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REVIEW

# Diseases in tropical and plantation crops as affected by climate changes: current knowledge and perspectives

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Tropical and plantation crops include important crops for food security and alternative energy resources. Even so, there are few studies on the impact of climate change on diseases of these crops. Findings from previous studies concerning some climate-change effects on diseases of coffee, sugarcane, eucalyptus, cassava, citrus, banana, pineapple, cashew, coconut and papaya have been summarized to provide a context. By reviewing available methods to evaluate the impact of climate change on diseases of tropical and plantation crops, we present trends for some diseases and their management strategies, identify critical gaps in knowledge, and suggest experimental and analytical approaches to advance knowledge. As the projected climate conditions will probably vary greatly in the future from continent to continent and from developed to developing countries, studies must be conducted under tropical regions considering their specific environmental conditions. Multifactor studies under realistic field situations, such as free air $CO_2$ enrichment with increasing $CO_2$ and $O_3$ concentrations incorporating spectral reflectance measures *in situ* for realistic assessment of plant growth, are a way forward. Effects of a changing climate on chemical and biological controls are discussed in the context of changing global outlook on environmental demands for the future.

*Keywords*: atmospheric $CO_2$ and $O_3$ concentration, crop management strategies, FACE facilities, open top chambers, tropical plant diseases

## Introduction

Potential effects of climate change on agriculture, according to the IPCC (Solomon *et al*., 2007), include reduced yields in warmer regions as a result of heat stress; damage to crops, soil erosion and inability to cultivate land caused by heavy precipitation events; and land degradation resulting from increasing drought. Crop simulation models, driven by future climate scenarios from global circulation models, suggest that the reduction in agricultural production would be more severe in tropical regions, where there is still a shortage of food production (Cerri *et al*., 2007).

Certainly, the increased frequency of extreme weather events will result in the increased importance of abiotic stresses under future climate. With respect to biotic stresses, few studies have been done on the impact of climate change on diseases of tropical and plantation crops, despite coffee, sugarcane, eucalyptus, rubber, oil palm, cassava, coconut, citrus and other fruits being important tropical crops for domestic consumption and export earnings. Diseases are responsible for losses of at least 10% of global food production, representing a threat to food security (Strange & Scott, 2005). Agrios (2005) estimated that annual losses by disease cost $220 billion and stated that to these should be added 6–12% losses of crops after harvest, which are particularly high in developing tropical countries lacking infrastructure. Besides direct losses, the methods for disease control – especially the chemical methods – can result in environmental contamination and in residual chemicals in food, in addition to social and economic problems.

Climate change will increase uncertainty in the production of many crops in tropical countries, including many developing countries where these crops may form an important basis of the gross domestic product. For example, Gay *et al.* (2006) verified that the projected climate-change conditions for the year 2020 indicate that coffee production in Veracruz (Mexico) might not be economically viable for producers, since the model indicates a reduction of 34% of the current production. For Brazil, according to Assad *et al.* (2004), a reduction in suitable coffee-growing areas greater than 95% is expected in Goiás, Minas Gerais and São Paulo States, and about

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75% in Paraná State in the case of a temperature increase of 5·8°C. Any disruption to production caused by plant diseases will impact on the economy and society, with far-reaching implications beyond simple production losses. Coffee leaf rust, caused by *Hemileia vastatrix*, is considered the main disease of the crop, as it is estimated that disease losses, in the absence of effective control measures, can amount to 30% of production (Kushalappa & Eskes, 1989; Zambolim *et al.*, 1999). In South America, production of green coffee was almost 4 million tonnes in 2008 (FAO, 2010), constituting an important export product in several countries. Analysis of the potential impact of climate change on coffee leaf rust is essential for the adoption of adaptation measures, in order to avoid more serious losses. The limited information available on climate-change impact on tropical crops and future projections are mostly based on modelling studies. Little empirical knowledge necessary for the development of adaptation strategies is available.

In general, long-term datasets are particularly rare in relation to tropical and plantation crop diseases, which are a prerequisite for finding fingerprints of inter-annual climatic variation on plant diseases (Jeger & Pautasso, 2008), making it difficult to check if changes are already occurring.

A discussion of the potential impact of climate change on plant diseases of economic significance in Australia, including sugarcane and eucalyptus diseases, was published by Chakraborty *et al.* (1998). Ghini & Hamada (2008) edited a book discussing the impact of climate change on diseases of the main crops in Brazil, including important diseases of the tropical region. Given the limited empirical data, the purpose of the present review is to discuss experimental approaches available for evaluating the impact of climate change on diseases of tropical and plantation crops, present the trends and management strategies for some diseases, identify critical gaps in knowledge and suggest experimental and analytical approaches to advance knowledge.

