African Journal of Biotechnology Vol. 11(10), pp. 2417-2428, 2 February, 2012
Available online at http://www.academicjournals.org/AJB
DOI: 10.5897/AJB10.2442
ISSN 1684–5315 © 2012 Academic Journals

Review

The effect of climate change on plant diseases

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Accepted 9 December, 2011

The effects of climate change on plant diseases have been the subject of intense debate in the last decade; research in this sense has been carry out, however, more information is needed. Elevated temperatures and carbon dioxide concentrations associated with climate change will have a substantial impact on plant-disease interactions. Changes in temperature affect both the host and the pathogen; thus, risk analyses must be conducted for each pathosystem to determine the effects of climate change. Studies have been performed under controlled conditions, and the effects of high CO_2 levels have been identified; however, field responses such as the adaptation of pathogens over time may be different. The climate influences the incidence as well as temporal and spatial distribution of plant diseases. The most likely effect of climate change in poleward modifies agroclimates zones, this causing a shift in the geographical distribution of host pathogens. Considering this climate change could profoundly affect the status of agricultural diseases, the focus of this study was to review studies related to the effects of climate change on plant diseases. Taking into account the work done, this review addresses the impact of climate change on plant diseases, considering the effect on crop grown, development and the impact on crop production.

Key words: CO_2, global warming, temperature effect on diseases.

INTRODUCTION

Much of the food we eat comes from crops, which are affected by pests, diseases and extreme weather conditions. Studies have shown that diseases, insects and weeds interfere with 36.5% of crop production around the world. In total, 14.1% of crop losses are attributed to the occurrence of diseases, which represents an annual loss of $220 billion dollars (Agrios, 2005). In addition to monetary losses, crop destruction causes malnutrition and hunger. To reduce the effects of plant diseases, millions of kilograms of pesticides are used to treat seed, soil and harvested fruits every year, which increases production costs and environmental pollution.

Plant diseases are malfunctions caused by plant pathogenic organisms and those caused by other factors (the so called non infectious diseases) are termed disorder (Mehrotra, 2003). The malfunction result in adverse changes in the form, function, or integrity of the plant and may lead to partial impairment or death of plant parts or of the entire plant (Agrios, 2005). Three basic elements are required for the development of an infectious disease: a susceptible host, a virulent pathogen and favorable weather conditions for infection, host colonization and propagule production. If any of the three factors are altered, the progress of any one disease can change. Although interactions among the three factors must be matched, weather is an important variable due to its dynamic behavior.

As described in the report of the Intergovernmental Panel on Climate Change (IPCC, 2007), overwhelming scientific evidence suggests that the planet is experiencing climate change. This is a singular problem of global importance. The greatest effects of climate change may be observed over long periods of time and involve complex interactions between natural (ecological and climatic facts), social, economical and political

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Table 1. Risk analysis studies on the effects of climate change.

Author	Study	Result
Evans et al. (2007)	In the UK, the effects of climate change on Phoma were assessed (*Leptosphaeria maculans*)	epidemics will not only increase in severity but also spread northwards by the 2020s
Salinari et al. (2006)	Future scenarios of downy mildew on grapevine (*Plasmopara viticola*) were simulated from the results of two climate change models. The results suggested that the incidence of disease would increase and the production of grapes in northwestern Italy would decrease.	Predicted an increase of the disease pressure in each decade to consequence of more favorable temperature conditions
Van Standen et al. (2004)	Climate modeling was conducted to predict the habitat distribution of pathogenic fungi *Sphaeropsis sapinea* and *Cryphonectria cubensis* in South Africa and the potential distribution of pathogens under climate change.	A much smaller area of South Africa is predicted to be suitable for the occurrence of *C. cubensis* than for *S. sapinea*, but a range shift westward in suitable habitat for C. cubensis
Chakraborty et al. (2002)	Anthracnose and host models were evaluated under the effects of climate change..	Favorable areas for hosts were identified, and wheat rust was modeled
Kocmánková et al. (2007)	A model to assess the severity of *Phytophthora infestans* under climate change was developed.	A marked shift of the disease in the infestation pressure to higher altitude.

processes (Martínez and Fernandez., 2004). Around the world, rates of land change will increase greatly over the next 20 to 50 years, and human populations continue to grow (Alig et al., 2004; Theobald, 2005). The nature, pattern, and ecological and societal consequences of land change will vary on all spatial scales as a result of spatial variation in human preferences, economic and political pressures, and environmental sensitivities (Carpenter et al., 2007). Extreme weather conditions will affect life on the planet, depending on their intensity and duration in the rain or the temperature, as well as the level of vulnerability of the society or an ecosystem, the impacts of climate can vary from imperceptible to catastrophic, with economic consequences. The atmospheric concentration of CO_2 has risen significantly and has reached its highest level in the last 650,000 years (Siegenthaler et al., 2005). Since 2000, the increase of CO_2 concentration is greater than that of previous decades (Canadell et al., 2007). Similar trends have been observed for the concentration of methane (CH_4), nitrous oxide (N_2O) and other greenhouse gases (Spahni et al., 2005; IPCC, 2007).

Since the last century, scientists have predicted that global temperature would raise due to an increase in the concentration of greenhouse gases in the atmosphere from natural and anthropogenic sources (IPCC, 1990, 1992, 1996, 2007). In the past 150 years, the average surface temperature has increased by 0.76°C (IPCC, 2007) and could increase from 2.4 to 6.4°C in the period of 2090-2099 relative to 1980 to 1999. High atmospheric CO_2 concentrations, temperatures and changes in precipitation patterns as well as the frequency of extreme weather phenomena will significantly affect crop grow and production, and therefore the presence of diseases will be altered under these conditions (Rosenzweig and Tubiello, 2007). Climate change will affect each region differently, and its impacts will be observed gradually.

Understanding the potential effects of changes in agriculture, pests and diseases on plants is an important issue. Several analyses on the effects of climate change on agriculture have been conducted at the regional and global level. In these studies, emphasis has been placed on agricultural production (Rosenzweig et al., 2001; IPCC, 2007; Schlenker and Roberts, 2008; Schlenker and Roberts, 2009). Although, plant diseases play an important role in agriculture (Agrios, 2005), a limited amount of information on the potential impacts of climate change on plant diseases is available (Table 1). The risk of production losses due by diseases is likely to increase due to climate change; however, production losses are rarely considered in climate assessments (Reilly et al., 2001; Anderson et al., 2004). Thus, the objective of this review was to integrate advances in potential responses of plant diseases to climate change and to express the need for research in this area. Taking into account the work done, this review addresses the impact of climate change on plant diseases, considering the effect on crop grown, development and the impact on crop production, for this purpose laboratory and field researches as well modeling studies were reviewed. And, with this information expose the research needs in this area.

EFFECT OF CLIMATE CHANGE ON CROPS

The environment may affect the availability, growth stage, succulence, and genetic susceptibility to diseases of plants (Agrios, 2005). Therefore, agricultural production is extremely susceptible to climate change. According to the IPCC (2007), climate change will reduce yields in the XXI century. However, the effects of climate change will be highly variable and dependent on the region. Climate change will affect temperature, precipitation, CO_2 levels and frequency of extreme weather events, so these will have a significant effect on agricultural production and the temporal and spatial distribution of pests and diseases (Nicholls, 1997; Peng et al., 2004; Rosenzweig and Tubiello, 2007; Ghini et al., 2008).

