



Research approaches, adaptation strategies, and knowledge gaps concerning the impacts of climate change on plant diseases

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ABSTRACT

This review discusses the present trends in studies on the impacts of climate change on plant diseases. Firstly, the approaches used for studying the potential effects of altered temperature, water availability, CO₂ and O₃ air concentrations, and UV-B radiation on components of the disease cycle are explained and discussed. Next, the impact of changes in climate patterns on the geographic and temporal distribution of diseases by integrating biological and epidemiological models into geographic and climate databases are assessed. Finally, adaptation strategies are discussed and areas where there is a recognized lack of knowledge are highlighted. The literature shows that different pathosystems respond in different ways to climate change. Thus, case-by-case studies on the responses of crop species or varieties and their diseases to climate change are necessary. In addition to that, wide-scale projections of disease risk are necessary in order to identify research priorities, whereas industry must be strategically directed and public policies developed to establish adaptation measures and to prevent potential food security crisis. Only by conducting long-term and multidisciplinary studies can we reduce the uncertainty regarding the effects of climate change on plant diseases.

Key words: carbon dioxide, global warming, ozone, temperature.

Introduction

Rockström et al. (2009) quantified the safe operating limits for the Earth's biophysical systems, which should not be exceeded, due to serious environmental damages and consequent problems for humanity. However, climate change has already crossed these proposed limits, as well as limits indicated for loss of biodiversity and for changes in the nitrogen cycle. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), scientific evidence demonstrates that the increase in the average global temperature since the Industrial Revolution (approximately 1750) is the result of anthropogenic activity, especially driven by greenhouse gas emissions and land use changes. These altered climatic patterns, which are reflected in the regulation of physical and biological systems, globally and especially in South America, follow the projections discussed by Valverde & Marengo (2010).

Agriculture is being altered by climate change, as evidenced in several studies on agronomic data and long-term climate series. Lobell et al. (2011) correlated data on monthly temperatures and rainfall from 1980 to 2008 with production of corn, wheat, rice, and soybeans in several countries. The production of these crops represents 75% of the calories consumed directly and indirectly by humans. Models that related the productivity of these four crops

to climate changes within this period have indicated that global production of corn and wheat decreased by 3.8% and 5.5%, respectively. However, as there was an increase of global production for soybean and rice, winners and losers largely balanced out. The negative effects of climate change were pronounced enough in a number of countries to offset increases in productivity that arose from technological innovation, CO₂ fertilization (due to the increased CO₂ atmospheric concentration), and other factors.

The impacts of climate change on plant diseases pose a serious threat to food security (Strange & Scott, 2005; Gregory et al., 2009; Chakraborty & Newton, 2011). The presence of mycotoxins in food is a major issue associated with food security and climate change in temperate countries. Paterson & Lima (2010) argue that increased temperature in developed countries with temperate climates, like regions of Europe and the USA, can make conditions favorable for an increase in mycotoxins levels in food. Another concern is that the altered geographic and temporal distribution of plant diseases can result in the intensified use of fungicides, thereby increasing residues in food (Ghini, 2008; Miraglia et al., 2009). Similarly, the environmental role played by plant diseases in ecosystem services may be altered by climate change (Cheatham et al., 2009).

Climate change can directly and indirectly affect plants, pathogens, plant-pathogen interactions, vectors, biological control agents, and endophytic and mycorrhizal

microorganisms. Climate change alters plant-pathogen-environment interactions at local, regional, and continental scales, resulting in new distribution patterns. Increased temperature, for example, can favor a particular step in the cycle of host-pathogen relationships but be unfavorable to another step. The changing interactions between climatic variables will also alter the intensity of epidemics. Thus, although extremely difficult to perform, only analyses that consider a complex system of interactions between the three basic elements of an epidemic may indicate whether the risk of diseases will increase or decrease.

