popularity of organic food, primarily among consumers in the USA and Europe and, to a lesser extent, in other countries (Havelaar *et al.*, 2010). Organic food brings with it inherent benefits and risks to the consumer in relation to synthetic agrochemicals, environmental pollutants, animal feed contaminants and drugs, plant toxins, mycotoxins, biopesticides and foodborne pathogens of humans and animals, amongst others (Magkos *et al.*, 2006). In this case study, we have restricted discussion to issues relevant to FHB of wheat, which has received considerable attention in the literature on organic food. The occurrence of one or more of the FHB mycotoxins, DON, nivalenol and zearalenone, has been reported in wheat grains, flour and cereal-based foods including bread, noodles, semolina, breakfast cereal and baby food. Mycotoxin concentrations have been higher, lower or similar in organic produce compared with conventional food (Magkos *et al.*, 2006). One study showed higher median, mean and maximum DON concentrations in organic than in conventional wheat samples, despite an overall lower incidence in the organic crops (Malmauret *et al.*, 2002). Based on these findings, a stochastic model simulating DON exposure and incorporating the frequency and levels of wheat consumption suggests that consumers of organic wheat are more likely to exceed maximum allowable daily intake levels than consumers of conventional wheat (Leblanc *et al.*, 2002).

Disease management, climate change and food security

All crop protection could be considered as an integrated approach since pesticides are directly applied only when there is a perceived or actual threat. However, such applications of conventional crop protection products often disrupt the many processes keeping such organisms in some sort of benign balance in non-epidemic situations. These factors or processes can be categorized in terms of risk mitigation and risk enhancement (Fig. 2). These rate-determining processes are the result of complex interactions between these 'remediating' and 'enhancing' influences. Each process itself is a complex biological system with multiple components, each influenced by climatic variables in different ways. The challenge is to rank the influences of both the processes and the key environmental/climatic influences in parallel in order to construct influence models to predict the likely effects of climate change on production systems. Garrett *et al.* (2011) offer one approach to improve understanding of these complexities.

The robustness, vulnerability or sensitivity of different processes should be assessed together with the feasibility of manipulating them. For example, enhancing endophytic colonization of plants offers prospects of enhanced abiotic and biotic tolerance, thus addressing multiple consequences of climate change in some plants. However, the magnitude of the responses is likely to be limited and for many plants appropriate endophytes may not be available. There are also many practical issues in establishing and maintaining colonization that have not yet been determined. By comparison, deployment of a major gene for resistance effective under a range of environmental conditions delivers high efficacy for a narrow target disease control with limited duration and high vulnerability. Enhanced efficacy can be delivered through incorporating heterogeneity into both the crop and risk mitigation processes, effectively spreading risk, albeit at the expense of maximum gain from implementation of less durable options, such as deployment of resistant cultivars in extensive monoculture or extensive use of a single fungicide (Newton *et al.*, 2009). However, if the challenge of increasing food production by 50% by 2050 can be met only by deploying cultivars with single or multiple resistance genes or by use of fungicides, it will be difficult to argue for an alternative approach that may not produce the highest attainable yields.

There are many possible intervention points in the crop–pest/pathogen interaction, but decisions on which are to be prioritized will depend on a combination of their likely effects and the feasibility of manipulating them in a beneficial way that is both practical and acceptable. Many treatments require initial investment in capacity and resource building referred to above, but if the potential benefits are great then this should guide investment. Rankings are suggested in terms of high, medium or low in Fig. 1, but their validity should be the focus of research policy debate. To be an effective input to policy debates, potential strategies must accompany cost estimates for various levels of adaptations. For instance, losses from phoma stem canker of oilseed rape caused by *Leptosphaeria maculans* can be minimized with a 'low' adaptation strategy, which may require some farmer-led changes to adopt best management practices, but 'high'-level long-term success will require significant changes and investments from the public and private sector, including the farmer (Barnes *et al.*, 2010).