## Experimental approaches

Understanding and predicting climate-change impact in crops requires approaches involving experimental manipulation of temperature, precipitation, $CO_2$ and $O_3$. A multifactor approach mimics the way climate change alters agroecosystems, allowing realistic impact assessment. Nevertheless, multifactor studies of climate-change effects have never been done with tropical and plantation crop diseases. There are some examples of studies dealing with more than one factor, mostly in controlled environments, for diseases of annual crops (Tiedemann & Firsching, 2000; Plessl *et al.*, 2007) and in free to air $CO_2$ enrichment (FACE) facilities for forestry species (Karnosky *et al.*, 2002), but temperature has been a difficult parameter to control in field studies. Mikkelsen *et al.* (2008) discussed the design and functionality of multifactorial experiments with particular focus on interactions and artefacts related to the combined treatments. The experimental design of a multifactor climate-change experiment with elevated $CO_2$, warming and drought at Brandbjerg, Denmark, described by the authors, confirms that it is difficult to reach the target temperature. Experimental studies of the long-term effects of increased $CO_2$ and $O_3$ concentrations on tropical and plantation crops in more realistic field settings have not yet been done on a comprehensive scale. The general rule that high concentration of atmospheric $CO_2$ results in higher yield and plant development is not always applicable to these crops. Trials conducted by Gleadow *et al.* (2009) demonstrated that total cassava biomass and edible-tuber yield decreased linearly with rising atmospheric $CO_2$ concentration, probably as a result of lower photosynthetic capacity caused by stomata exceptionally sensitive to $CO_2$.

Despite general evidence of beneficial effects of $CO_2$ on the host plant, it is not well known if these effects will still take place in the presence of pathogens or other limiting factors, particularly in tropical countries. Studies under controlled conditions might not reflect plant responses in the field, where there are variations and interactions among temperature, precipitation and other variables. FACE and open-top chambers (OTCs) offer more realistic options to understand how rising atmospheric composition of $CO_2$ and $O_3$ can influence host–pathogen interaction, disease severity and management of tropical and plantation crops. There are several OTC (Bortier *et al.*, 2000; Riikonen *et al.*, 2008) and FACE facilities worldwide, ranging from annual crops to forestry species, and some of these have dealt with plant diseases (Percy *et al.*, 2002; Mitchell *et al.*, 2003; Eastburn *et al.*, 2010). Recently, Ainsworth & Long (2005), Erbs & Fangmeier (2006) and Chakraborty *et al.* (2008) have reviewed and summarized FACE research in several FACE facilities. However, among the FACE and OTC studies described by them, none were with tropical or plantation crops.

The OTCs designed for temperate climate are not suited to tropical regions, because they alter the microclimate within an OTC. The temperature reached inside the OTC, in tropical situations is much higher than ambient conditions when compared with temperate situations, causing significant changes in the microenvironment. Light intensity is particularly diminished, wind velocity is lower and relative humidity is higher (Lessin & Ghini, 2009). New OTC designs and environmental control systems are necessary to address the requirements of tropical plant pathosystems.

A FACE facility is under construction in Brazil to study the effects of increased $CO_2$ concentration on coffee diseases, pests and weeds, as well as plant physiology and other related organisms (Climapest project, website: http://www.macroprograma1.cnptia.embrapa.br/climapest). Six 10-m-diameter elevated $CO_2$ rings have been constructed, each with separated controllers that measure $CO_2$ concentration, air humidity and temperature, precipitation, wind speed and direction, barometric pressure, soil temperature and humidity. The system instrumentation is based on wireless sensor network technology. Environmental sensors have been adapted to ZigBee modules. The wireless sensor network-based instrumentation will facilitate system installation and maintenance, and will increase its portability. The experimental site is situated at Jaguariúna, São Paulo State (latitude 22°14′10″S, longitude 46°59′09″W, 570 m a.s.l.). The coffee plantation that includes the experimental plots is 7 ha in size. The Climapest FACE aims to study the individual and combined effects of high $CO_2$ concentration, water and N supply. To evaluate the impact of increased $CO_2$ concentration on plant diseases, pests and weeds in forest species, apple, peach, soybean, grape, corn, cotton, castor beans, forage crops, coffee, cassava and banana, the Climapest project is installing six mini-FACE facilities throughout the country (Belém, Pará State; Petrolina, Pernambuco State; Sete Lagoas, Minas Gerais State; Londrina, Paraná State; Jaguariúna, São Paulo State; and Vacaria, Rio Grande do Sul State).

Both the fabrication of facilities and the running of long-term FACE studies on tropical and plantation crops are expensive because of plant height, high temperatures promoting greater loss of gases and increased cost of monitoring equipment. These problems may present impediments to the establishment of new FACE facilities in tropical regions. Ainsworth *et al.* (2008) stated that the major limiting factor for FACE is the cost of the large quantities of $CO_2$ that are released, which varies dramatically between FACE experiments, depending on the final concentration of $CO_2$, source of $CO_2$, plot volume fumigated, wind speed and uniformity of the vegetation. These authors proposed a new generation of large-scale and low-cost FACE experiments. For example, the use of gradients of each climate variable is important to obtain more accurate models of disease development, instead of discrete levels (Chakraborty *et al.*, 2008).