The complexity of the pathogen-host-environment interaction often makes it difficult to attribute disease occurrence to climate change. Thus, in many cases, diseases are due to natural or man-made introductions, changes in cultural practices, changes in pathogen populations due to the use of fungicides or other control methods, or introduction of new cultivars or varieties, as well as climate variability. According to Garrett et al. (2009), the following points should be investigated before stating that plant disease patterns have changed due to climate change: “(a) the pathogen is known to have been present throughout the area during the period in question, (b) the genetic composition of the pathogen and host populations has apparently not shifted to change resistance dynamics, (c) management of the system has not changed in a way that could explain the changes in disease pattern, (d) the climatic requirements of the pathogen and/or vector are well-understood and better match the climate during the period of greater disease pressure and (e) the change in disease pattern has been observed long enough to establish a convincing trend beyond possible background variation”. Considering the difficulty in obtaining this information, there is little evidence that climate changes has resulted in altered distribution and intensity of plant disease epidemics.

One of the first evidences in literature is the occurrence of needle blight in *Pinus contorta* var. *latifolia* Dougl. ex Loud., caused by *Dothistroma septosporum* (Dorog.) Morelet, in British Columbia, Canada. The first report of this disease was in the early 1960s, and between 1984 and 1986, trees with symptoms of needle blight were observed over an area of 10 ha. Woods et al. (2005) evaluated 40,898 ha and observed that 37,664 ha contained infected plants, with dead trees being observed in 2,741 ha. The authors observed that the epidemic coincided with increased summer rainfall in the region. Nevertheless, Woods (2011) stated that the epidemic and its link to climate change were not as easily predictable as the mountain pine beetle (*Dendroctonus ponderosae* Hopkins) epidemics, which exceeded the scale of all previously recorded outbreaks. Hannukkala et al. (2007) used data from 69 years of late blight (*Phytophthora infestans* (Mont) de Bary) incidence in potatoes in Finland to associate the increased epidemic frequency of the disease with climate change and the absence of crop rotation. The climate became more favorable for late blight in the 1990s, resulting in an approximately fourfold

increase in sales of fungicides in the country from 1980 to 2002.

The potential effects of climate change on diseases of food crops were reviewed by Luck et al. (2011). The literature concerning the impacts on diseases in tropical and plantation crops was reviewed by Ghini et al. (2011), and that concerning the effects on forest diseases was reviewed by Sturrock et al. (2011). The impacts of climate change on diseases of important crops in Brazil were discussed by Ghini & Hamada (2008) and Ghini et al. (2011). An interesting focus of study still to be explored according to Tubby & Webber (2010) is the effect of climate change on diseases of forest species in urban areas, as these species will be most affected, due to faster and relatively more extreme alterations than in rural areas. The effects of an increased dry season, for example, should be more severe on trees in urban situations, due to limited space for root development in the small land patches they occupy and the reduced area for water infiltration. Drought, which is associated with greater temperature increases in urban areas, may predispose plants to attack by various pests and pathogens. For this reason, the authors suggested that plants in urban areas may serve as indicators and thus may allow for detecting problems in their early stages before the pests and pathogens spread to extensively cultivated areas.

Despite predictions that extreme events resulting from climate change will occur more frequently, which should make abiotic diseases more important, this review focuses on biotic diseases. First, we present studies on the effects of altered patterns of climate-based variables, such as temperature, water availability, carbon dioxide (CO₂), ozone (O₃), and ultraviolet-B radiation (UV-B). Next, we discuss projections of future scenarios and forecasting methodologies for patterns of geographic and temporal distribution of epidemics as a consequence of climate change followed by a discussion on adaptation strategies and areas for future research. Although there are still few articles on this topic, recent publications (Figure 1) and reviews (for example, Manning & Tiedemann, 1995; Ghini, 2005; Garrett et al., 2006; Chakraborty et al., 2008; Ghini et al., 2008; Ghini et al., 2011) have summarized the knowledge available. Rather than re-summarizing the information already presented in those reviews, in the present article, we discuss the trends in new research on the subject.