Pests and pathogens frequently co-exist with crops in benign relationships where symptoms or damage remain

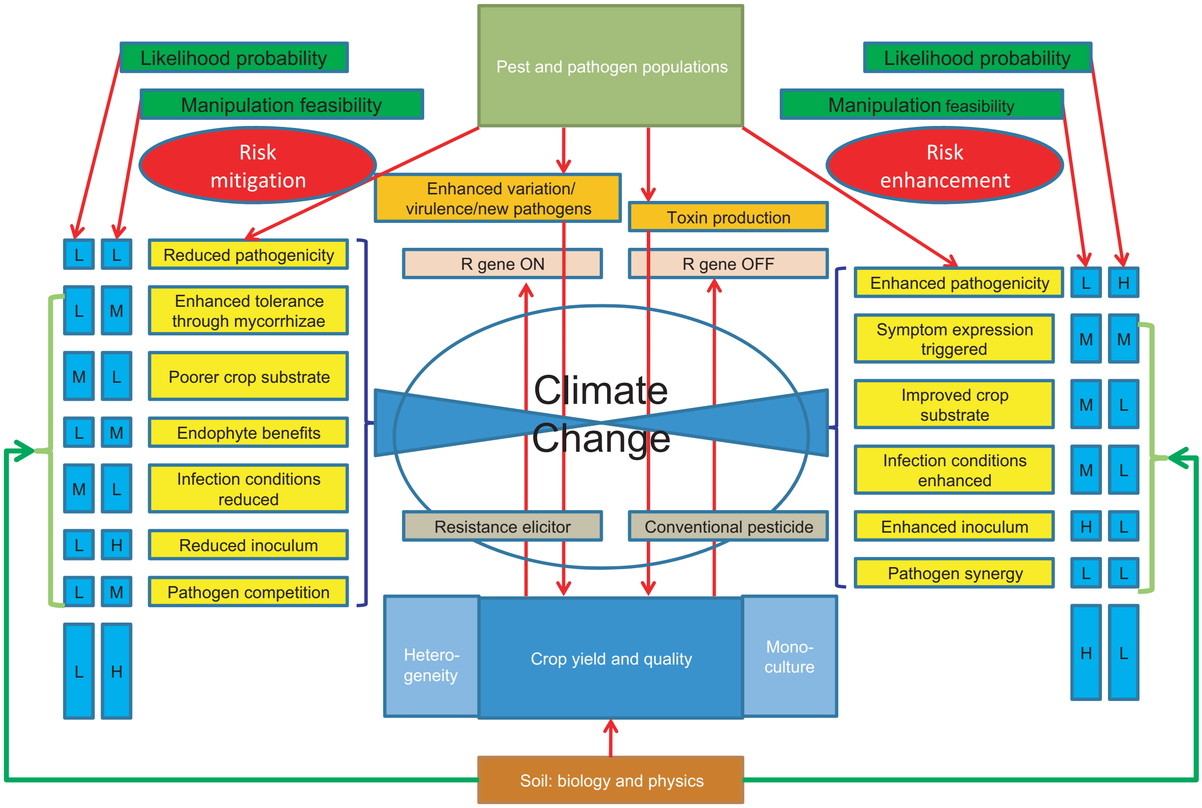

Figure 2 Influence of climate change on rate-determining processes that are the result of the complex interaction between the 'enhancing' (right) and 'mitigating' (left) influences on plant and pest/pathogen interactions. Rankings for likelihood probabilities and manipulation feasibility are initial approximations requiring critical review.

below problematic or even visually detectable thresholds (Newton *et al.*, 2010b,c). The mechanisms by which this happens could represent the key processes leading to resilience and sustainability, essentially the traits necessary for responding to climate change. The selection resulting from pest and pathogen elimination strategies often leads to 'boom–bust' cycles where such strategies rely on a narrow range of highly effective resistance genes or pesticides. Even resistances, such as the *Sr31* stem rust resistance in wheat that has been effective in cultivars for over 30 years, can be overcome by new races of *Puccinia graminis* f. sp. *tritici* like Ug99. This race, originating in Uganda in 1999, has continued its global spread (Vurro *et al.*, 2010), reaching South Africa in 2010 (http://www.nature.com/news/2010/100526/full/news.2010.265.html doi: 10.1038/news.2010.265). Since *Sr31* has previously been effective there is great reliance on this gene across much of the world's wheat area, and its breakdown will therefore have very serious consequences in food security terms in vulnerable parts of the world where alternative crop protection methods and resistant cultivars are not available (Flood, 2010). By increasing crop biomass and the number of infection cycles over more growing days, climate change will produce large rust populations, which may accelerate the evolution of new rust races on large spatial scales (Chakraborty *et al.*, 2010).