Pritchard & Amthor (2005) discussed the benefits and limitations of different methods of studying effects of environmental change on crops. Each method of experimentally controlling environmental conditions has advantages and disadvantages. Under controlled conditions, superior control of temperature, humidity, gas concentrations and other variables can be reached. However, studies conducted in controlled conditions might not reflect plant responses in the field, where there are variations and interactions among temperature, precipitation and other factors. Light levels, for example, are often low inside chambers and the spectral quality usually differs from that of the sun. Despite these limitations, controlled conditions are useful for evaluating epidemiological parameters, changes in aggressiveness of pathogen populations (Chakraborty & Datta, 2003) and plant physiology. A particular approach is the European Ecotron, which is a closed controlled-environment facility dedicated to the study of ecosystems and organisms under current and future environmental changes. There is a set of three experimental facilities housing a series of confinement units on a large (macrocosm), medium (mesocosm) or small scale (microcosm), allowing a range of high quality simultaneous environmental simulations, with high quality measurements. The purpose is to keep the conditions as realistic as possible by working with natural light, intact soil monoliths, large samples of ecosystems and with *in situ* reference measurements.

Studies on the effects of $CO_2$ and $O_3$ should be performed with methods that allow changes only in the target variable, whilst others remain constant. These studies become difficult because of the inability to create an environment free from artefacts and equipment necessary to expose the plant to the target gas to be tested. The search for more realistic conditions has led to the use of OTC and FACE experiments. The OTCs can be used for studies with increased concentrations of $CO_2$ and $O_3$ because of the ability to conduct trials at all stages of plant development, with less interference from the structures, except for the reduction of solar radiation and the increase in temperature caused by the plastic. Plants can be grown directly in soil, which is an advantage compared with pot trials. Studies in pots should be avoided because they may limit of root growth and change the soil structure. Moreover, using OTCs it is possible to obtain responses to the gas in natural conditions, including daily fluctuations and seasonal climate. However, FACE experiments allow more natural conditions, because of the release of $CO_2$ and $O_3$ under field conditions.

In addition to the high cost of establishing FACE and OTC facilities, assessing and measuring disease severity and other pathogen-related traits in large plant canopies of tropical and plantation crops is another factor limiting research in this area. Remote sensing has been useful for monitoring areas planted to specific crops, for detecting plant diseases and insect infestations, and for contributing to accurate crop production forecasts (Campbell, 2007). Factors of plant stress, such as insufficient water or nutrients, adverse climatic conditions, plant diseases, and insect damage on crops, cause physiological and morphological changes within plants; and these factors can be associated with the spectral behaviour of the plants. For example, plant pathogens may alter leaf colour by causing chemical changes within plant cells or by growing on plant surfaces; and insects and pathogens can change morphological characteristics by ingesting or detaching plant material (Jackson, 1986).

Remote sensing applications rely on knowledge of the spectral properties of individual leaves and plants above a background of soil and plant litter, and this information, often termed 'ground truth' is acquired *in situ*, which for plant diseases relies on plant pathology expertise. Field measurements are obtained by a field spectroradiometer which is a unit consisting of an array of photosensitive detectors, with filters or a diffraction grating to separate radiation into several spectral regions, and this procedure is called ground-based radiometry.

One of the earliest studies examining the spectral responses of a diseased crop is credited to Colwell (1956), and since then other research has been conducted by adopting ground-based radiometry, for example, with *Maize dwarf mosaic virus*-infected and *Helminthosporium maydis*-infected corn leaves (Ausmus & Hilty, 1972);

barley infected by cereal powdery mildew (Lorenzen & Jensen, 1989); leaf spectral reflectance for powdery mildew disease in golden euonymus (Carter, 1993); bean infected by *Botrytis fabae* (Malthus & Madeira, 1993); and powdery mildew and take-all disease in wheat (Graeff *et al*., 2006). Studies relating the spectral responses of diseased crop canopies with ground-based radiometry are essential as a scientific base to the use of satellite multispectral scanner data to detect and monitor plant disease.

The use of hyperspectral data and hyperspectral analytical approaches have increased in the past decade, with technological advances in aircraft-borne sensors and satellite remote sensing. Hamid Muhammed & Larsolle (2003) used the whole spectrum in the objective examination of how different parts of it contribute in describing disease severity in wheat with hyperspectral reflectance measures, processing them using independent component analysis and principal component analysis. Blackburn (2007) proposed the use of hyperspectral data combined with light detection and ranging (lidar) remote sensing for quantifying chlorophyll pigments of plants. According to Osama *et al.* (2007), numerous studies have shown the applicability of lidar-based remote sensing to estimate plant properties such as canopy height, canopy structure, carbon stock, and species; and several studies have also demonstrated the usefulness of lidar in assessing large-scale plant growth responses. However, the potential of 3D lidar has not yet been fully exploited for monitoring plant responses to stress, including plant diseases and insect damage on crops. Under the forecasted conditions of climate change, i.e. the enrichment of $CO_2$ and $O_3$ atmospheric concentrations, higher temperature and water stress, new interactions between plants and their environment could occur and the host–pathogen interaction could be altered, with consequent changes in the spectral properties of the plant.

