<fresh page><cn>5. <ct>Crop disease, management and food security

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<a>5.1 Introduction

We are in the midst of a global food crisis. Projected world population growth, socioeconomic protection, globalization of agricultural markets, food pricing, biosecurity policy and the demand for environmentally sustainable advances in productivity are increasingly impacting on agriculture as a secure food source, and as a major reservoir of export income. The agricultural dimension to ensuring food security is complex, involving constant adaptations in practices to combat abiotic and biotic constraints, as well as a move in developed nations towards on-farm use of renewable energies, fluctuating food pricing and the even less predictable effects of climate change and severe weather events. Biotic epidemics have the potential to severely disrupt agricultural trade, reduce export revenue, undermine consumer confidence, threaten economically sustainable food production, and cost governments millions in integrated disease management programmes. In particular, sustainable management of plant borne diseases, that would otherwise significantly reduce or completely remove a food source, is of great concern. Plant pathogens are estimated to reduce global production of potato by 21.2 per cent wheat by 12.6 per cent maize by 11.2 per cent and rice by 12.2 per cent.

Pathogens directly affect our crop-derived food through reduced yield and quality. The impacts of direct yield losses are felt most in developing nations where millions of people rely on a relatively few staple food crops that may be destroyed in a single season without effective disease management. Subsistence farmers are particularly impacted through a vicious cycle when, apart from not producing enough to feed their families, little or no seed can be saved for sowing in the following season. This concern

also remains in the developed world where, although generally affordable, the chemicals currently used for the management of crop diseases are damaging to the environment and in many cases slated for removal from general use. In these cases, alternative methods must be found that offer affordable and effective disease control whilst maintaining yields. Even when repeated chemical interventions are permitted, these may not be efficient at halting a disease epidemic, resulting in the inability of enterprises to meet market demands and jeopardizing future trade agreements.

Producers have an obligation to ensure that the food they produce is fit for consumption or downstream processing, and rigid tolerance levels have been set worldwide regarding contamination by substances toxic to humans or animals in the food chain. Other quality measures are set by the marketplace regarding expectation of physical, biochemical and visual characteristics. The marketability of a product and the premiums which will be paid may be affected by blemishes, seed shrivelling or discolouration. This again impacts the ability for producers to meet market demand and trade agreements.

Effective management of plant disease epidemics is therefore a key strategy to ensuring adequate food for all. There is a considerable need for governments to acknowledge pathological threats to sustainable food production and to allocate adequate resources to facilitate protection from exotic and endemic pathogens. Adequate protection requires biosecurity measures to be fully implemented and should include surveillance and response protocols. Management should be aimed at reducing the risk of disease epidemics and in an optimal situation would include diagnostic systems capable of rapid identification, *a priori* knowledge of how a disease would progress through modelling of disease severity and incidence, and the application of pre-emptive and post-emergent control measures.

<a>5.2 Disease threats to sustainable food production

Globalization of agriculture has led to the cultivation of crops continents away from their centres of origin, and often with a limited genetic pool. Consequently, the breeding

and cultivation of crops in ‘new’ areas has occurred in isolation from pathogenic organisms that would otherwise co-evolve with host diversity ensuring natural selection for resistance. This has meant that genes conditioning resistance to important pathogens may be lacking from the narrow base of many of our elite cultivars. Subsequently, the migration of pathogens or pathogenic strains to adopted regions of cultivation has significantly increased susceptibility to epidemic devastation of crops, and the impending starvation of a dependent population. At the same time, intensive agriculture and monoculture drives the evolution of plant pathogens, selecting for variations of pathogens with the highest fitness under specific farming conditions.¹

This was demonstrated with brutal clarity by the Irish potato famine of the 1840s, when a virulent strain of the late potato blight oomycete, *Phytophthora infestans*, struck Europe. The nutritional reliance of a significant proportion of the Irish population on an adopted monoculture, the lack of pathogenic resistance, and environmental conditions synergistic with epidemic development, inevitably led to the starvation of one million inhabitants and resulted in the mass emigration of close to two million.² At least one source of infection is thought to have originated in the northern Andes region of South America, and to have been conveyed to Europe on ships transporting guano, where it was in great demand as a fertilizer on European and British farms. *Phytophthora infestans* continues to cost billions of dollars annually in potato crop failure and control management strategies around the world.