For rust and other biotrophic pathogens that follow a 'gene-for-gene' model of host-pathogen specificity, more sustainable disease management will come from combinations of resistance genes, assembled using marker-assisted selection or transgenic approaches. These approaches are being used with wheat rust (Bariana *et al.*, 2007; Ellis *et al.*, 2007). Once developed, resistance sources can be evaluated using facilities mimicking future climate scenarios including increased temperature (Huang *et al.*, 2006) to ascertain their longevity. Pre-emptive breeding can also start in these facilities to identify and replace the most vulnerable genes/gene combinations.

Many necrotrophic pathogens that have broad host ranges do not follow gene-for-gene specificity when host resistances are available, they generally rely upon multiple defence mechanisms each offering a partial reduction in disease severity, but not complete protection. A necrotrophic pathogen is able to grow saprophytically after the crop starts to senesce, producing large quantities of inoculum that can infect subsequent crops, thereby often losing the advantage of using a partially resistant variety to reduce inoculum (Melloy *et al.*, 2010). Under climate change, increased biomass of crops and alternative host plants will further increase inoculum production. To be effective, partial resistance has to be combined with agronomic and other practices to develop robust integrated crop protection strategies, which will not suffer such boom–bust cycles. Knowledge of pathogen biology and epidemiology in farming systems must improve significantly to account for changes in geographical distribution of crops to better manage necrotrophs under climate change. As croplands move to match climatic suitability, breeding targets themselves will change with changing pathogen spectra, disease dynamics and relative economic values (Ortiz *et al.*, 2008).

For crops such as potato, economic production is often impossible without the application of pesticides. Pesticide usage may increase if changing crop physiology interferes with the uptake and translocation of pesticides or change in other climatic factors (e.g. more frequent rainfall, washing away residues of contact pesticides) mean that there is a need for more frequent applications. Faster crop development at increased temperature could also increase the need for application of pesticides. Worldwide, for every 100 agricultural workers, between one and three suffer acute pesticide poisoning, leading to many thousands of fatalities; developing countries experience 99% of the deaths while using 25% of the world's production of pesticides (UNEP, 2004). Development and use of disease-resistant varieties offers economic, health and ecological benefits, as demonstrated by the use of Bt-cotton in many countries, including China (Huang *et al.*, 2003), where the use of pesticides is a major concern.

Examples of extreme weather events such as hurricanes causing the spread of plant pathogens to new areas are common (Rosenzweig *et al.*, 2005) and are expected to increase with the projected increase in the frequency of extreme weather events under climate change. In addition to lost production, this can restrict market access, limiting valuable export earnings for some developing countries. For example, Karnal bunt has caused the wheat trade from many regions to be restricted to maintain the disease-free status of importing countries and, more recently, to avoid its potential use as a biological weapon (Anderson *et al.*, 2004). The need for a co-ordinated surveillance system complemented by robust diagnostic networks and widely accessible information systems has never been greater. But the cost of effective surveillance can be high for many developing countries. CAB International are developing a Global Plant Clinic network where 'plant doctors' provide immediate diagnoses and advice if possible and have resources and expertise for more problematic diagnoses (http://www.cabi.org). This facility can provide quality-controlled data for a community surveillance system, leading to early detection of new pests and diseases and informing strategy and research from local to global levels because it is facilitated by a well-integrated international organization. This illustrates the roles of policy, national and international agency in defining and implementing solutions to problems of global dimensions, but with very local implications (Newton *et al.*, 2010c). Actions need to take place at a range of scales, through many agencies of different types, bringing together knowledge, expertise and strategy in unique ways. The time-scale of these actions may similarly be wide-ranging, from fundamental understanding of pathogen population processes and resistance mechanisms, through to propagation and appropriate distribution of cultivars to farmers in specific locations. Such is the scope of initiatives like the Borlaug Global Rust Initiative, addressing the worldwide consequences of climate change on a particular disease, with a potentially huge direct effect of inaction on food availability (http://www.globalrust.org).