## Potential impact of climate change on tropical and plantation crop diseases

A limited number of studies have considered the potential impact of climate change on diseases and pests of tropical and plantation crops. Much of the literature deals with modelling approaches to determine how the distribution of a particular disease/pest may change under a future climate scenario and only a handful have used experimental approaches (Ghini & Hamada, 2008; Ghini *et al*., 2008a). The effects of elevated $CO_2$ and/or $O_3$ have rarely been included in these assessments.

Deutsch *et al.* (2008) integrated empirical fitness curves describing the thermal tolerance of terrestrial insects with the projected geographic distribution of climate change for the next century to estimate the direct impact of warming on insect fitness across latitudes. The authors observed that warming in the tropics, although relatively small in magnitude, is likely to have the most deleterious consequences because tropical insects are relatively sensitive to temperature change and are currently living very close to their optimal temperature. In contrast, species at higher latitudes have broader thermal tolerance and are living in climates that are currently cooler than their physiological optima, so that warming may even enhance their fitness. Thus, it was concluded that the greatest extinction risks from global warming may be in the tropics. This is particularly important for viruses transmitted by insect vectors, such as *Pineapple mealybug wilt-associated virus*, transmitted by *Dysmicoccus brevipes* and *D. neobrevipes* (Sether *et al*., 2001, 2005); *Papaya ringspot virus* (PRSV-P), transmitted by different species of aphid (Rezende & Martins, 2005); and Citrus leprosis virus, transmitted by *Brevipalpus phoenicis* (Feichtenberger *et al*., 2005). A reduction in vector population may decrease the importance of some viruses in tropical regions.

A modelling approach has been used to determine the potential impact of climate change on the most important diseases of coffee, sugarcane, eucalyptus, cassava, citrus, banana, pineapple, cashew, coconut, mango and papaya, employing detailed knowledge of environmental conditions favourable for disease development and predicted climate change projected for the next several decades. In coffee, the potential impact of climate change on the spatial distribution of the coffee nematode (races of *Meloidogyne incognita*) and leaf miner (*Leucoptera coffeella*) in Brazil was determined using a geographic information system (Ghini *et al*., 2008b). Future scenarios focused on the 2020s, 2050s and 2080s [IPCC scenarios A2 and B2 (Nakicenovic & Swart, 2000)] were obtained from five General Circulation Models, available from the Data Distribution Centre of Intergovernmental Panel on Climate Change (http://www.ipcc-data.org/sres/gcm_data.html; Watson, 2001). Geographic distribution maps were prepared using models to predict the number of generations of the two pests. Maps obtained for scenario A2 projected an increased infestation of the nematode and of the insect pest as a result of a greater number of generations per month than occurred during 1961–1990. The number of generations also increased in the B2 scenario, but the magnitude was lower than in the A2 scenario for both organisms.

Coffee leaf rust, caused by *H. vastatrix*, is the most destructive disease of coffee in all tropical regions (Kushalappa & Eskes, 1989; Zambolim *et al*., 1999). The fungus attacks all commercial coffee cultivars, causing premature drop of infected leaves and reduced yield. Besides rainfall and temperature, the severity of coffee leaf rust is influenced by the amount of initial inoculum and the capacity of cultivars to shed infected leaves (Bergamin Filho *et al*., 1990). In Brazilian conditions, Chalfoun *et al.* (2001) observed changes in the annual date of the first reported occurrence of coffee rust, compared to what had been observed during the 1980s and 1990s. Possibly, these results were related to the increase in minimum average temperature during the winter, extending the sporulation period for the pathogen to September–October. The effect of elevated atmospheric $CO_2$ concentration on the latent period of coffee leaf rust was evaluated by Mendes (2009). Coffee seedlings were grown at concentrations of 400, 500, 700 and 900 p.p.m. $CO_2$ and inoculated with urediniospores of the pathogen under controlled conditions (22°C and 100% relative humidity). The average latent period of coffee leaf rust was 36·4 days at 400 p.p.m., reduced to 21·2, 21·4 and 18·7 days at 500, 700 and 900 p.p.m. $CO_2$, respectively.

According to Sanguino (2008), the importance of diseases that affect sugarcane, such as smut (*Ustilago scitaminea*), *Sugarcane mosaic virus* (SCMV), leaf scald disease (*Xanthomonas albilineans*) and ratoon stunting disease (*Leifsonia xyli* subsp. *xyli*), can be changed only by direct human interference. Climate change is unlikely to affect the importance of these diseases. As these diseases are systemic, their main means of spreading is by the use of infected material for vegetative propagation, or by infected cutting instruments. However, according to Chakraborty *et al.* (1998), diseases such as leaf scald may undergo increased spread via severe storms and cyclones. Pineapple disease of sugarcane, caused by *Ceratocystis paradoxa*, will probably be reduced in significance as it is favoured by low soil temperatures (Chakraborty *et al.*, 1998).