Yields will increase due to a sharp rise in the concentration of CO_2, and productivity will be limited by other nutrients or climatic events such as drought or floods (Amthor, 2001; Fuhrer, 2003; Long et al., 2005; Gregory et al., 2005; Stern, 2007). According to the IPCC (2007), crop productivity at mid to high latitudes (areas from 35° to 90°) will increase slightly as the average temperature increases by 1 to 3°C, depending on the crop type. Alternatively at lower latitudes, especially seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1-2°C), because increases in the frequency of droughts and floods will affect local crop production negatively, which would increase risk of hunger (IPCC, 2007).

Temperature on crop growth, development and impact on yield

Temperature influences crop growth and development through its impact on enzyme and membrane controlled processes. Carbon acquisition by photosynthesis typically has a temperature optimum close to the normal growth temperature for a given crop, while the carbon loss via respiration increases with temperature (Lambers et al., 1998). Therefore, crop growth will be indirectly controlled by temperature due to the balance between photosynthesis and respiration rates. Temperature also serves as a controlling factor for developmental processes, and the accumulation of low or high temperatures often serves as cues for flowering and fruit maturation stages (Atkinson and Porter, 1996). Because of the importance of temperature an increment could lead to longer growing seasons (this means a major quantity of accumulated heat or degree days in the period, but a minor chill hour), reduction of cycles of crops (so the rate of heat will be faster), efficiency of photosynthesis (negative or positive). Temperature changes also vary both regionally and seasonally. In this sense, Schlenker and Roberts (2009) studied the nonlinear temperature effects in USA under climate change in: corn, soybean and cotton, and find that yields increase with temperature up to 29°C for corn, 30°C for soybeans, and 32°C for cotton but that temperatures above these thresholds are very harmful resulting in an reduction on yields. The relationship between temperatures and crop yields was used to derive the effects of changes in average weather on crop yields. They found important impacts under climate change for corn, soybeans, and cotton imply a 79, 71, and 60% reductions in yields, respectively, under the rapid warming scenario and a 44, 33, and 25% under the slower warming scenario.

CLIMATE CHANGE EFFECTS ON PLANT DISEASES

The climate influences the incidence as well as temporal and spatial distribution of plant diseases. The main factors that control growth and development of diseases are temperature, light and water; similarly these factors affect type and condition of host crop (Rosenzweig et al., 2001; Agrios, 2005). The environment may affect plant pathogen, therefore, survival, vigor, rate of multiplication, sporulation, direction, distance of dispersal of inoculums , rate of spore germination and penetration can be affected (Su, et al., 2004; De Wolf and Isard, 2007; Kang et al., 2010). Plant diseases develop under a well-defined, optimal range of climatic variables (such as temperature, rain, relative humidity, etc); however, the occurrence and severity of a disease in an individual plant is defined by the deviation of each climatic variable within the optimal range for disease development (Figure 1), thus climate affects all life stages of the pathogen and host (Agrios, 2005).

In general, high moisture and temperature must be favorable and act together in the initiation, development of plant diseases, as well as germination and proliferation of fungal spores of the vast majority of pathogens (Agrios, 2005). Moreover, powdery mildew conidia are anomalous in their ability to germinate in low moisture. Some do so even at 0 % relative humidity (RH) (Yarwood, 1978) that is conias of *Erisiphe cichoracearun* germinate from 7 to 32°C with a RH of 60 to 80% (Khan and Khan, 1992); spores of *Erysiphe necator* germinate at temperatures from 6 to 23°C with a RH from 33 to 90 % (Bendek et al., 2007). Due to the large variation in the response of plant pathogens to climate change, the incidence of pathogens must be characterized as a function of the temperature and humidity.

The climate is becoming increasingly extreme and unpredictable (Paul et al., 2009), and climate change is affecting plants in natural and agricultural ecosystems (Stern, 2007). Climate change also disrupts and alters the distribution of pests and diseases, which poses a threat to agriculture (Rosenzweig et al., 2000; Scherm et

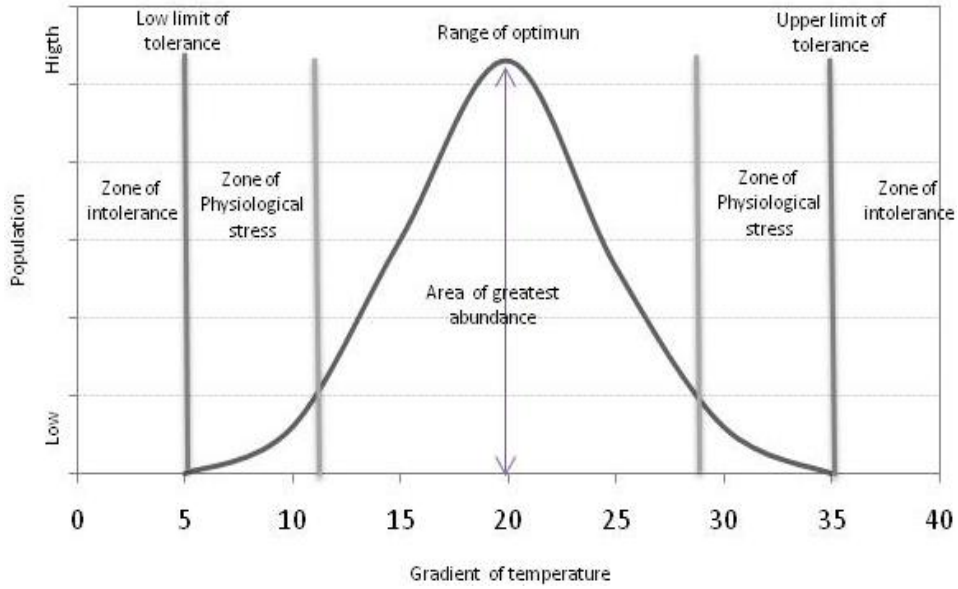

Figure 1. Germination responses shape from conidia of *Erysiphe cichoracearum* as function of temperature. Three areas are identified: area of greatest abundance near of range optimum, survive area or zone of physiological stress, and zone of intolerance where the specie is absent.

al., 2000; IPCC, 2001; Paul et al., 2009).

Changes in rainfall patterns and temperature can induce severe epidemics in plants because some types of pathogens will tend to favour others (Coakley et al., 1999; Chakraborty, 2005; Rosenzweig and Tubiello, 2007). Moreover if these changes cause unfavorable condition for pathogens diseases could be reduced or not present. Severity will depend on the characteristics of each pathogen and its development as a function of environmental factors as well as the magnitude of changes in temperature and wetness in agro-ecological areas. The range of many pathogens is limited by climatic requirements for infection and development. Studies in this order have been carried out and in many cases have been predicted to lead to geographic expansion (Chakraborty et al., 2002; Baker et al., 2000; Boshoff et al., 2002; Olwoch et al., 2003; Anderson et al., 2004; Bergot et al., 2004; Van standen et al., 2004; Salinari et al., 2006; Evans et al., 2007). When the host is present, pathogens with short life cycles, high reproduction rates and effective dispersion mechanisms respond quickly to climate change, resulting in faster adaptation to climatic conditions (Coakley et al., 1999). Nevertheless, little research on the effects of climate change on plant diseases has been conducted in the XXI century (Garrett et al., 2006). Thus, future research should focus on the generation of relevant information to determine how pathogens will respond to climate change. For this purpose it is necessary considering major disease of the main crops.