Temperature and water availability

Temperature directly influences the growth and development of plants and pathogens. Thus, alterations of this climatic variable can affect both the host's susceptibility and the pathogen's virulence mechanisms. Temperature affects the infection cycle from the spore germination process until colonization of the host's tissues and also plays a decisive role in pathogen reproduction and survival, which may lead to an increased or reduced disease severity (Campbell & Madden, 1990). For several rust pathogens, including *Puccinia allii* Rudolphi (Gilles & Kennedy,

2003), *Phakopsora euvtitis* Ono (Angelotti et al., 2011) (Figure 2), *Puccinia substriata* Ellis & Barthol (Tapsoba & Wilson, 1997), and *Phakopsora pachyrhizi* Syd. & P. Syd. (Marchetti et al., 1976), temperatures above 25°C reduced the urediniospore germination rate. For *Phytophthora ramorum* S. Werres, A.W.A.M. de Cock temperatures above 22°C and 26°C are known to reduce the production of sporangia and chlamydospores, respectively (Englander et al., 2006).

According to the simulated scenarios, the projected increase in temperature can favor higher incidence of certain diseases, due to reduced host resistance (Wright et al., 2000). Genetic variability in response to altered temperature allows pathogens and/or plants to adapt to new environments (Evans et al., 2008; Travers et al., 2010; Pangga et al., 2011). Thus, understanding the responses of defense genes in plant populations may be of great importance for determining the plants' potential for adapting to climate change (Garrett et al., 2006).

Plant resistance to *Tobacco mosaic virus* (TMV) is mediated by the *N* gene, which is sensitive to high temperatures. Above 27°C, no hypersensitivity reaction occurs, making plants susceptible to this pathogen (Wright et al., 2000). Wheat cultivars with the *Sr6* gene are resistant to stem rust (caused by *Puccinia graminis* Pers. f. sp. *tritici* Eriks & Henn.) when grown at 18°C; however, these cultivars are susceptible when grown at 27°C (Moerschbacher et al., 1989). The same pattern occurs with other genes for resistance to stem rust of wheat (Chakraborty et al., 2011). In contrast, for rice, the gene for resistance, *Xa7*, was more effective at 35°C – 29°C (day-night temperatures) than at 29°C – 21°C, whereas other genes for resistance to *Xanthomonas oryzae* pv. *oryzae* [(Ishiyama) Swing et al.] were less effective at high temperatures (Webb et al., 2010). In the *Brassica napus* L. x *Leptosphaeria maculans* (Desmaz.) Ces. & de Not. pathosystem (stem canker), disease severity is more intense in Australia, where average temperatures are higher

than in Europe (West et al., 2001). The increased disease severity occurs because resistance mediated by the *Rlm6* gene is ineffective above 25°C (Huang et al., 2006). Such studies are extremely important for integrated management and choosing cultivars to be grown in different regions because the breaking of resistance, influenced by increased temperature, can prevent production in places that have climatic conditions unfavorable to host resistance.

In addition to temperature, water stress, caused by the reduced rainfall that is projected for many regions, can also alter plant susceptibility to pathogens by stimulating or inhibiting defense mechanisms. Therefore, the effects of water stress on the risk of occurrence of plant diseases have also been investigated in different pathosystems (Maxwell et al., 1997; Clover et al., 1999; Mayek-Perez et al., 2002; Xu et al., 2008). Plant-pathogen interactions may respond differently to water stress, which may increase plant susceptibility, as observed in the *Macrophomina phaseolina* (Tassi) Goid x *Phaseolus vulgaris* L. interaction (Mayek-Perez et al., 2002). According to Boyer (1995), increased susceptibility occurs because there is reduced photoassimilate production, reducing the plant's ability to produce defensive compounds. Additionally, plant growth is reduced under water stress without reducing disease development. In contrast, other studies have shown that plants inoculated with *Brome mosaic virus* (BMV), *Cucumber mosaic virus* (CMV), *Tobacco mosaic virus*, and *Tobacco rattle virus* exhibit resistance to water stress (Xu et al., 2008). According to the authors, increased production of such substances as prolines, sugars, putrescines, and antioxidants in infected plants may explain drought tolerance. Understanding plant defensive mechanisms and pathogen virulence may have potential agricultural applications, mainly because drought will be a limiting factor for production (Wollenweber et al., 2005). Each plant and pathogen species responds to climate change via different mechanisms, which will increase the complexity