Booth *et al.* (2000) performed a risk analysis for the occurrence of *Cylindrocladium quinqueseptatum*, an important causal agent of leaf blight in eucalyptus in several production regions in the world. The authors also used some simple climate-change scenarios to suggest areas in mainland South East Asia which may become vulnerable to *C. quinqueseptatum* over the next 50 years. Moraes *et al.* (2008) studied the potential impact of climatic change on eucalyptus rust disease (*Puccinia psidii*), elaborating distribution maps of the disease under scenarios A2 and B2. The maps showed that there will be a reduction of the favourable area in Brazil. Considering the environmental conditions for the pathogen, such a reduction will be gradual for the decades of 2020, 2050 and 2080, mainly in warm regions.

The nursery diseases caused by *Ralstonia solanacearum, Xanthomonas* sp. and *Quambalaria eucalypti* should remain the most important diseases in the future for eucalyptus, because they are favoured by high temperatures (Alfenas *et al.*, 2004). Under field conditions, diseases caused by *Ceratocystis fimbriata*, *Cylindrocladium* sp., *R. solanacearum* and *Xanthomonas* sp. will require special attention because they are also favoured by high temperatures and the pathogens are aggressive. Furthermore, secondary pathogens will have a greater chance of causing losses, mainly through plant stress, caused by changes in temperature and precipitation, especially because resistant genetic material is not being selected to control these pathogens. Among the factors responsible for the increased importance of secondary diseases, there is increased plant predisposition to unfavourable climate conditions (R. G. Mafia, A. C. Alfenas and R. A. Loss, Aracruz Celulose and Viçosa University, Brazil, personal communication).

Bacterial blight caused by *Xanthomonas axonopodis* pv. *manihotis* is the most important disease of cassava (*Manihot esculenta*), limiting production and causing losses of 50–100% in susceptible cultivars, compared with only 5–7% in resistant cultivars (Verdier, 2002; Massola Jr & Bedendo, 2005). In regions where the current temperature is above the bacterium's optimum temperature (22–26°C, according to Verdier, 2002), the importance of the disease will tend to remain similar or lower because rising projected temperatures will be unfavourable to it. For regions where current temperature is below the optimum, the increase in temperature will favour the occurrence of epidemics.

The Brazilian citrus industry is the largest among the tropical countries and the state of São Paulo accounts for 83% of the country's production. Jesus Júnior *et al.* (2008a) analysed the impact of climate change on citrus diseases in São Paulo State and predicted that for citrus variegated chlorosis caused by *Xylella fastidiosa*, under future scenarios of climate change for the central and southern regions of Brazil, the production of shoots in spring and summer would increase, increasing the population of leafhoppers (*Dilobopterus costalimai*, *Oncometopia facialis* and *Acrogonia* sp.), considered the main vectors of the bacterium (Milanez *et al.*, 2002) and consequently the incidence of the disease. Symptoms of diseased plants may be aggravated by increased temperature and period of water deficit. With rising temperatures, there should also be a change in the abundance of leafhoppers. Citrus huanglongbing (= greening; 'Candidatus *Liberibacter*' spp.) can also show an increase in intensity under more favourable conditions for the vector (*Diaphorina citri*). The projected reduction in precipitation in this region could stimulate the early development of the mite population (*Brevipalpus phoenicis*) and consequently increase the viral disease, citrus leprosis. However, extreme drought events can reduce the mite population. Jesus Júnior *et al.* (2008a) concluded that the importance of citrus black spot (*Guignardia citricarpa*) and floral rot (*Colletotrichum acutatum*) could increase with rising temperatures.

Black Sigatoka (*Mycosphaerella fijiensis*) is considered the most damaging and costly disease of banana in the world (Ploetz *et al.*, 2003). Ghini *et al.* (2007) studied the potential impact of climatic change on black Sigatoka by using IPCC scenarios A2 and B2 to project distribution maps of the disease. The maps projected a reduction of the favourable area to the disease in Brazil resulting from a reduction in relative humidity to levels below 70%. Such reduction will be gradual for the 2020s, 2050s and 2080s and will be greater for scenario A2 than for B2. Despite this, extensive areas will remain favourable to this disease, especially from November to April, which is currently the most favourable period. Jesus Júnior *et al.* (2008b) used the IPCC scenarios and classified areas as highly favourable, favourable, relatively favourable, little favourable and unfavourable to develop maps representing future worldwide spatial distribution of black Sigatoka. The predictions suggested the same results obtained by Ghini *et al.* (2007), i.e. in the future, favourable areas for the development of the disease will decrease. Panama disease (*Fusarium oxysporum* f. sp. *cubense*) is another important disease which is prevalent in most banana-growing regions (Ploetz *et al.*, 2003). In contrast to the black Sigatoka story, Gasparotto & Pereira (2008) suggested that the importance of Panama disease will increase with climate change, explaining that rising temperatures and periods of drought will alter plant physiology, causing stress, and possibly increasing the aggressiveness of *F. oxysporum* f. sp. *cubense* in susceptible cultivars.