Harvell et al. (2002) demonstrated that warm winters with high night temperatures facilitate the survival of pathogens, accelerate life cycles of vectors and fungi, and increase sporulation and aerial fungal infection. Moreover, the results of the aforementioned study suggested that the number of pathogens moving northward will increase as increasing temperature makes that previously inclement areas are more conducive.

Climate change will modify host physiology and resistance, and alter the stages and rates of the development of pathogens; examples of these are: soybean studies carried out by Eastburn (2010) found that elevated CO_2 and O_3 induced changes in the soybean canopy density and leaf age; On Arabidopsis Lake and Wade (2009) identified more stomata on resistant varieties and fewer on susceptible varieties and resistant varieties become more susceptible to powdery mildew; Plessl et al. (2007) recognized no effect on potato growth or canopy structure, so increased levels of b-1-3 glucanases; Kobayashi et al. (2006) found that on rice increased number of tillers per plant under elevated CO_2. The most likely effect of climate change in poleward shift of agroclimates zones, this causing a shift in the geographical distribution of host pathogens (Mina and Sinha, 2008). Therefore, new diseases may become prevalent in northern areas, causing considerable losses in agricultural production (Kocmánková et al., 2009). New disease complexes may arise, and some diseases may cease to be economically important. But, pathogens will follow migrating hosts and infect vegetation in natural plant communities not previously exposed to the often more aggressive strains from agricultural crops (Mina and

Sinha, 2008).

Evans et al. (2007) conducted a study in the UK to assess the effects of climate change on Phoma on oilseed rape (*Leptosphaeria maculans*). In the aforementioned study, a model of the prognosis of the disease was used in combination with a climate change model predicting UK temperature and rainfall under CO_2 emission scenarios for the 2020 and 2050s. It was also found that epidemics will not only increase in severity but also spread northwards by 2020s. According to the author, such predictions can be used to guide policy and practice in adapting to the effects of climate change on food security and wildlife. And suggests that these results demonstrate how predicted global warming can increase risk of the range and severity of plant diseases of worldwide importance so conclude that is necessary to develop models to predict the effects of climate change on others plant diseases especially in delicately balanced agricultural or natural ecosystems.

Salinari et al. (2006) used two climate change models to simulate future scenarios of downy mildew on grapevine (*Plasmopara viticola*). In this study a empirical model predicted an increase of the disease pressure in each decade and more severe epidemics were direct consequence of more favorable air temperatures and rainfall reduction conditions during the months of May and June. Authors argue, that simulation analysis suggests that the impact of increased temperatures on enhancing disease pressure exceeded the limiting effect of reduced rainfall, and from a biological point of view, this result can be explained by considering that temperature and wetness act together on the pathogen. Thus the production of grapes in northwestern Italy would decrease. And conclude that as adaptation response to future climate change, more attention would have to be paid in the management of early downy mildew infections.

Van Standen et al. (2004) conducted a climate modeling study to predict habitat distribution in South Africa due to pathogenic fungi *Sphaeropsis sapinea* and *Cryphonectria cubensis,* under conditions of climate change. Results indicated that climate change will alter the distribution of the evaluated pathogens. High-risk areas identified for *Sphaeropsis* dieback coincide with the summer rainfall hail belt. A much smaller area of South Africa is predicted to be more suitable for the occurrence of *C. cubensis* than for *S. sapinea,* but a range shift westward in suitable habitat *for C. cubensis* is predicted under a climate change scenario. The author concludes that these preliminary results, and further refinement of the model, will lay a valuable foundation for future risk assessment and strategic management planning in the South African forestry industry.

Chakraborty et al. (2002) studied anthracnose (*Colletotrichum. gloeosporioides)* and a host (*Stylosanthes scabra*) model under the effects of climate change and demonstrated that favorable areas for the host will be modified. This is partly due to lower annual rainfall in inland areas under this climate scenario and to increasing temperatures. However, their results suggested that the pathogen would likely migrate to areas where the host is established. Moreover, a modeling study on wheat rust under the effects of climate change was published by Chakraborty et al. (2002), who used a dynamic simulation model to evaluate wheat stripe rust epidemics under climate change. Result show that although the response was not consistent among cultivars of wheat, a location effect was very noticeable in that in some areas diseased leaf area decreased for future climates, occasionally there was slightly less disease in 2030, but with higher levels of disease in 2070. Thus incidence of disease decreased in some areas of Australia; this may be explained by the sensitivity of pathogens to heat and atmospheric moisture and how the distribution shift under climate change. Furthermore the yield loss is brought about by the interaction between the change in climate, the phenology of the cultivar and the impact of disease; however, as a result of climate change the potential yield of wheat and the timing of phenology events will change irrespective of the presence of disease.

In the study of Kocmánková et al. (2007) a model was developed allowing the risk assessment of early outbreaks or increases in the intensity of Potato late blight (*Phytophthora infestans*) under the climate change in central Europe. Under all climate change scenarios a marked change was noted in the infestation pressure of evaluated disease and in the higher number of favorable days for Potato late blight outbreak. The results show the shift of the infestation pressure to the beginning of the year and describe an increasing trend of critical number reaching to the detection of the first *P. infestans* occurrence for 2025 and 2050.

Effect of increased CO_2 concentrations on pathogens

The concentration of CO_2 in the atmosphere reached 379 ppm in 2005, which exceeds the natural range of values of the past 650,000 years (IPCC, 2007). An increase in CO_2 levels may encourage the production of plant biomass; however, productivity is regulated by water and nutrients availability, competition against weeds and damage by pests and diseases (Table 2). Alternatively, a high concentration of carbohydrates in the host tissue promotes the development of biotrophic fungi such as rust (Chakraborty et al., 2002). Thus, an increase in biomass can modify the microclimate and affect the risk of infection (Burdon, 1987; Agrios, 2005; Lambers et al., 2008). In general, increased plant density will tend to increase leaf surface wetness duration and regulate temperature, and so make infection by foliar pathogens more likely (Huber and Gillespie, 1992; Dalla Marta et al. 2005; Dalla Pria et al., 2006). However, how abiotic

Table 2. Effect of increased CO_2 concentrations on pathogens.