Of current great concern, and on a potentially much larger scale than that of the Irish potato famine, is stem rust of wheat caused by the fungus *Puccinia graminis* and, in particular, the highly virulent strain Ug99 that evolved in Uganda and was discovered in 1999. Wheat is the most important staple food crop of more than one third of the world’s population, contributing more calories and proteins than any other cereal crop. Ug99 is now moving across the African continent and has already arrived on the east

¹ EH Stukenbrock and BA McDonald, ‘The evolutionary emergence of plant pathogens in agroecosystems’ (2008) 46 *Annual Review of Phytopathology* 75–100.

² DD Stuthman, ‘Contribution of durable disease resistance to sustainable agriculture’ (2002) 124 *Euphytica* 253–258.

coast and is making its way towards the world's largest populations, India and China. To date, very few sources of resistance have been found.³ The rust disease is referred to as 'the polio of agriculture' because it was thought to have been eradicated nearly 50 years ago, during the Green Revolution. This occurred between the 1940s and late 1970s when governments invested heavily in agricultural research to develop superior, mainly cereal, crop varieties. Dr Norman Borlaug, the 'Father of the Green Revolution' is credited with enabling the implementation of high yielding cultivars, irrigation, hybridized seed and chemical management that saved over a billion people from starvation.

Another stark example of the impacts of disease on a recent plant food imports involves the African adoption of cassava from its place of origin in South America. Owing to its habitual resilience and reliability of yields, cassava evolved into a vital food crop in the impoverished, nutrient-deficient countries of Sub-Saharan Africa where it became a major carbohydrate source. Unfortunately, cassava developed susceptibility to the Cassava Mosaic Virus (CMV); a small single-stranded DNA Geminivirus (twin particle virus), indigenous to Africa but absent in the native habitats of South America. In the 1990s a particularly virulent strain caused a devastating epidemic in Uganda and neighbouring countries. Such was the sensitivity of local cultivars and the consequent crop failures that famine ensued and many farmers abandoned cassava cultivation, further destabilizing food security in East Africa.⁴ Over the last decade, greater awareness of problems associated with lack of CMV resistance and low genetic diversity has led to a gradual increase in the range of cultivars planted.⁵ While this

³ P Njau, Y Jin, J Huerta-Espino, B Keller and RP Singh, 'Identification and evaluation of sources of resistance to stem rust race Ug99 in wheat' (2010) 94 *The American Phytopathological Society* 413–419.

⁴ GW Otim-Nape 'The current pandemic of cassava mosaic virus disease in Uganda' in BM Cooke, DG Jones and B Kay (eds.), *Epidemiology of Plant Diseases* (2nd ed., Kluwer Academic, 2006), 521–550.

⁵ GW Otim-Nape, T Alicai and J Thresh, 'Changes in the incidence and severity of Cassava mosaic virus disease, varietal diversity and cassava production in Uganda' (2001) 138 *Annals of Applied Biology* 313–327; JM Tresh, 'Plant virus epidemiology:

appears to have been an effective strategy, it is by no means the only option, and indeed there are concerns that this has not been appropriately complemented by other techniques.⁶ Over-reliance on a single technique can in itself act as a selective factor for development of an epidemic.⁷ For example, CMV is vectored by the Sweet Potato Whitefly *Bemisia tabaci*, a well-known vector for virus diseases, and disease incidence is directly related to the abundance of the vector.⁸ A complementary CMV control strategy would therefore be to reduce populations of *B. tabaci*.

The Ugandan CMV case clearly demonstrates the epidemiological risk of global transplantation of crops into areas far away from where the crop originally co-evolved with resident pathogens.⁹ In its new location, the crop encountered a pathogen that was probably not present where it came from and the highly virulent 'Uganda strain' of CMV

The concept of host genetic vulnerability' (2006) 67 *Advances in Virus Research* 89–125.

⁶ J Legg, J Whyte, R Kapinga and J Teri, 'Management of the cassava mosaic disease pandemic in East Africa' in PK Anderson and FJ Morales (eds.), *Whitefly and Whitefly-borne Diseases in the Tropics: Building a Global Knowledge Base for Action*, (International Centre for Tropical Agriculture, Colombia, 2006).