Pineapple fusariosis, caused by *Fusarium subglutinans* f. sp. *ananas*, may be reduced in significance by increased temperatures. This observation is based on the work of Matos *et al.* (2000), who reported a reduction in the incidence of *Fusarium* when the temperature exceeded 35°C and rainfall decreased. The importance of pineapple mealybug wilt, caused by the complex called *Pineapple mealybug wilt-associated virus* (PMWaV-1, PMWaV-2 and PMWaV-3), transmitted and spread by *D. brevipes* and *D. neobrevipes* (Sether *et al.*, 2001, 2005), on the other hand, may increase because the vectors could be stimulated by rising temperatures. PMWaV is widespread in all pineapple-producing areas (Sanches *et al.*, 2000).

Climate change will favour the occurrence of epidemics of cashew (*Anacardium occidentale*) powdery mildew (*Oidium anacardii*), both in Africa and Brazil, where currently they are of secondary importance (Freire *et al.*, 2002; Adejumo, 2005). Epidemics of anthracnose (*Colletotrichum gloeosporioides* and *Colletotrichum acutatum*), which is the most important disease of cashew in Brazil, will be more frequent under the IPCC future climate scenarios for Brazil (Hamada *et al.*, 2008). Relatively major changes in the incidence of anthracnose, black mould (*Pilgeriella anacardii*) and powdery mildew of cashew with droughts during 2005 and 2006, and excessive rainfall in 2008 and 2009, suggests that these diseases may be easily influenced by a changing climate (J. E. Cardoso and F. M. P. Viana, Embrapa Tropical Agroindustry, Brazil, personal communication).

Climate change will reduce the importance of black leaf spot (*Camarotella torrendiella* and *Camarotella acrocomiae*), phytomonas wilt (*Phytomonas* sp.), blight and leaf spots (*Bipolaris incurvata*) and heart rot (*Phytophthora* spp.), but not of leaf blight (*Botryosphaeria cocogena*) of coconut palm (*Cocos nucifera*) in Brazil (D. R. N. Warwick, V. Talamini, R. R. C. Carvalho and A. M. F. Silva, Embrapa Coastal Tablelands, Brazil, personal communication). Again, these assessments are projected based on observed effects of reduced precipitation and increased temperature.

*Papaya ringspot virus* (PRSV-P) is transmitted by different species of aphid. It is estimated that the damage caused by this disease will increase in severity with the expected increase in temperature. Mangrauthia *et al.* (2009) observed that at temperatures between 26 and 31°C symptoms were more severe. Jesus Júnior *et al.* (2007) evaluated the impact of climate change on leaf lesions (*Asperisporium caricae*) of papaya in Brazil and found that in the future, there will be a reduction in the area favourable to this disease. However, the authors point out that large areas will still be favourable to it, particularly in Espirito Santo State, a leading producer of papaya in Brazil.

In summary, there is limited information on the impact of climate change on diseases of tropical and plantation crops as a result of lack of experimental studies (Table 1). The potential effects of climate change depend on specific host–pathogen combinations, and associated beneficial microorganisms; hence, impact cannot be generalized without further detailed studies. In general, the discussions above are based on projected future scenarios using the knowledge available in the literature for hosts, pathogens and diseases. Thus, there is an uncertainty associated with the fitness of hosts and pathogens. In some cases, certain cultivars will not be grown where they are currently growing and there will be a change in the geographical distribution of crops, and this aspect has not been considered.

## Impact on disease management strategies

Disease management strategies are influenced by climate conditions. Because of the limited information about the impact of climate change on tropical and plantation crop diseases, pests and weeds, it is difficult to predict the effects on integrated pest management. Certainly, quarantine measures to control emerging pathogens, for example, will be very important in order to prevent the spread of the pathogens into new areas, because of the alterations in disease geographical and temporal distribution resulting from climate change.

According to Coakley & Scherm (1996), soilborne pathogens will remain more difficult to control than foliar pathogens because of fewer management options. Once the soil is infested, some pathogens can survive for years, even in the absence of a susceptible host. Therefore, quarantine measures and exclusion will continue to play an important role in controlling these diseases.

There have been few discussions on how chemical control will be affected by climate change, despite the importance of this subject. One of the few papers on this subject was published by Ziska & Goins (2006), who concluded that depending on weed species ($C_3$ or $C_4$ metabolism), elevated $CO_2$ concentration can increase weed biomass, decrease yields, and reduce glyphosate herbicide efficacy for Roundup Ready soybean. Changes in temperature and precipitation can alter fungicide residue dynamics in foliage, and product degradation can be modified (Coakley *et al.*, 1999). Alterations in plant morphology or physiology, resulting from growth in a $CO_2$-enriched atmosphere or from different temperature and precipitation conditions, can affect the penetration, translocation and mode of action of systemic fungicides, as demonstrated by Edis *et al.* (1996) for the herbicide chlorotoluron. Besides, changes in plant growth can alter the period of higher susceptibility to pathogens, which can determine a new fungicide application calendar (Coakley