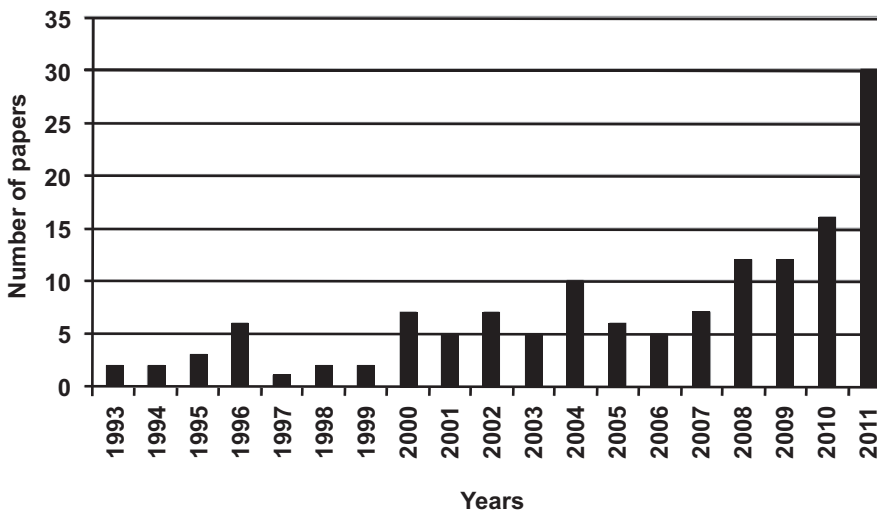


FIGURE 1 - Number of papers that assess the impacts of climate change on plant diseases published in indexed journals from 1993 to mid-2011.

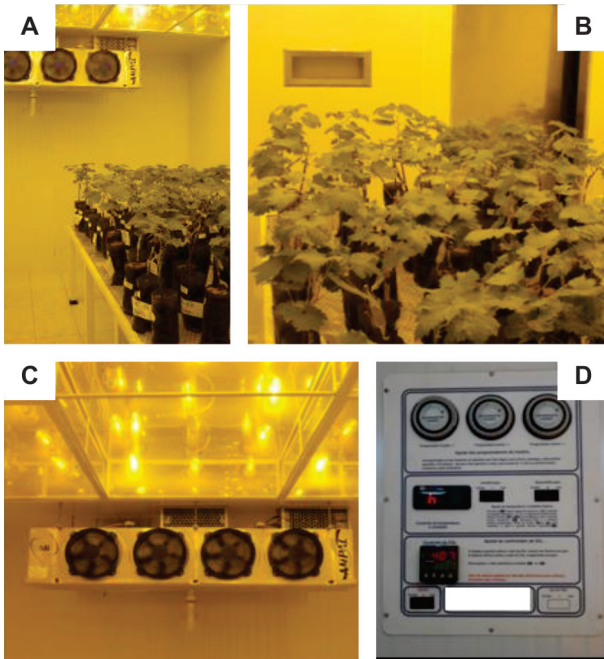


FIGURE 2 - Growth chamber: **A-B.** grape seedlings used for studies of the effects of climate change on phytosanitary problems; **C.** illumination and humidification system; **D.** panel for regulating environmental conditions (Petrolina, PE, Brazil).

of pathogen-host interactions in the future climate (La Porta et al., 2008; Travers et al., 2010). Elucidating these mechanisms through studies at the molecular level can guide policies and practices to adapt to the effects of climate change (Evans et al., 2008; Eastburn et al., 2011).