⁷ MS Wolfe, 'Can the strategic use of disease resistant hosts protect their inherent durability?' in T Jacobs and JE Parlevliet (eds.), *Durability of Disease Resistance* (Kluwer Academic Publishers, 1993).

⁸ J Holt, JM Jeger, JM Tresh, GW Otim-Nape, 'An epidemiological model incorporating vector population dynamics applied to African cassava mosaic virus disease, (1997) 34 *Journal of Applied Ecology* 793–806.

⁹ RAC Jones, 'Plant virus emergence and evolution: origins, new encounter scenarios, factors driving emergence, effects of changing world conditions, and prospects for control' (2009) 141 *Virus Research* 113–130; RN Strange and PR Scott (2005), 'Plant disease: A threat to global food security' (2005) 43 *Annual Review Phytopathology* 83–116.

remains a significant threat, recently also occurring in West Africa.¹⁰ Moreover, although resistance to the mosaic virus has been identified, as is often the case with viruses, a mutation has rapidly emerged. The variant then fills the ecological niche at a pandemic rate, again removing the staple food source in one of the most impoverished areas of the world.¹¹ Meanwhile, another Geminivirus, Maize Streak Virus, continues to threaten the staple food crop maize, which provides up to 50 per cent of daily calories in parts of Africa. Management of this disease is further impeded due to it being transmitted by at least six insect hopper species and surviving as reservoirs in up to 80 alternate species of the Poaceae plant family, many of which grow wild in the same environment.¹²

Of course, pathogens do not always impact crop plants directly to cause food loss. Rather, there may be a more complex interaction that leads to humans not producing sufficient food to eat. Brown spot disease of rice involves the *Cochliobolus miyabeanus* fungus and was the reason for the 1942 Bengal famine that killed 2 million. However, rather than solely caused by the pathogen, the disease is a complex reaction that also involves the abiotic constraint of silicon deficiency. Although overcome through application of calcium silicate, this remains an unsustainable and costly approach and one that is unrealistic in many parts of the world where rice is the staple food. Also in an indirect sense, Smut disease of Napier Grass, caused by *Ustilago kamerunensis* mycoplasma, impacts on food security in Kenya. The high population pressure in Kenya means farms are small and cows are kept in stalls and mainly fed Napier grass under

¹⁰ F Tiendrébéogo, P Lefeuvre, M Hoareau, and VSE Traore, 'Occurrence of East African cassava mosaic virus-Uganda (EACMV-UG) in Burkina Faso' (2009) 58 *Plant Pathology* 783–783.

¹¹ M Padidam, S Sawyer and CM Fauquet, 'Possible emergence of new Geminiviruses by frequent recombination' (1999) 265 *Virology* 218–225.

¹² A Varani, et al., 'Recombination, decreased host specificity and increased mobility may have driven the emergence of maize streak virus as an agricultural pathogen' (2008) 89 *Journal of General Virology* 2063–2074.

zero grazing practices. However, the Smut disease destroys the grass biomass, effectively reducing the milk and meat production.¹³

5.3 Factors influencing disease occurrence

Pathogens are in a constant state of evolutionary flux, developing variants capable of permeating the resistance of genotypes of the most important global crops. If we are to adequately protect sustainable food production, we must further appreciate and comprehend the complexity of pathogenicity, proliferation, disease cycles, and evolutionary variants, by investing in research initiatives, educating industry, and strengthening the resources of plant protection services. Once a disease has established, two key indicators of its impact are severity and incidence. While severity refers to the amount of tissue affected, incidence refers to the number of plants affected. These concepts are invaluable in judging the seriousness of a disease outbreak. Even with high incidence and every plant affected, an epidemic may not represent much of a threat if the severity has stabilized at an insignificant level. In a cropping system, the main concern is whether these two indicators combine to cause significant yield loss and hence the urgency and scale of management strategy that should be applied.