Table 1 Potential effects of climate change on tropical and plantation crop diseases

| Host | Pathogen | Disease severity | Reasons for effects | Reference |
|---|---|---|---|---|
| Banana | *Mycosphaerella fijiensis* | – | Reduced relative humidity | Ghini *et al.* (2007), Jesus Júnior *et al.* (2008b) |
| | *Fusarium oxysporum* f. sp. *cubense* | + | Increased temperatures and periods of drought | Gasparotto & Pereira (2008) |
| Cashew | *Oidium anacardier*, *Colletotrichum gloeosporioides*, *Colletotrichum acutatum*, *Pilgeriella anacardii* | + | Increased precipitation | J.E. Cardoso and F.M.P. Viana, personal communication |
| Cassava | *Xanthomonas axonopodis* pv. *manihotis* | ± | Depends on the region | H.S.A. Silva and E.C. Andrade, personal communication |
| Citrus | *Xylella fastidiosa*, 'Candidatus *Liberibacter*' spp.), Citrus leprosis virus | + | Increased vector population | Jesus Júnior *et al.* (2008a) |
| | *Guignardia citricarpa*, *Colletotrichum acutatum* | + | Increased temperatures | Jesus Júnior *et al.* (2008a) |
| Coconut palm | *Camarotella torrendiella*, *Camarotella crocomiae*, *Phytomonas* sp., *Bipolaris incurvata*, *Phytophthora* spp. | – | Reduced precipitation and increased temperature | D.R.N. Warwick, V. Talamini, R.R.C. Carvalho and A.M.F. Silva, personal communication |
| Coffee | *Hemileia vastatrix* | + | Increased winter temperatures and $CO_2$ concentration | Chalfoun *et al.* (2001); Pozza & Alves (2008); Mendes (2009) |
| | *Meloidogyne incognita* | + | Increased temperatures | Ghini *et al.* (2008b) |
| Eucalyptus | *Cylindrocladium quinqueseptatum* | + | Increased temperatures and precipitation | Booth *et al.* (2000) |
| | *Puccinia psidii* | – | Increased temperatures | Moraes *et al.* (2008) |
| | *Ralstonia solanacearum, Xanthomonas* sp., *Quambalaria eucalypti* | = | Increased temperatures | Alfenas *et al.* (2004) |
| | *Ceratocystis fimbriata*, *Cylindrocladium* sp., *R. solanacearum*, *Xanthomonas* sp. | + | Increased temperatures and stressed plants | R.G. Mafia, A.C. Alfenas and R.A. Loss, personal communication |
| Papaya | *Asperisporium caricae* | – | Increased temperatures and reduced relative humidity | Jesus Júnior *et al.* (2007) |
| Pineapple | *Fusarium subglutinans* f. sp. *ananas* | – | Increased temperatures | Matos *et al.* (2000) |
| Sugarcane | *Ustilago scitaminea*, SCMV *Potyvirus*, *Xanthomonas albilineans*, *Leifsonia xyli* subsp. *xyli* | = | Spread by the use of infected material for vegetative propagation or infected cutting instrument | Sanguino (2008) |
| | *Ceratocystis paradoxa* | – | Increased temperatures | Chakraborty *et al.* (1998) |

+: increased severity; –: decreased severity; =: no change.

*et al.*, 1999; Chakraborty & Pangga, 2004; Pritchard & Amthor, 2005).

The fungicide market will certainly change. Chen & McCarl (2001) performed a regression analysis between pesticide usage [provided by the United States Department of Agriculture (USDA)] and climate variations in several US locations, with climate data provided by the National Oceanic Atmospheric Administration (NOAA). Average per-acre pesticide usage cost for corn, cotton, potatoes, soybeans and wheat were found to increase as precipitation increased. Similarly, average pesticide usage cost for corn, cotton, soybean and potatoes increased, whilst the pesticide usage cost for wheat decreased with rising temperatures. Despite the increasing fungicides market in tropical areas, no study has been performed to assess these changes.

However, the main impact of climate change on chemical control may be felt via changing attitudes towards the use of chemicals for plant disease control. The fact that humankind is suffering the consequences of anthropogenic activity on this planet to sustain the ever-growing human population and its increasing needs will raise awareness that this activity must be conducted in a sustainable way. Society may increasingly exert pressure to phase out chemicals such as fungicides in favour of non-chemical methods for plant disease control.

One of the direct consequences of climate change on pathogen–host relationships will be altered genetic resistance to diseases. Many changes in plant physiology can alter the resistance mechanisms of cultivars obtained by both traditional and genetic-engineering methods. Several studies provide evidence of these alterations, such as significant increases in photosynthetic rates, papillae production, silicon accumulation in appressorial penetration sites, higher carbohydrate accumulation in leaves, more wax, additional epidermal cell layers, increased fibre content, reduction in nutrient concentration and alteration in the production of resistance-related enzymes (Hibberd *et al.*, 1996; Chakraborty *et al.*, 2000). There are few studies to verify the effects of increased $CO_2$ concentration on disease control using resistant cultivars. According to Braga *et al.* (2006), exposure to $CO_2$-enriched atmospheres changed inducible defence responses in soybean plants against pathogens. These changes occurred in individual metabolites and were dependent on cultivar resistance patterns. On the other hand, there are a larger number of studies regarding the effects of temperature and other climate variables. Huang *et al.* (2006), for example, concluded that temperature and leaf wetness duration affected the phenotypic expression of *Rlm6*-mediated resistance in leaves and subsequent spread of *Leptosphareria maculans* in *Brassica napus* down petioles to produce stem cankers.