Carbon dioxide and ozone

The concentration of atmospheric CO₂ has significantly increased since the Industrial Revolution. The average atmospheric concentration of this gas reached 393 μmol mol⁻¹ in 2011, exceeding the concentrations of the last 800,000 years (180 to 300 μmol mol⁻¹) (Lüthi et al., 2008; NOAA, 2011). Projections indicate that the concentration CO₂ should increase to between 730 and 1020 μmol mol⁻¹ in 2100 under the A2 scenario (IPCC, 2007). Many studies have examined the beneficial effects of elevated atmospheric CO₂ concentration on plant growth, although there may be differences in responses between species (Pritchard & Amthor, 2005). Plants grown at elevated CO₂ concentrations exhibit altered morphology, anatomy, chemical composition, and gene expression profiles in addition to increased biomass and yield (Braga et al., 2006; Souza et al., 2008).

The increased atmospheric CO₂ concentration should increase C3 plant productivity an estimated 10 to 20% and C4 plant productivity an estimated 0 to 10% (Ainsworth & Long, 2005). However, these values should be lower in commercially cultivated areas because of limiting factors, such as pests, diseases, competition, nutrient availability, and stress caused by temperature and drought.

The Free Air Carbon Dioxide Enrichment (FACE) experiments conducted over the last 20 years have allowed the study of the impacts of increased atmospheric CO₂ concentrations on plant diseases and other environmental variables under field conditions, such as increased O₃ concentration, temperature, and rainfall. In FACE facilities (Figure 3), large quantities of CO₂ are released

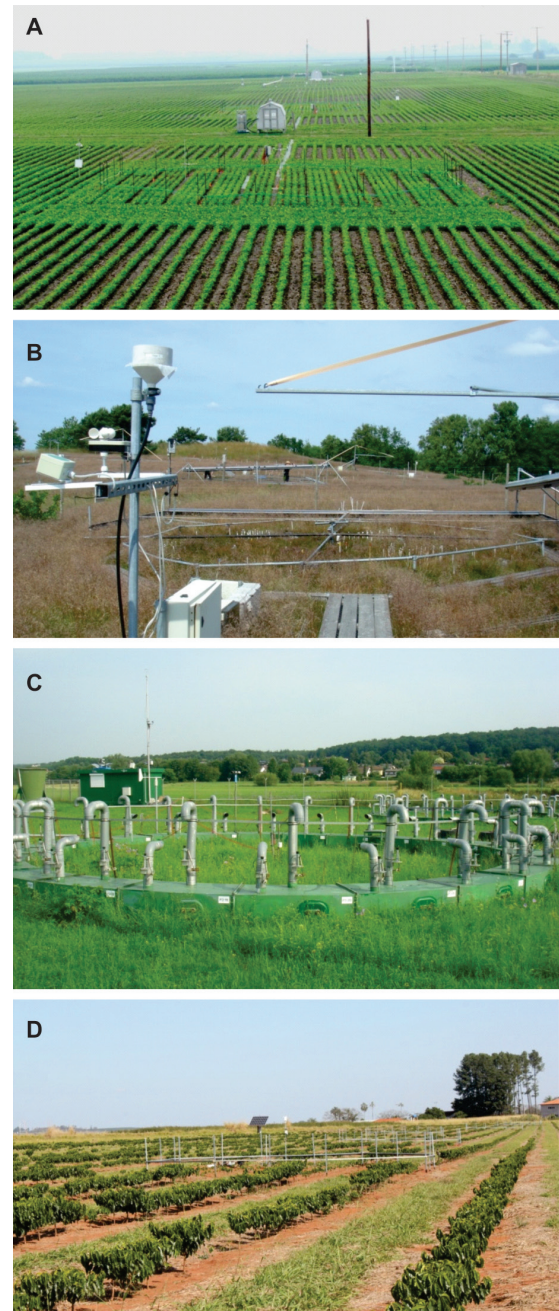


FIGURE 3 - Free Air Carbon Dioxide Enrichment (FACE) facilities for studying the impacts of increased atmospheric CO₂ concentration (**A.** SoyFACE, USA, photo: André Torre Neto; **B.** Climaite FACE, Denmark; **C.** Giessen FACE, Germany; **D.** Climapest FACE with coffee crop, Brazil).