Most disease management strategies have evolved through repeated trial and error and are designed to consider the three factors of the ‘disease triangle’, host, pathogen and environment, which, when in optimal combination for the pest or pathogen, will lead to disease and possible epidemic. Conversely, when in optimal combination for the plant, the disease will not develop. This concept may be expanded to the ‘disease quadrangle’ when the external environment is considered separately to the micro-environment around the plant and when the environmental and genetic constituents are considered

¹³ SW Mwendia, M Wanyoike, RG Wahome and DM Mwangi, ‘Effect of napier head smut disease on napier yields and the disease coping strategies in farming systems in central Kenya’ (2007) 19 *Livestock Research for Rural Development* Article #109. Retrieved November 2, 2011, from <<http://www.lrrd.org/lrrd19/8/mwen19109.htm>>.

individually (Figure 5.1). Of these factors, the environment is the least easily controlled. Cultural practices have been investigated with varied levels of success, as have changes to micro-environmental parameters such as temperature, water content, dew period and light intensity. This has led to changes in row spacing, planting density, drip irrigation, tillage, pruning and raised beds. Also great gains in yields have been achieved since the Green Revolution through breeding plants with selected resistance genes. However, this strategy alone or in combination with cultural practices is generally insufficient to control the majority of disease epidemics.

INSERT Figure 5.1

<figure caption>Figure 5.1 The disease quadrangle: host, pathogen and environmental parameters contributing to disease expression

The interrelationship between the host, pathogen and environmental components must be considered in the development of sustainable disease management practice. The major components and some considerations of their interactions are discussed below.

5.3.1 Host

The genetic characteristics of the host include its genome (genotype), genetic resistance to a pathogen, and the genetic diversity of the crop population. Scientific advances have allowed for much greater understanding and manipulation of genetic host factors such as disease resistance genes.

Compared to natural systems, modern agricultural systems tend to be characterized by temporal stability, and genetic and trophic uniformity. This is because of human selection for desired plant characteristics and management considerations. However, these characteristics increase the epidemiological risk, as evidenced by the comparative rarity of damaging epidemics in indigenous, undisturbed plant communities.¹⁴ A genetically heterogeneous plant population is less vulnerable to an epidemic, through mechanisms such as increasing the spatial distance between susceptible plants.¹⁵ Agricultural homogeneity entails little natural variability in disease resistance.¹⁶

Another central host characteristic is its ontogenic resistance, meaning how the plant's pathogen resistance varies throughout its lifecycle. The exact pattern of ontogenic resistance varies between species, with some more resistant at a young age, others at a later age, while others fluctuate.¹⁷ Understanding ontogenic patterns allows for economic and environmental benefits, since pesticide applications can be restricted only to the times when the plant is vulnerable.¹⁸

5.3.2 Pathogen

¹⁴ Jones, 'Plant virus emergence and evolution' above n<ts>10.

¹⁵ MS Wolfe, 'The current status and prospects of multiline cultivars and variety mixtures for disease resistance, (1985) 23 *Annual Review of Phytopathology* 251–273.

¹⁶ Wolfe 'Strategic use of disease resistant hosts' (1993), above n<ts>9; KS McCann, 'The diversity - stability debate' (2000) 405 *Nature* 228–233.

¹⁷ M-P Develey-Riviere and E Galiana, 'Resistance to pathogens and host developmental stage: a multifaceted relationship within the plant kingdom' (2007) 175 *New Phytologist* 405–416; D Zagory and WJ Libby, 'Maturation-related resistance of *Pinus radiata* to western gall rust' (1985) 75 *Phytopathology* 1443–1447.

¹⁸ A Ficke, DM Gadoury, and RC Seem, 'Ontogenic resistance and plant disease management: A case study of grape powdery mildew' (2002) 92 *Phytopathology* 671–672.

The reproductive characteristics of the pathogen are one of the key determinants of its threat potential. In general, high-risk pathogens have the ability to multiply both sexually and asexually, and have a large potential for gene flow and mutation.¹⁹ High-risk reproductive characteristics allow the pathogen to respond quickly and effectively to factors that may hinder it, whether these be host, human, or environment related. Evolution of plant pathogens may result in a new virulent strain that is resistant to existing controls, or a harmless organism evolving into a virulent pathogen.²⁰ Viruses are particularly concerning, because of their rapid evolution and because by some estimates nearly half of emerging plant pathogens are viruses.²¹ Maximizing host heterogeneity again provides an epidemiological advantage.