Author	Study	Effect
Hibberd et al. (1996)	The effect of elevated concentrations of CO_2 on the infection of barley by *Erysiphe graminis* was determined.	The percentage of conidia that progressed to produce colonies was lower in plants grown in 700 than in 350ppm CO_2.
Tiedemann and Firstching (2000).	Interactive effects of elevated CO_2 and O_3 levels on wheat leaves infected with leaf rust fungus *Puccinia triticina* were described.	Elevated CO2 increased the photosynthetic rates of the diseased plants by 20 and 42% at the ambient and elevated ozone concentrations, respectively.
Jwa and Walling (2001).	The effects of elevated CO_2 concentrations on the development of *Phytophthora parasitica* (root rot) in tomato were evaluated.	The extra CO_2 completely counterbalanced the negative effect of the pathogenic infection on overall plant productivity.
Chakraborty et al. (2002).	The germination rates of conidia of *C. gloeosporioides* were determined.	spore germination was reduced and extended incubation period was at 700 ppm, and Anthracnose severity was reduced.
Karnosky et al. (2002).	Elevated CO_2 and tropospheric O_3 concentrations were related to infection by rust (*Melampsora medusae* f. sp tremuloidae) in aspen (*Populus tremuloides* Michx.)	Three- to five-fold increases in levels of rust infection index were found.
Pangga et al. (2004).	The relative importance of canopy size and induced resistance to *Colletotrichum gloeosporioides* was examined at atmospheric CO_2 concentrations of 350 and 700 ppm. Susceptible *Stylosanthes scabra* (Fitzroy) were evaluated in a controlled environment facility (CEF) and the field.	Up to twice as many lesions per plant were produced in the high CO_2 plants, because the enlarged canopy trapped many more pathogen spores.
Kobayashi et al. (2006).	*Pyricularia oryzae* Cavara and *Rhizoctonia solani* Kühn were evaluated.	Rice plants grown in an elevated CO_2 concentration were more susceptible to leaf blast than those in ambient CO_2.
Eastburn et al. (2010).	The effects of carbon dioxide (CO_2) and ozone (O_3) on three soybean diseases (downy mildew, Septoria and sudden death syndrome) were determined in the field.	Changes in atmospheric composition altered disease expression. Elevated CO_2 reduced downy mildew disease severity. But increased brown spot severity and without effect in sudden death syndrome.
Strengbom and Reich (2006).	The incidence of leaf spot on mature leaves of *Solidago rigida* was assessed. The incidence of disease was reduced by half under ECO2 concentrations.	Disease incidence was lower in plots with either elevated [CO_2] or enriched N (-57 and -37%, respectively) than in plots with ambient conditions.
Matros et al. (2006).	The response of tobacco to *potato virus Y* was evaluated.	The titre of viral coat-protein was markedly reduced in leaves under these conditions at both nitrogen levels. The accumulation of phenylpropanoids, may result in an earlier confinement of the virus at high CO2.
Lake and Wade (2009).	Interactions between *Erysiphe cichoracearum* and *Arabidopsis thaliana* under elevated levels of CO_2 were assessed.	The number of established colonies (networks of mycelia) on mature leaves increased significantly
Runion et al. (2010).	The effects of elevated atmospheric CO_2 concentrations on two southern forest diseases (*Cronartium quercuum* and Fusarium *circinatum*) were assessed.	In general, disease incidence was decreased by exposure to elevated CO2, and increased the latent period (time to sporulation) for fusiform rust on red oak seedlings.

Table 2 Contd

Shin and Yun (2010)	The effects of elevated levels of CO_2 and temperature on the Incidence of four major chili pepper diseases (Anthracnose (*Colletotrichum acutatum*), Phytophthora blight (*Phytophthora capsici*)) and two bacterial diseases (bacterial wilt (*Ralstonia solanacearum*) and bacterial spot (*Xanthomonas campestris* pv. *vesicatoria*)) were determined.	Elevated CO2 and temperature significantly increased the incidence of two bacterial diseases. Anthracnose decreased and Phytophthora blight slightly increased.
McElrone et al. (2010)	Effect of elevated CO2 and interannual climatic variability affect *Cercospora* leaf spot diseases of two deciduous trees	When significant changes did occur, disease incidence and severity always increased under elevated CO_2.

stress factors interact to affect plants will be a key to understanding climate change effects on plants (Mittler, 2006; Niinemets and Valladares, 2008); By the contrast low concentration of carbohydrates, in the host tissue also promotes development of diseases, this because the susceptibly of plants increase by stress (caused by climate or fertilization).

Experimental research on the effects of high atmospheric CO_2 concentrations on plant–pathogen interactions has received little attention, and conflicting results have been published. Elevated levels of CO_2 can directly affect the growth of pathogens. For example, according to Chakraborty et al. (2002), the growth of the germ tube, appressorium and conidium of *C. gloeosporioides* fungi is slower at high concentrations of CO_2 (700 ppm). Germination rates of conidia on leaves were lower at CO_2 concentrations of 700 ppm than those observed at 350 ppm. However, once the pathogen infects the plant, the fungus quickly develops and achieves sporulation. In contrast, the rate of germination sporulation was greater at high concentrations of CO_2 (700 ppm). In another study Hibberd et al. (1996) evaluated powdery mildew in barley, and found that an acclimation of photosynthesis at elevated CO_2 and an infection-induced reduction in net photosynthesis caused larger reductions in plant growth at elevated CO_2; also, the percentage of conidia that progressed to produce colonies was lower in plants grown in high CO_2 (700 ppm) than in low CO_2 (350 ppm) and lower percentage of conidia producing hyphae in 700 ppm CO_2, it was due to a higher proportion of the spores being arrested at the appressorial stage. Elevated ozone can have a similar effects (Plazek et al., 2001; Plessl et al., 2005) such as a 3 to 5-fold increase in rust infection on poplar, however this response is reduced by elevated CO_2 (Karnosky et al., 2002). Tiedemann and Firsching (2000) analyzed the direct effects of elevated ozone and carbon dioxide on spring wheat infected with *Puccinia recondita* f. sp. *tritici.* Crop yield and growth were measured for plants exposed to two levels each of carbon dioxide and ozone and either inoculated with rust or left uninoculated. Results showed that ozone damage to leaves is largely dependent on both carbon dioxide concentrations as well as disease. Additionally, elevated carbon dioxide levels appeared to reduce and delay leaf damage caused by ozone (Tiedemann and Firsching, 2000).

As suggested by Chakraborty (2005) a lack of knowledge for model host-pathogen interactions that must be met through a baseline of empirical studies. Models can then be used to extrapolate, predict and validate potential impacts. Some authors suggest that elevated CO_2 concentrations and climate change may accelerate plant pathogen evolution, which can affect virulence. Researches in this direction have been carried out. In this regard, Mulherin et al. (2000), evaluated the response of tobacco (Xanthi-nc NN) grown under elevated CO_2 to inoculation with tobacco mosaic virus (TMV) in two concentration of CO_2 (360 and 720 ppm); they found that plants grown at 720 ppm CO_2 produced fewer TMV lesions per leaf versus plants grown at 360 ppm CO_2. However, the mean lesion area at 720 ppm CO_2 was larger versus plants grown at 360 ppm CO_2. Acording to the authors this indicates that elevated CO_2 alters endogenous foliar salicylic acid levels and affects plant response to TMV inoculation, and conclude that elevated CO_2 will affect plant-pathogen interactions. Moreover, Mcelrone et al. (2005) assessed how elevated CO_2 affects a foliar fungal pathogen, *Phyllosticta minima*, of *Acer rubrum* growing in the understory at the Duke Forest free-air CO_2 enrichment experiment in Durham, North Carolina. *A. rubrum* saplings in the 6th, 7th, and 8th years of the CO_2 exposure revealed that elevated CO_2 significantly reduced disease incidence, with 22, 27, and 8% fewer saplings and 14, 4, and 5% fewer leaves infected per plant in the three consecutive years, respectively. Mcelrone et al. (2005) concludes that the potential dual mechanism of reduced stomata opening and altered leaf chemistry that results in reduced disease incidence and severity under elevated CO_2 may be prevalent in many plant pathosystems where the pathogen targets the stomata.