into the environment, allowing the assessment of the effects on plants and ecosystems under natural conditions, without interference by experimental apparatuses. Due to these advantages, studies on the impacts of increased concentrations of gases are ceasing to be conducted in closed and artificially controlled environments, despite the higher cost of field trials. Some plant diseases have been studied in FACE experiments (Chakraborty et al., 2008), including leaf rust (*Melampsora medusae* Thuem. f. sp. *tremuloidae*) of *Populus tremuloides* Michx. (Karnosky et al., 2002; Percy et al., 2002); foliar leaf spot [*Phyllosticta minima* (Berk. & M.A. Curtis) Underw. & Earle] of *Acer rubrum* L. (McElrone et al., 2005); rice blast [*Magnaporthe oryzae* (T.T. Hebert) M.E. Barr] (Kobayashi et al., 2006); mosaic (*Soybean mosaic virus*) (Bilgin et al., 2008), brown spot (*Septoria glycines* Hemmi), downy mildew [*Peronospora*

manshurica (Naumov) Syd.], and sudden death syndrome (*Fusarium virguliforme* O'Donnell et T. Aoki) (Eastburn et al., 2010) of soybean; and crown rot (*Fusarium pseudograminearum* O'Donnell & T. Aoki) (Meloy et al., 2010) and stripe rust (*Puccinia striiformis* f. sp. *tritici* Eriks. & Henn.) of wheat (Chakraborty et al., 2011). Additionally, Li et al. (2009) studied the effects of incorporating rice straw, with N fertilization and increased atmospheric CO₂ concentration on the plant-parasite nematode community in a FACE experiments involving wheat in China.

In addition to this facility, studies on the effects of increased CO₂ concentration on plant diseases can be conducted in open-top chambers (OTCs), which are structures covered by a plastic film that helps to maintain high concentrations of the gas inside the field plots (Figure 4). In open-top chamber experiments conducted in Brazil, the



FIGURE 4 - Open-top chambers for studying the impacts of increased air CO₂ concentration (A-B. Jaguariúna SP, Brazil; and C. in Petrolina, PE, Brazil).

severity of rice blast and downy mildew of soybean increased with increasing CO₂ concentration (Goria, 2009; Lessin et al. 2009). Lessin et al. (2011) observed reduced severity of soybean rust with increasing CO₂ concentration. However, no trials on the effects of increased O₃ concentration on plant diseases have yet been conducted in Brazil.

Manning & Tiedemann (1995) summarized the responses of plants to increased concentrations of CO₂ and O₃ and analyzed their potential effects on pathogen-host interactions. Eastburn et al. (2011) compared the effects predicted by these authors with the results from research published since 1995. Increased plant biomass production under elevated CO₂ resulted in a greater amount of tissue that can be infected by pathogens, especially necrotrophs. The number of plant stomata was generally unaffected by either CO₂ or O₃, but stomatal opening was significantly restricted altering the infection rate of diseases caused by stomata invading pathogens. Other responses expected by Manning & Tiedemann (1995) have yet to be adequately studied, such as increased crop residues, resulting in a higher pathogen survival rate, accelerated ripening or senescence, and stimulation of necrotrophic pathogens.

Tropospheric O₃ concentration, which results from the burning of fossil fuels, has increased from 0.5 to 2.5% per year over the past 20 years, and forecasts indicate that the concentration of this gas will likely continue to grow (Bilgin et al., 2008). Increased O₃ concentration has a negative effect on biomass because it causes or accelerates tissue necrosis in plants. Consequently, the effects of increased O₃ are opposite those caused by CO₂. A meta-analysis by Morgan et al. (2003) concluded that average shoot biomass in physiologically mature soybeans grown at high O₃ concentrations was reduced by approximately 34%, and seed yield was reduced by 24%. Other stress treatments, such as UV-B and drought, did not alter the plants' response to O₃, but an increased CO₂ concentration reduced the loss caused by O₃ due to reduced stomatal conductance.