Polycyclic pathogens, that have short reproductive cycles and can produce several generations in a single growing season, are a greater risk for sudden epidemics and yield losses. On the other hand, with monocyclic pathogens, the amount of inoculum tends to accumulate over several seasons. The human epidemiological variable comes into play in determining the control response, based on whether the pathogen is mono- or polycyclic. For monocyclics, the management aim is to reduce initial inoculum, whereas for polycyclics, action management is generally targeted at reducing the number of times the pathogen can reproduce in the course of the growing season.

Pathogen virulence is also determined by several factors related to its inoculum. One important factor in this regard is where the inoculum is produced and how it is transported. Spores produced on the leaf surface are likely to spread further much faster

¹⁹ BA McDonald and C Linde, 'Pathogen population genetics, evolutionary potential and durable resistance' (2002) 40 *Annual Review of Phytopathology* 349–379.

²⁰ MJ Jeger, SE Seal and F Van den Bosch, 'Evolutionary epidemiology of plant virus disease' (2006) 67 *Advances in Virus Research* 162–203.

²¹ PK Anderson, AA Cunningham, NG Patel, FJ Morales, PR Epstein and P Daszak, 'Emerging infectious diseases of plants: pathogen pollution, climate change and agrotechnology drivers', (2004) 19 *Trends in Ecology and Evolution* 535; A Moya, EC Holmes, and F Gonzalez-Candelas, 'The population genetics and evolutionary epidemiology of RNA viruses' (2004) 2 *Nature Reviews Microbiology* 279–288.

than soil borne pathogens. Some of the most severe epidemiological threats, such as rusts, mildews and leaf spots, are caused by pathogenic fungi whose spores spread in the air over very large distances, given the right environmental variables such as wind currents. Furthermore, the amount of inoculum determines virulence, although this effect is moderated by environmental factors such as temperature and moisture.²²

5.3.3 Environment

Environmental variables determine epidemiology by affecting resilience and fitness for both the host and the pathogen. Host and pathogen will frequently co-exist until environmental variables such as temperature, moisture, wind, light or soil parameters reach a state conducive to invasion and subsequent development of an epidemic.

Temperature is one central environmental variable. A given elevated temperature may stress the plant and make it more susceptible to disease, while at the same time causing increased pathogen reproduction.²³ But such effects are not uniform, and may be difficult to predict in real-life situations. Temperature extremes can also kill pathogens. Anthropogenic high temperatures form the basis for the pathogen control technique known as solarization.²⁴ Conversely, many pathogens fail to survive low temperatures during winter, and in cooler climates there are concerns that this important natural control method will be lost as a result of climate change.

²² A Dinoor and N Eshed, 'The role and importance of pathogens in natural plant communities' (1984) 22 *Annual Review of Phytopathology* 443–466.

²³ CD Harvell, CE Mitchell, JR Ward, S Altizer, AP Dobson, RS Ostfeld and MD Samuel, 'Climate warming and disease risks for terrestrial and marine biota' (2002) 296 *Science* 2158–2162.

²⁴ G Bonanomi, M Chiurazzi, S Caporaso, G Del Sorbo, G Moschetti and S Felice, 'Soil solarization with biodegradable materials and its impact on soil microbial communities' (2008) 40 *Soil Biology and Biochemistry* 1989–1998.

The presence of vectors and alternate pathogen hosts are also considered environmental variables. Pathogens that reproduce inside plant tissue, rather than on the outside surface, require a vector in order to spread. By controlling the vector, one can also control the pathogen.²⁵ Meanwhile, many pathogens require an alternate host as part of their life cycle. Whilst removing the alternate host is, in theory, enough to stop an epidemic, this is often not possible since there may be many alternates.