According to Lake and Wade (2009) elevated carbon dioxide concentrations and climate change may accelerate plant pathogen evolution, which can affect virulence. Authors suggest that plant–pathogen interactions under increasing CO_2 concentrations have the potential to disrupt both agricultural and natural systems severely, yet the lack of experimental data and the subsequent ability to predict future outcomes constitutes a fundamental knowledge gap. Furthermore, nothing is known about the mechanistic bases of increasing pathogen aggressiveness. Lake and Wade (2009) studied the case *Erysiphe cichoracearum* in the interaction of Arabidopsis thaliana *L. Stomatal* and found that density, guard cell length, and trichome numbers on leaves developing post-infection are increased under elevated CO_2 in direct contrast to non-infected responses. Considering this conclude that many plant pathogens utilize epidermal features for successful infection, these responses provide a positive feedback mechanism facilitating an enhanced susceptibility of newly developed leaves to further pathogen attack.

Eastburn et al. (2010) evaluated the effects of elevated CO_2 and O_3 on three soybean diseases: downy mildew (*Peronospora manshurica*), Septoria (*Septoria glycines*) and sudden death syndrome (*Fusarium virguliforme*). Their results suggested that changes in the composition of the atmosphere altered the expression of the disease, and plant responses to the diseases varied considerably. For instance, the severity of downy mildew damage was significantly reduced at high levels of CO_2. In contrast, high levels of CO_2, alone or in combination with high concentrations of O_3, increased the severity of *Septoria glycines*. Alternatively the concentration of CO_2 and O_3 did not have an effect on sudden death syndrome. The authors concluded that high levels of CO_2 and O_3 induced changes in the soybean canopy density and leaf age, likely contributed to disease expression modification. Thus, the increase in both CO_2 and O_3 will alter disease expression for import fungal pathogens of soybean.

Kobayashi et al. (2006) evaluated the effects of elevated CO_2 concentrations on the interactions between rice, *Pyricularia oryzae* Cavara and *Rhizoctonia solani* Kühn, and found that rice plants were more susceptible to injury. Thus, the authors concluded that rice cultivated at sites with high concentrations of CO_2 may have an increased risk of infection by the aforementioned pathogens. The production of photosynthates by the host increases at high concentrations of CO_2, and if the infection is present, provides the pathogen a better substrate for growth and increases spore production (Runion, 2003). But, other elements affect pathosystems, so this statement could not be generalized. Therefore evaluations are necessary to increase the knowledge in this area.

The effects of an increase in temperature and ultraviolet radiation on pathogens

Due to changes in temperature and precipitation regimes, climate change may alter the growth stage, development rate and pathogenicity of infectious agents, and the physiology and resistance of the host plant (Charkraborty et al., 1998; Charkraborty and Datta, 2003). A change in temperature could directly affect the spread of infectious disease and survival between seasons. Ultraviolet radiation plays an important role in natural regulation of diseases. Evidence suggests that sunlight affects pathogens due to the accumulation of phytoalexins or protective pigments in host tissue. A change in temperature may favor the development of different inactive pathogens, which could induce an epidemic. Increase in temperatures with sufficient soil moisture may increase evapotranspiration resulting in humid microclimate in crop and may lead to incidence of diseases favored under these conditions (Mina and Sinha, 2008).

Temperature is one of the most important factors affecting the occurrence of bacterial diseases such as *Ralstonia solanacearum, Acidovorax avenae* and *Burkholderia glumea*. Thus, bacteria could proliferate in areas where temperature-dependent diseases have not been previously observed (Kudela, 2009). As the temperature increases, the duration of winter and the rate of growth and reproduction of pathogens may be modified (Ladányi and Horváth, 2010). Similarly, the incidence of vector-borne diseases will be altered. Climate can substantially influence the development and distribution of vectors. Changes may result in geographical distribution, increased overwintering, changes in population growth rates, increases in the number of generations, extension of the development season, changes in crop-pest synchrony of phenology, changes in interspecific interactions and increased risk of invasion by migrant pests (Porter et al., 1991; Kamata et al., 2002; Newman et al., 2003; Newman, 2004; Fabre et al., 2005; Mondor et al., 2005; Memmott et al., 2007; Parmesan, 2007). Because of the short life cycles of insects, mobility, reproductive potential, and physiological sensitivity to temperature, even modest climate change will have rapid impacts on the distribution and abundance of vectors. Thus, increase in temperature may be result in high rate of development of insect, obtaining a greater number of insect generations per cycle. Furthermore increase in temperature could determine the distribution of areas favorable for overwintering (Garrett et al., 2006), or even more lethal zones where the insect cannot survive.

Temperature in nematodes is important. So thermal constant is the amount of heat or total effective temperature that each specie requires to complete its life cycle. Considering this, studies has been carried out using thermal constant with the aimed to assess the potential impact of climate change on the spatial distribution of coffee nematodes. In these sense, Ghini et al. (2008) study the spatial distribution under effect of climate change. The species included were coffee nematodes (races of *Meloidogyne incognita*) and leaf miner (*Leucoptera coffeella*), they estimated the number of generations for the climatological normal from 1961 to 1990 and future climates (2020, 2050, and 2080) in scenarios A2 and B2. And conclude that the infestation of *Meloidogyne incognita* races 1, 2 and 4, and *Leucoptera coffeella* on coffee under the future scenarios will increase when compared with the climatological normal from 1961–1990. The number of generations of nematodes and coffee leaf miner will increase in both scenarios (A2 and B2), but for B2, it will be lower than in the A2 scenario.

RESEARCH NEEDS

Research on the effects of climate change on plants and Research on the effects of climate change on plants and pathogens have been conducted; however, more research is still needed in the following areas:

(i) The effect of climate change on crop production and disease. Given the variable responses of pathosystems to altered atmospheric composition studied to date (Manning and Tiedemann, 1995; Chakraborty et al., 2000, 2008; Garrett et al., 2006; Kobayashi et al., 2006), more work is needed to quantify changes in host–pathogen interactions particularly for important crop species under natural conditions.
(ii) The effectiveness of disease management strategies. Assessing current management strategies and proposing alternatives for the next decades will prepare us for the challenge of climate change. This will allow our mitigation measures to be more efficient and adaptable to change.
(iii) The risk of disease must be analyzed to determine the geographical distribution and modification of diseases due to climate change.
(iv) Plant diseases and crops must be modeled. Mathematical models can be used to perform quantitative analysis of the phytosanitary problems. They provide a very powerful tool to understand and represent interactions among weather, crop and disease variables (Allman and Rhodes, 2004). Mathematical models can help to assess the probability of introduction, reproduction and dispersion of diseases, and the magnitude of their effects on crops yield and quality in current scenarios and under climate change.
(v) Factors limiting the survival of pathogens should be characterized (e.g., temperature, humidity, CO2, O3 and radiation).

The present review indicates that a considerable amount of research has been carried out; however, more detailed work is required. Each region or country has different needs, and different strategies must be developed to facilitate progress.

CONCLUSION

In this review, an overview on the current research on climate change is presented. Climate change is an important phenomenon that affects agricultural production. By anticipating the future, we can prepare ourselves for problems caused by climate change, especially those related to agricultural activities, which generate the greatest amount of food consumed by humans. For several centuries, pests and plant diseases have played an important role in agricultural production. Because global warming may modify areas affected by pests and diseases, studies must be performed to assess pest and disease stages under the effects of climate change, determine the magnitude of disease and identify measures to minimize the risk of infection.