Future prospects

If food production has to increase by 50% in the next 40 years from a shrinking land resource, this will require a sustained and huge investment of capital, time and effort. In common with the past triumphs of world agriculture that gave us the green revolution to save millions from starvation, a major component of the solution will have to come from improved technology. This technology will need to produce, process, distribute and market food that is sufficient, safe and nutritious to meet the dietary needs and preferences of the world human population, without affecting the sustainability of the natural environment. The long-neglected global research and development investment in agriculture and food must at least be doubled to accelerate development and application of promising technology. Between 1991 and 2000, total agricultural research and development spending declined by 0·4% annually in Africa, but increased by 3·3% in Asia. As a result, land productivity in East Asia increased from US\$1485 ha^{-1} in 1992 to US\$2129 ha^{-1} in 2006, but declined in sub-Saharan Africa from 79% of that in East Asia in 1992 to 59% in 2006 (IFPRI, 2008).

Any discussion about food security is incomplete without acknowledging the complex web of sociopolitical, trade and other issues, which are often more important than production and processing issues, where climate change will primarily mediate the influence of plant diseases to affect production, quality and safety of food. This review is a timely reminder to all plant protection specialists that their excellent science deployed to minimize crop losses can, and needs to, contribute to an informed policy debate. If the goal of retaining an increasing amount of the attainable yield and quality is to be achieved, communication of research must extend beyond the farm gate to promote increased awareness among policy makers and the society at large. In the first instance, research outputs can be made more policy friendly with a 'clear take home message'.

Whilst researchers are accustomed to deal with uncertainty, this is often not true for other members of the community and it is not easy to convey messages about new findings with a specified level of certainty. Yet, it is clear that detailed prediction of climate change is unlikely to be accurate for given locations and the operations that depend on them. Determination of trends is important both for modelling biological processes and their interactions and for their experimental validation. Crop yield-loss models, largely the consequences of the often complex biological interactions that result in disease, must be integrated with crop growth models, and the same trend values will need to be used to parameterize both (Evans *et al.*, 2008; Gregory *et al.*, 2009; Butterworth *et al.*, 2010; Fitt *et al.*, 2011). However, the effects of infection or infestation tolerance, an area frequently not addressed in yield-loss assessment, must also be calibrated and included under climate-change conditions by experimentation (Newton *et al.*, 2010b). The economic and social implications of these biological processes should concern pathologists greatly and be used as a tool to prioritize targets for research, particularly where these require long-term capacity-building and technology development (e.g. the application of advanced genomics techniques to characterize host, pest and pathogen collections). Policy makers routinely juggle many issues, including more acute problems relating to climate change such as rising sea level, increased prevalence of human diseases like malaria, flood and extreme weather events. Clear economic and social implications backed by unequivocal and excellent science can help increase awareness.

Water-limiting environments, pest and diseases, declining fertility, availability and degradation of the soil resource are among key constraints to increasing production and quality of food. Climate change adds an extra layer of complexity to an already complex agro-ecological system. Plant pathologists and other crop protection professionals routinely develop and deploy strategies and tools based on well-established principles to manage plant diseases and many may also be applicable under climate change when projected changes, processes and interactions are factored in. Therefore, research to improve adaptive capacity of crops by increasing their resilience to diseases may not involve a totally new approach, although managing plant diseases may have the added advantage of mitigating rising CO_2 concentrations (Mahmuti *et al.*, 2009). The bulk of any new investment to improve control of disease in food crops, therefore, needs only to accelerate progress of new and existing promising strategies and approaches and not to 're-invent the wheel' under the guise of climate-change research. Such an investment model will ensure that disease management solutions span the entire range of uncertainties associated with climate change, including the 'business as usual' scenario.

There has been only limited empirical research on plant diseases under field conditions that realistically mimic climate change and this severely restricts the development of options to enhance crop adaptation or disease management under climate change. In addition, much knowledge has been gathered on potential effects of global climate change using models. Initial assessments are now available for some countries, regions, crops and particular pathogens. From a food-security perspective, emphasis must now shift from impact assessment to developing adaptation and mitigation strategies and options. Two broad areas of empirical investigation will be essential; firstly, to evaluate under climate change the efficacy of current physical, chemical and biological control tactics including disease-resistant cultivars, and secondly, to include future climate scenarios in all research aimed at developing new tools and tactics. Transgenic solutions (Huang *et al.*, 2002) must receive serious consideration in integrated disease management strategies to improve food security.

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