Climate change is one of the key challenges facing modern food production. Given its capacity to significantly alter the behaviour of all four main variables (host, pathogen, environmental and human) and potentially render useless a lot of current epidemiological knowledge, climate change is a major issue for plant epidemiology. It is also an issue fraught with uncertainty. As plants generally respond to increased CO₂ concentrations with increased vigour, one result in many locations will be increased biomass and subsequent higher microclimatic humidity, improving conditions for a range of foliar-borne diseases such as rusts and mildews.²⁶ At the same time, the effects of increased UV-B radiation, another climate change effect, have in some studies been shown to increase flavonoid production and therefore disease resistance, while in other studies the opposite effect has occurred.²⁷ Increased vector habitat range and abundance is another major concern. Great expansion is expected of areas with environmental conditions favourable to vectors like Whitefly or Corn Flea Beetle, which in the future may not die over winter.²⁸

²⁵ TM Perring, NM Gruenhagen and CA Farrar, 'Management of plant viral diseases through chemical control of insect vectors' (1999) 44 *Annual Review of Entomology* 457–481.

²⁶ WJ Manning and AV Tiedemann, 'Climate change: potential effects of increased atmospheric carbon dioxide (CO₂), ozone (O₃), and ultraviolet-B (UV-B) radiation on plant diseases' (1995) 88 *Environmental Pollution* 219–245.

²⁷ Ibid.

²⁸ Jones, 'Plant virus emergence and evolution', above n<ts>10.

5.3.4 Human

In the broadest sense, human factors include any practice that affects pathogen survival and spread. Deliberate human variables that aim to reduce epidemics and secure food range from large-scale political initiatives such as quarantine measures, to modern practices such as chemical spraying, to age-old but still relevant practices such as roguing (removing plants) and crop rotation (the latter again underlining how diversity is a fundamental pathogen control principle, in that rotations provide temporal diversity).²⁹ Simple measures can still be very effective: for instance, storing infected seed for a period of time before planting or choosing a well-drained soil are effective ways to reduce fungal threats.³⁰ On the other hand, human factors that unintentionally increase epidemiological risk include global trade and travel, which act as pathogen vectors,³¹ and emerging on-farm practices that may have been adopted for economic or environmental reasons. As the practice of stubble retention has increased, so have epidemics of necrotrophic fungi, because the otherwise beneficial human practice also changes environmental variables like moisture content, to the pathogen's benefit.³²

5.4 Disease management strategies

²⁹ MR Finckh, 'Integration of breeding and technology into diversification strategies for disease control in modern agriculture' (2008) 121 *European Journal of Plant Pathology* 399–409.

³⁰ KD Lindbeck, TW Bretag and R Ford, 'Survival of *Botrytis* spp. on infected lentil and chickpea trash in Australia' (2009) 38 *Australasian Plant Pathology* 399–407.

³¹ Jones, above n<ts>10.

³² MS McLean, BJ Howlett and GJ Hollaway, 'Epidemiology and control of spot form of net blotch (*Pyrenophora teres* f. *maculata*) of barley: a review' (2009) 60 *Crop and Pasture* 303–315; Lindbeck et al., above n<ts> 31.

Mitigation strategies emerge from many quarters, creating a sustainable balance of complementary approaches to disease control. The application of chemical pesticides to crops, seed, and propagative material is often vital. Many crops benefit from the judicious application of pesticides, and this remains one of the principal control methods available for pathogens and their vectors.³³ In developing regions, the application of pesticides may be crucial in retaining seed viability and sustainable food production. Diseases caused by mycoplasmas, viruses, and viroids are transmitted by vectors and control of vector mobility, by means of insecticides, polyethylene traps, and reflective mulches, significantly limits infection and distribution.

Cultural agricultural practices exert a dominant role in integrated disease management, and are crucial in developing countries where economic access to chemical pesticides and agricultural technology is limited. For centuries, traditional practices of crop rotation, intercropping, and maintenance of genetic diversity have been adopted to control disease and sustain food production. Seasonal, environmental, and microclimatic conditions exert a significant role in disease epidemiology. Paddock selection, harvest management, sowing schedule, and crop density are important components of agricultural systems that can be manipulated to limit the severity and incidence of pathogen invasion. Sterilization of machinery, transport equipment, and storage vessels, the destruction of infectious crops, and biological eradication utilizing suppressive soils and antagonistic organisms, are strategies that can be integrated into a sustainable disease management protocol.