Exposure to altered atmospheric conditions can modify fungal disease expression. Studies had shown that exposure at elevated CO_2 increases disease incidence or severity in some cases (Shin and Yun, 2010; McElrone, 2010; Eastburn et al., 2010; Kobayashi et al., 2006; Mitchell et al., 2003; Thompson and Drake, 1994) but in other cases decreased (Hibberd et al., 1996; Mulherin et al., 2000; Jwa and Walling, 2001; Chakraborty et al., 2002; Pangga et al., 2004; McElrone et al., 2005; Eastburn et al., 2010;). These highlight how the host–pathogen interactions make it difficult to devise general principles that govern changes across fungal pathosystems. So increase or decrease disease will be in function of the host and pathogen. Hence the importance of conducting studies on main crops and major disease for each region.

Temperature is one of the main factors in conjunction with the rain to determine the incidence and severity of disease, but the effect could be positive and negative. This requires us to anticipate what might happen in the future. Considering this, climate change may affect the actual, spatial and temporal distribution of diseases; however, the magnitude of these effects remains unclear. Because the security of food could be at risk due to a change in the incidence of diseases, more research must be conducted. Disease risk analyses based on host-pathogen interactions should be performed, and research on host response and adaptation should be conducted to understand how an imminent change in the climate could affect plant diseases.

ACKNOWLEDGEMENT

This research was partially supported by the Mexican National Council of Science (CONACYT).

REFERENCES

Agrios GN (2005). Plant Pathology. 5th Ed. Elsevier, USA. p. 922

Allman ES, Rhodes JA (2004). Mathematical models in biology an introduction. Cambridge University Press. p. 193

Alig RJ, Kline JD, Lichtenstein M (2004). Urbanization on the US landscape: looking ahead in the 21st century. Landscape Urban Plan. 69: 219-34.

Amthor JS (2001). Effects of atmospheric CO2 concentration on wheat yield: review of results from experiments using various approaches to control CO_2 concentration. Field Crops Res. 73: 1-34.

Anderson PK, Cunningham AA, Patel NG, Morales FJ, Epstein PR, Daszak P (2004). Emerging infectious diseases of plants: pathogen pollution, climate change andagrotechnology drivers. Trends Ecol. Evol. 19: 535-544.

Atkinson D, Porter JR (1996). Temperature, plant development and crop yields. Trends Plant Sci. 1: 119-124.

Baker RHA, Sansford CE, Jarvis CH, Cannon RJC, MacLeod A, Walters KFA (2000). The role of climatic mapping in predicting the potential geographical distribution of non-indigenous pests under current and future climates. Agric. Ecosyst. Environ. 82: 57-71

Bendek CE, Campbell PA,Torres R, Donoso A, Latorre BA (2007). The risk assessment index in grape powdery mildew control decisions and the effect of temperature and humidity on conidial germination of *Erysiphe necator.* Spanish J. Agr. Res. 5(4): 522-532

Bergot M, Cloppet E, P´erarnaud V,D´equ´eM, Marcais B, Desprez-Loustau ML (2004). Simulation of potential range expansion of oak disease caused by *Phytophthora cinnamomi* under climate change. Glob. Change Biol. 10: 1539-52

Boshoff WHP, Pretorius ZA, van Niekerk BD (2002). Establishment, distribution, and pathogenicity of *Puccinia striiformis* f. sp. *tritici* in South Africa. Plant Dis. 86: 485-92

Burdon JJ (1987). Diseases and Population Biology. New York: Cambridge Univ. Press.

Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis ET, Ciais P, Conway TJ, Gillett NP, Houghton RA, Marland G (2007). Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proc. Natl. Acad. Sci. U. S. A. 104: 1866-18870.

Carpenter SR, Benson BJ, Biggs R, Chipman JW, Foley JA, Golding SA, Hammer RB, Hanson PC, Johnson PTJ, Kamarainen AM, Kratz TK, Lathrop RC, McMahon KD, Provencher B, Rusak JA, Solomon CT, Stanley EH, Turner MG, Zanden MJV, Wu C, Yuan H (2007). Understanding regional change: a comparison of two lake districts. BioScience, 57: 323-35.

Chakraborty S (2005). Potential impact of climate change on plant–pathogen interactions. Australas. Plant. Pathol. 34: 443-448.

Chakraborty S, Datta S (2003). How will plant pathogens adapt to host plant resistance at elevated CO_2 under a changing climate? New Phytologist, 159: 733-42.

Chakraborty S, Luck J, Hollaway G, Freeman A, Norton R, Garrett KA, Percy K, Hopkins A, Davis C and Karnosky DF (2008). Impacts of global change on diseases of agricultural crops and forest trees. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutri. Nat. Res. 3: 1-15.

Chakraborty S, Murray G, White N (2002). Impact of Climate Change on Important Plant Diseases in Australia. A report for the Rural Industries Research and Development Corporation. RIRDC Publication No W02/010. RIRDC Project No CST-4A.

Chakraborty S, Murray GM, Magararey PA (1998). Potential impact of climate change on plant diseases of economic significance to Australia. Australas. Plant. Pathol. 27: 15-35.

Chakraborty S, Tiedemann AV, Teng PS (2000). Climate change: potential impact on plant diseases. Environ. Pollut. 108: 317-326.

Coakley SM, Scherm H, Chakraborty S (1999). Climate Change and Plant Disease. Annu. Rev. Phytopathol. 37: 399-426.

Dalla Marta A, Magarey RD, Orlandini S (2005). Modelling leaf wetness duration and downy mildew simulation on grapevine in Italy. Agr. Forest. Meteorol. 132: 84-95.

Dalla Pria M, Christiano RCS, Furtado EL, Amorim L, Bergamin Filho A (2006). Effect of temperature and leaf wetness duration on infection of sweet oranges by Asiatic citrus canker. Plant Pathol. 55: 657-663.

De Wolf ED, Isard SA (2007). Disease cycle approach to plant disease prediction. Annu. Rev. Phytopathol. 45: 203-220.

Eastburn DM, Degennaro MM, Delucia EH, Dermody O, Mcelrone AJ (2010). Elevated atmospheric carbon dioxide and ozone alter soybean diseases at SoyFACE. Global Change Biol. 16: 320-330.

Evans N, Baierl A, Semenov AM, Gladders P, Fitt BDL (2007). Range and severity of a plant disease increased by global warming. J. R. Soc. Interface. 5: 525-531.

Fabre F, Plantegenest M, Mieuzet L, Dedryver CA, Leterrier JL, Jacquot E (2005). Effects of climate and land use on the occurrence of viruliferous aphids and the epidemiology of barley yellow dwarf disease. Agric. Ecosyst. Environ. 106: 49-55.

Fuhrer J (2003) Agroecosystem responses to combinations of elevated CO_2, ozone and global climate change. Agric. syst. Environ. 97: 1-20.

Garrett, KA, Dendy SP, Frank EE, Rouse MN, Travers SE (2006). Climate change effects on plant disease: genomes to ecosystems. Annu. Rev. Phytopathol. 44: 489-509.

Ghini R, Hamada E, Bettiol W (2008). Climate change and plant disease. Sci. Agric. (Piracicaba, Braz.), 65: 98-107.