There is almost no information on the impact of climate change on biological control of plant disease (Ghini *et al.*, 2008a). Stacey (2003) discussed evidence of the effects of climate change on biological control agents (entomopathogens, predators and parasitoids) of pests. The few results obtained focus on the impact of climate change on the composition and dynamics of the microbial community of the phyllosphere and the soil, which can be very important for plant health (Rezácová *et al.*, 2005; Kanerva *et al.*, 2006; Lagomarsino *et al.*, 2007). Analysing the effects of climate change on commercialized biocontrol agents of plant diseases in Brazil, Bettiol & Ghini (2009) stated that *Bacillus subtilis* and *Trichoderma* spp., the main agents available in the tropics, will be less affected than some others. However, they stated that *Coniothyrium minitans* and *Clonostachys rosea*, depending on region, may have reduced efficacy in controlling diseases.

Key soil aspects for microbial activity will be modified under a changing climate, including soil nutrient availability, soil temperature and soil water content. In addition, the amount of nitrogen introduced into natural and agricultural systems through fertilizers and pollutants can have significant effects on the microbiota (Nosengo, 2003). Grüter *et al.* (2006) concluded that exposing soil to an environment of 600 p.p.m. $CO_2$ did not quantitatively alter the soil's bacterial community. This is not surprising given that the level of soil $CO_2$ fluctuates widely and can easily exceed these levels. The same authors concluded that one of the potential effects of climate change is on plant diversity, which can lead to changes in soil bacterial composition (types of bacteria and frequency of occurrence). Using a FACE experiment to evaluate the effects on saprotrophic fungi, Rezácová *et al.* (2005) observed that *C. rosea*, an important biological control agent of *Botrytis* and other pathogens, and *Metarrhizium anisopliae*, one of the most important entomopathogens for insect pest control, were strongly associated with the cover crop in a high-$CO_2$-concentration environment. The authors suggest the abundance of these fungus species can indicate an increase in the suppressiveness of soil to phytopathogenic fungi and other pests.

Warwick (2001) conducted one of the few detailed studies on the effect of climatic conditions on biological control efficiency, demonstrating the effects of rainfall regime and time of application of *Acremonium persicinum* for control of black leaf spot of coconut, caused by *Camarotella torrendiella* and *C. acrocomiae*. The application of the biocontrol agent gave best results in the rainy season and when performed in the afternoon. Such studies will be important for maintaining the efficiency of biological control both natural and through the introduction of bioagents. The prediction of the effects of climate change on biological control of plant disease is complex and currently based on indirect observations. Nevertheless, the vulnerability of biocontrol agents will surely be higher with climate change, since this is one of the problems with applying antagonists (Garrett *et al.*, 2006).

The adaptability of some agricultural systems can help minimize the negative impact of climate change with the adoption of new cultivars and other practices. Most tropical and plantation crops are perennial, which hinders the adoption of management measures in the short term because of the high cost of replacing the plants. Cultures located in marginal areas will suffer a period of chronic stress, leading to increased predisposition to diseases. Developing countries will have more difficulties adapting to climate change, because of lower technological development and scarce resources available for the adoption of measures. Developing countries need strong cooperation from industrial countries, as well as non-governmental organizations and international scientific societies, to adapt to the impact on food production caused by plant diseases under future climate scenarios.

In general, climate change will favour biological control, both natural and introduced, since awareness towards environmental problems will demand measures that minimize pollutant emissions, reduce the use of chemical pesticides and increase sustainability. Therefore, the biological equilibrium of agricultural systems will be benefited, leading to an increase in the complexity of the system, and consequently, to biological control. To achieve that, specialists from different agriculture-related areas need to go beyond disciplinary boundaries and position the impact of climate change in a broader context, including the whole agroecosystem.

## The way forward

Maintaining the sustainability of agricultural systems directly depends upon plant protection. In a few decades, climate change may alter the current scenario of plant diseases and their management. These changes will certainly have effects on productivity. Therefore, studying the impact on important plant diseases is essential to minimize yield and quality losses, helping in the selection of strategies to work around problems (Chakraborty *et al.*, 2000). For pathosystems discussed above, long-term studies on host physiology, epidemiology, genetics and evolution of host–pathogen populations under changing climate using different experimental strategies (OTC, FACE, controlled conditions) should be considered when planning investigations.

Interdisciplinary approaches, preferably by international programmes, must be adopted to assess the effects of climate change on diseases of tropical and plantation crops. The complexity of the processes involved and their relationships require communication between professionals in the various areas concerned.

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