One of the most effective and economically viable approaches to disease management is the cultivation of genetically resistant crops. Spontaneous variation in disease resistance can be selected, and genes for resistance introduced by conventional hybridization techniques or through genetic modification. While genetic modification technology has been used widely in insect and weed control, there are relatively few examples of its

³³ Strange and Scott, 'Plant disease', above n<ts>10.

successful use in controlling plant pathogen epidemics.³⁴ This may be largely due to legal restrictions and safety concerns. In spite of significant resistance, proponents maintain that genetically modified (GM) crops promise several hopeful future lines of inquiry, such as interfering with the bacterial quorum sensing employed by the pathogen to express virulence genes once population size has reached a given level.³⁵ Whether such techniques become more widespread in the future will be reliant on social and political decisions.

5.5 Biosecurity and quarantine measures

Barriers in the ability to import, export and trade produce within and between growing regions also significantly impact on food security. Biosecurity is a strategic and integrated concept that incorporates policy and regulatory frameworks that scientifically analyse and manage the biological, social, political and environmental risks associated with the introduction and spread of diseases within cropping regions. Efficient biosecurity protocols, together with detection and diagnostic systems, are fundamental to the effective containment and control of pathological plant invasions.³⁶ The prompt recognition of exotic or emerging epidemics of endemic diseases and their aetiology allows for risk assessment, recognition of dissemination pathways, and pre-emptive modelling of potential pathogenic impact and distribution. In many developed countries,

³⁴ DB Collinge, OS Lund and H Thordal-Christensen, 'What are the prospects for genetically engineered, disease resistant plants?' (2008) 121 *European Journal of Plant Pathology* 217–231.

³⁵ X Cui and R Harling, 'N-acyl-homoserine lactone-mediated quorum sensing blockage, a novel strategy for attenuating pathogenicity of Gram-negative bacterial plant pathogens' (2005) 111 *European Journal of Plant Pathology* 327–339.

³⁶ LA Meyerson and JK Reaser, 'Bioinvasions, bioterrorism, and biosecurity' (2003) 1 *Frontiers in Ecology and the Environment* 307–314.

national eradication programmes to mitigate incursions of specific exotic or endemic diseases are initiated only after the recognition of a pathogen possessing the potential to significantly impact agricultural industries and subsequent food production. Every member of the the World Trade Organization (WTO) is bound by the Sanitary and Phytosanitary (SPS) Agreement,³⁷ which guides the types and timing of measures put in place to protect plant health. Actions performed under the SPS Agreement, such as quarantine, exclusion and/or disease-free status declaration, are based on scientific evidence and risk analyses within internationally accepted guidelines. However, the actions may directly or indirectly affect international trade, particularly if they are used in a non-tariff trade barrier setting.³⁸

The biosecurity infrastructure crucial to resisting invading pathogens is often under-resourced or absent in developing countries reliant on locally-produced staples, resulting in increasing fragility in the food supply system. On the other hand, geographic isolation and vast population distribution has significantly protected island nations like Australia from extensive exotic pathogen colonization, providing agricultural industries with a competitive advantage in international markets. In these cases, government backed stringent quarantine and biosecurity policies, incorporating pre-border, border and post-border surveillance and interception, have been implemented to maintain the sustainability of agricultural industries, and protect unique agro-ecosystems. Specifically, exclusion of pathogenic organisms through plant and vector quarantine is the primary line of defence against exotic invasions. However, national regulatory quarantine and biosecurity systems are continually challenged by the exponential expansion in global agricultural commodity trade. Infected seed, propagative material, foodstuffs, and intact plants are common pathways by which a pathogen may traverse vast distances and become established in foreign regions.

³⁷ 1994 Agreement on the Application of Sanitary and PhytoSanitary Measures, 1867 UNTS 493, <http://www.wto.org/english/docs_e/legal_e/15-sps.pdf>.

³⁸ CD Stansbury, SJ McKirdy, AJ Diggle and IT Riley, 'Modeling the risk of entry, establishment, spread, containment, and economic impact of *Tilletia indica*, the cause of karnal bunt of wheat, using an Australian context' (2002) 92 *Phytopathology* 321–331.

Evolving biosecurity policy continually provokes intensive industrial and political controversy around the world as traditional trade barriers fall.