Ghini R, Hamada E, Pedro Junior MJ, Marengo JA, Gonçalves RR (2008). Risk analysis of climate change on coffee nematodes and leaf miner in Brazil. Pesquisa Agropecuária Brasileira. (43): 187-194

Gregory PJ, Ingram JSI, Brkalcich M (2005). Climate change and food security. Phil. Trans. R. Soc. B. 360: 2139-2148.

Harvell HC, Mitchell CE, Ward JR, Altizer S, Dobson AP, Ostfeld RS, Samuel MD (2002). Climate warming and disease risks for terrestrial and marine biota. Science, 296: 2158-2162.

Hibberd JM, Whitbread R, Farrar JF (1996). Effect of elevated concentrations of CO_2 on infection of barley by *Erysiphe graminis*. Physiol. Mol. Plant Pathol. 48: 37-53.

Huber L, Gillespie TJ (1992). Modeling leaf wetness in relation to plant disease epidemiology. Annu. Rev. Phytopathol. 30: 553-77

IPCC (1990). Climate change: the IPCC scientific assessment. Houghton J. T., Jenkins G. J., Ephraums JJ (Eds). Intergovernmental Panel on Climate Change. Cambridge University, UK.

IPCC (1992). Climate change 1992: the supplementary report to the IPCC scientific assessment. Houghton JT, Callender BA, Varney S.K. (Eds.). Intergovernmental Panel on Climate Change. Cambridge University, UK.

IPCC (1996). Climate change 1995: the science of climate change. Houghton JT, Meira Filho LB, Callender BA, Harris N, Kattenberg A, Maskell K (Eds). Intergovernmental Panel on Climate Change. Cambridge University, UK.

IPCC (2001). IPCC Third Assessment Report: Climate Change 2001. Cambridge University Press, Cambridge.

IPCC. (2007). Climate change 2007: Synthesis Report. Contribution of Working Group I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Pachauri RK, Reisinger A, (Eds) IPCC, Geneva, Switzerland.

Jwa NS, Walling LL (2001). Influence of elevated CO_2 concentration on disease development in tomato. New Phytologist, 149: 509-518.

Kamata N, Esaki K, Kato K, Igeta Y, Wada K (2002). Potential impact of global warming on deciduous oak dieback caused by ambrosia fungus *Raffaelea sp*. carried by ambrosia beetle *Platypus quercivorus* (Coleoptera: Platypodidae) in Japan. Bull. Entomol. Res. 92: 119-26

Kang WS, Yun SC, Park EW (2010). Nonlinear regression analysis to determine infection models of *colletotrichum acutatum* causing anthracnose of chili pepper using logistic equation. Plant Pathol. J. 26(1): 17-24.

Karnosky DF, Percy KE, Xiang BX (2002). Interacting elevated CO_2 and tropospheric O_3 predisposes aspen (*Populus tremuloides* Michx.) to infection by rust (*Melampsora medusae* f. sp *tremuloidae*). Global Change Biol. 8: 329-338.

Khan AU, Khan AM, (1992). Incidence and severity of cucurbit powdery mildew in Uttar Pradesh. Indian Phytopathology, 45(2): 190-193.

Kobayashi T, Ishiguro K, Nakajima T, Kim HY, Okada M, Kobayashi K (2006). Effects of elevated atmospheric CO_2 concentration on the infection of rice blast and sheath blight. Phytopathology, 96: 425-431.

Kocmánková E, Trnka M, Juroch J, Dubrovsky M, Semerádová D, Možný M, Žalud Z (2009). Impact of Climate Change on the Occurrence and Activity of Harmful Organisms. Plant Protect. Sci. 45: S48-S52.

Kocmánková E, Žalud Z, Trnka M, Semerádová D, Dubrovský M, Možný M, Juroch J (2007). The climate niches of colorado potato beetle and potato late blight in central Europe in 2050. In: MendelNet'07 Agro (Proceedings of International Ph.D. Students Conference). Mendel university of agriculture and forestry brno.

Kudela V (2009). Potential Impact of Climate Change on Geographic Distribution of Plant Pathogenic Bacteria in Central Europe. Plant Protect. Sci. 45: S27-S32.

Ladányi M, Horváth L (2010). A review of the potential climate change impact on insect populations – general and agricultural aspects. Appl. Ecol. Environ. Res. 8(2): 143-152.

Lake JA, Wade RN (2009). Plant–pathogen interactions and elevated CO_2: morphological changes in favour of pathogens. J. Exp. Bot. 60(11): 3123-3131

Lambers H, Chapin FS, Pons TL (2008). Plant physiological Ecology. Second edition. Springer Science Business media LLC.

Lambers H, Chapin FS, Pons TL (1998). Plant Physiological Ecology. Springer, New York.

Long SP, Ainsworth EA, Leakey ADB, Morgan PB (2005). Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggest recent models may have overestimated future yields. Phil. Trans. R. Soc. B. 360: 2011-2020.

Manning WJ, Tiedemann AV (1995). Climate change: potential effects of increased atmospheric Carbon Dioxide (CO_2), Ozone (O_3), and Ultraviolet-B (UVB) radiation on plant diseases. Environ. Pollut. 88: 219-245.

Martínez J, Fernandez BA (2004). Climate change. A view from Mexico. National Institute of Ecology. Secretary of Environment and Natural Resources. México D.F.

Matros A, Amme S, Kettig B, Buck-Sorlin GH, Sonnewald U, Mock HP (2006). Growth at elevated CO_2 concentrations leads to modified profiles of secondary metabolites in tobacco cv. SamsunNN and to increased resistance against infection with potato virus Y. Plant Cell Environ. 29: 126-137.

Mcelrone AJ, Hamilton JG, Krafnick AJ, Aldea M, Knepp RG, De Lucia EH (2010). Combined effects of elevated CO_2 and natural climatic variation on leaf spot diseases of redbud and sweetgum trees. Environ. Pollut. 158: 108-114.

Mcelrone AJ, Reid CD, Hoye KA, Hart E, Jackson RB (2005). Elevated CO_2 reduces disease incidence and severity of a red maple fungal pathogen via changes in host physiology and leaf chemistry. Glob. Change Biol. 11: 1828-1836

Mehrotra RS, Aggarwal A (2003). Plant Pathology. Tata McGraw-Hill Publishing Company. New Delhi. Second Edition.

Melching JS, Dowler, WM, Koogle DL, Royer MH (1989). Effects of duration, frequency, and temperature of leaf wetness periods on soybean rust. Plant Dis. 73: 117-112.

Memmott J, Craze PG, Waser NM, Price MV (2007). Global warming and the disruption of plant–pollinator interactions. Eco Let. 10: 710-717.

Mina U, Sinha P (2008). Effects of Climate Change on Plant Pathogens. Environ. News. 14(4): 6-10.

Mitchell CE, Reich PB, Tilman D, Groth JV (2003). Effects of elevated CO_2, nitrogen deposition, and decreased species diversity on foliar fungal plant disease. Glob. Change Biol. 9(3):438–451.

Mittler R (2006). Abiotic stress, the field environment and stress combination. Trends Plant Sci. 11:15–19.