5.6 Social and political considerations for disease management strategies

Existing socio-political structures in many ways run directly counter to the objective of a sustainable and efficient agriculture. For example, as shown, heterogenous crops have greater pathogen resistance, and can thereby reduce chemical use as well as other practices that entail greatly detrimental effects on society and nature as a whole. However, our economic system, with its defining desire for standardization and predictability, tends to consider agriculture as just another business sector (which it is clearly not, since it is engaged with dynamic, evolving and complex nature-based systems). Because of this, heterogenous crops are often dismissed in the developed world as too difficult to market.³⁹

Meanwhile, whilst constraints around the release of GM crops are necessary in terms of ensuring environmental health and safety, many disease resistant (or even immune) crop varieties have been shelved due to bureaucratic red tape and corporate positioning. Conversely, the release of some GM crops has greatly affected their market potential. An early touted success was the insertion of a Papaya Ringspot Virus (PRSV) coat protein gene into the papaya genome. This was the first consistently effective control of this disease, and it put a stop to devastating yield losses.⁴⁰

³⁹ Finckh, 'Integration of breeding and technology into diversification strategies', above n<ts>30.

⁴⁰ C Gonsalves, DR Lee and D Gonsalves, 'The adoption of genetically modified papaya in Hawaii and its implications for developing countries' (2007) 43 *Journal of Development Studies* 177–191.

Broader socioeconomic factors also determine the prevalence of other human practices. For instance, in a large cropping area a practice such as roguing is very labour and time intensive and this may mean it is excluded as a viable practice in industrialized, high-salaried countries. This again may lead to a preference for other control methods such as chemicals. Also, pathogen resistance is not the only consideration a farmer makes in cultivar selection. Pathogen-resistant cultivars may have less desirable phenotypic qualities, which impede their widespread adoption.

5.7 Conclusion

Global food production has outpaced population growth over the last 40 years.⁴¹ Indeed, on a global scale we most likely currently produce sufficient amounts to feed our growing population. The localized reasons for food insecurity are complex and include issues of governance, distribution, conflict, waste, crops grown for energy rather than food, erosion and reduced soil fertility. Simultaneously, we cannot ignore that in the coming few decades 95 per cent of the world's population expansion will be in developing countries. This will occur in regions historically hardest hit and least able to cope with crop failures caused by disease and especially where a narrow diversity of crop is grown. To secure an adequate food supply in developing countries, emphasis on plant pathology and biotechnology research must be focussed on future-proofing elite cultivars of staple food crops. This must be done whilst considering the potential impacts of climate change on pathogen distribution and intensity.⁴²

⁴¹ P Christou and RM Twyman, 'The potential of genetically enhanced plants to address food insecurity' (2004) 17 *Nutrition Research Reviews* 23–42.

⁴² PJ Gregory, SN Johnson, AC Newton and JS Ingram, 'Integrating Pests and Pathogens into the climate change/food security debate' (2009) 60 *Journal of Experimental Botany* 2827–2838.

The development of effective plant disease management should be based on an understanding of the complex interaction of multiple factors that contribute to the disease expression. Management based on one single strategy, or failing to recognize that variables are constantly evolving, will likely lead not only to control measures gradually losing effectiveness, but can in itself create the necessary foundation for the emergence of new, increasingly virulent pathogens. The basic recognition of dynamism becomes all the more crucial as our climate changes⁴³. While making exact predictions is impossible, it appears clear that the future will see change on a scale and speed previously unknown.

Simultaneously, the importance of biosecurity in protecting food production and the development of mitigation strategies to combat invading plant pathogens must intensify, particularly for staple food species. Whilst there are substantial costs inherent in biosecurity, eradication programmes, and integrated disease management, the direct and indirect benefits will forge improved economic and environmental sustainability of agricultural production. Ultimately, securing plant health will be crucial to the long-term viability of the world's agricultural industries. In short, we must act now to ensure our staple crops are protected and resilient to major pathogens under current and future climate scenarios to ensure food security for all.

⁴³ S Chakraborty and AC Newton, 'Climate change, plant diseases and food security: an overview' (2011) 60 *Plant Pathology* 2-14.