Mondor EB, Tremblay MN, Awmack CS, Lindroth RL (2005). Altered genotypic and phenotypic frequencies of aphid populations under enriched CO_2 and O_3 atmospheres. Glob. Change Biol. 11: 1990-96.

Mulherin KM, Karowe DN, Enyedi AJ (2000). Effects of elevated carbon dioxide on plant-pathogen interactions. In plant Biology 2000. Plant Biology Meeting. Symposium Elevated CO_2. Abstract number 368. San Diego, Ca. USA.

Newman J (2004). Climate change and cereal aphids: the relative effects of increasing CO_2 and temperature on aphid population dynamics. Glob. Change Biol. 10: 5-15

Newman JA, Gibson DJ, Parsons AJ, Thornley JHM (2003). How predictable are aphid population responses to elevated CO_2? J. Anim. Ecol. 72: 556-66

Nicholls N (1997). Increased Australian wheat yields due to recent climate trends. Nature. 387: 484-485.

Niinemets Ü, Valladares F (2008). Environmental Tolerance. Encyclopedia of Ecology, 2008 , pp.1370-1376

Olwoch JM, de Rautenbach CJD, Erasmus BFN, Engelbrecht FA, van Jaarsveld AS (2003). Simulating tick distributions over sub-Saharan Africa: the use of observed and simulated climate surfaces. J. Biogeogr. 30: 1221–32

Pangga IB, Chakraborty S, Yates D (2004). Canopy size and induced resistance in *Stylosanthes scabra* determine Anthracnose severity at high CO_2. Phytopathology, 94: 221-227.

Parmesan C (2007). Influences of species, latitudes and methodologies on estimates of phenological response to global warming. Glob. Chang. Biol. 13: 1860-1872.

Paul H, Ernsting A, Semino S, Gura S, Lorch A (2009). Agriculture and climate change: real problems, false solutions. Oxford, UK: EcoNexus.

Peng SB, Huang JL, Sheehy JE, Laza RC, Visperas RM, Zhong XH, Centeno GS, Khush GS, Cassman KG (2004). Rice Yields Decline with Higher Night Temperature from Global Warming. Proc. Natl. Acad. Sci. U. S. A. 101: 9971-9975.

Plazek A, Hura K, Rapacz H, Zur I (2001). The influence of ozone fumigation on metabolic efficiency and plant resistance to fungal pathogens. J. Appl. Bot. 75: 8-1.

Plessl M, Heller W, Payer HD, Elstner EF, Habermeyer J, Heiser I (2005). Growth parameters and resistance against *Drechslera teres* of spring barley (*Hordeum vulgare* L. cv. Scarlett) grown at elevated ozone and carbon dioxide concentrations. Plant Biol.

Plessl M, Elstner EF, Rennenberg H, Habermeyer J, Heiser I (2007). Influence of elevated CO_2 and ozone concentrations on late blight resistance and growth of potato plants. Environ. Exp. Bot. 60: 447-57.

Porter JH, Parry ML, Carter TR (1991) The potential effects of climatic change on agricultural insect pests. Agr. Forest. Meteorol. 57(1-3): 221-240.

Reilly J (2001). Agriculture: The potential consequences of climate variability and change for the United States US National Assessment of the Potential Consequences of Climate Variability and Change. Press Syndicate of the University of Cambridge. p. 136.

Rosenzweig C, Iglesias A, Yang XB, Chivian E, Epstein P (2001). Climate Change and Extreme Weather Events: Implications for Food Production, Plant Diseases, and Pests. Global Change Hum. Health. 2: 90-104

Rosenzweig C, Iglesias A, Yang YB, Epstein PR, Chivian E (2000). Climate Change and U.S. Agriculture: The Impacts of Warming and Extreme Weather Events on Productivity, Plant Diseases and Pest. Boston, MA, USA: Center For Health and the Global Environment, Harvard Medical School. Cambridge, MA. p. 46.

Rosenzweig C, Tubiello FN (2007). Adaptation and mitigation strategies in agriculture: an analysis of potential synergies. Mitig. Adapt. Strat. Glob. Change. 12: 855-873

Runion GB (2003). Climate Change and Plant Pathosystems: Future Disease Prevention Starts Here. New Phytologist, 159(3): 531-533.

Runion GB, Prior SA, Rogers HH, Mitchell RJ (2010). Effects of elevated atmospheric CO_2 on two southern forest diseases. New Forests, 39: 275-285.

Salinari F, Giosue S, Tubiello FN, Rettori A, Rossi V, Spanna F, Rosenzweig C, Gullino ML (2006). Downy mildew (*Plasmopara viticola*) epidemics on grapevine under climate change. Glob. Change Biol. 12: 1299-1307.

Scherm H, Sutherst RW, Harrington R, Ingram JSI (2000). Global networking for assessment of impacts of global change on plant pests. Environ. Pollut. 108: 333-341.

Schlenker W, Roberts M (2008). Estimating the Impact of Climate Change on Crop Yields: The Importance of Nonlinear Temperature Effects. National Bureau of Economic Research. Working Paper Series No. 13799.
Schlenker W, Roberts MJ (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. PNAS, 37(106): 15594-15598.
Shin JW, Yun SC (2010). CO_2 and Temperature Effects on the Incidence of Four Major Chili Pepper Diseases. Plant Pathol. J. 26(2): 178-184.
Siegenthaler U, Stocker TF, Monnin E, Luthi D, Schwander J, Stauffer B, Raynaud D, Barnola JM, Fischer H, Masson-Delmotte V, Jouzel J (2005). Stable carbon cycle-climate relationship during the late pleistocene. Science , 310: 1313-1317.
Spahni R, Chappellaz J, Stocker TJ, Loulergue L, Hausammann G, Kawamura K, Fluckiger J, Schwander J, Raynaud D, Masson-Delmotte V, Jouzel J (2005). Atmospheric methane and nitrous oxide of the late pleistocene from Antarctic ice cores. Science, 310: 1317-1321.
Stern N (2007). The economics of climate change: the Stern review. Cambridge, UK: Cambridge University Press. p. 712.
Strengbom J, Reich PB (2006). Elevated [CO_2] and increased N supply reduce leaf disease and related photosynthetic impacts on Solidago rigida. Oecologia, 149: 519-525.
Su H, van Bruggen AHC, Subbarao KV, Scherm H (2004) Sporulation of *Bremia lactucae* Affected by temperature, relative humidity, and wind in controlled conditions. Phytopathology, 94: 396-401.
Theobald DM (2005). Landscape patterns of exurban growth in the USA from 1980 to 2020. Ecol. Soc. 10: 32.
Thompson GB, Drake BG (1994). Insects and fungi on a C_3 sedge and a C_4 grass exposed to elevated atmospheric CO_2 concentrations in open-top chambers in the field. Plant Cell Environ. 17: 1161-1167.
Tiedemann AV, Firsching KH (2000). Interactive effects of elevated ozone and carbon dioxide on growth and yield of leaf rust-infected versus non-infected wheat. Environ. Pollut. 108: 357-363.
Van Standen V, Barend FN, Roux J, Winfield MJ, Van Jaarveld AS (2004). Modelling the spatial distribution of two important South African plantation forestry pathogens. Forest Ecol. Manag. 187: 61-73.
Yarwood CE (1978). History and taxonomy of powdery mildews. In; The Powdery Mildews (Ed. by Spencer DM), Academic Press. London.