Because of these effects, increased O₃ concentrations generally favor necrotrophic pathogens, which parasitize the dead tissues of the hosts. In contrast, biotrophic pathogens, which remove nutrients from living cells, generally benefit from increased CO₂ concentration, due to altered plant growth, thereby causing increased biomass production (Eastburn et al., 2011). When plants are grown in the presence of both gases, the opposing effects often offset each other. These generalizations, however, are not always observed, as several factors are involved in disease occurrence, not only the effects on host plant biomass.

UV-B

The reduced ozone layer in the Earth's stratosphere (from 12 to 50 km altitude) also affects agriculture. This layer functions as an important filter for solar radiation, particularly ultraviolet radiation (Godin-Beekmann, 2010). Ultraviolet radiation spectral region is constituted by wavelengths in the range 100 – 400 nm. UV-A radiation

(315 to 400 nm) is weakly absorbed by the ozone layer and is easily transmitted to the Earth's surface (Paul, 2000); UV-B radiation (280 to 315 nm) is efficiently filtered by the ozone layer; and UV-C radiation (100 to 280 nm) does not present a risk to the Earth because it is absorbed by other gases in addition to ozone, such as oxygen (Madronich et al., 1995; Paul, 2000). Of these types of radiation, UV-B has higher biological active radiation and, due to the reduced ozone layer, has higher incidence in some areas of the Earth (Madronich et al., 1995), rendering UV-B a public health concern (Jones, 1992; Tsai et al., 2009). The damaging effects of ultraviolet radiation on different ecosystems and organisms, as well as the cellular and molecular physiological changes it causes, have been the subject of numerous studies (Griffiths et al., 1998; Ballare et al., 2001; Hollosy, 2002; Johnson, 2003; Schade et al., 2005; Caldwell et al., 2007; Wu et al., 2009).

The Montreal Protocol was established with the intention of preserving the ozone layer, aiming to gradually reduce and/or substitute man-made gases that are harmful to O₃. Nevertheless, global O₃ is still lower than in the 1970s, causing the planet to experience the effects of a reduced ozone layer for several decades (McKenzie et al., 2007; Godin-Beekmann, 2010), if it is not reduced again by anthropogenic activities. Thus, in addition to the reduced ozone layer, resulting in increased terrestrial UV-B radiation (Madronich et al., 1998; Leun, 2004), it is important to study the synergistic effects with global warming and increased CO₂ atmospheric concentration (IPCC, 2007).

Ultraviolet radiation can act on plant diseases in two distinct ways: indirectly, by interfering with the induced host resistance against phytopathogens; or directly, by damaging the structures of the pathogen and biological control agents.

Action of UV-B radiation on the host

Under conditions of elevated UV-B radiation, photosynthesis is reduced, causing reductions in plant height and leaf area. The dry matter yield is also reduced, but the response depends on the plant species (Wu et al., 2009). Many studies show the harmful effects of UV-B radiation, which is readily absorbed by proteins, pigments, and nucleic acids on plants. Elevated UV-B radiation can result in accelerated degradation of biomolecules (Caldwell & Flint, 1994; Caldwell et al., 1998). According to Caldwell et al. (2007), increased incidence of UV-B radiation on plants may affect their long-term genetic stability, increasing the mutation frequency, which is considered harmful to the organism. In plant cells, UV-B/UV-A radiation disrupts cell membranes, denatures proteins, inactivates respiratory metabolism, causes oxidative stress, and damages DNA, RNA, and ribosomes (Griffiths et al., 1998). Plant growth can also be reduced due to stress caused by the formation of more defensive compounds (Germ et al., 2010; Jaakola & Hohtola, 2010) meant to protect the DNA from UV-B radiation (Rozema et al., 1997). Plant stress caused by

UV-B radiation can increase resistance to insects (Ballare, 2003) and also stimulate the expression of genes for plant resistance to phytopathogens (Kunz et al., 2006; Antognoni et al., 2007). However, this increased resistance may vary according to plant, cultivar, and study site (Paul & Gwynn-Jones, 2003). Izaguirre et al. (2003), studying the effects of UV-B radiation on *Nicotiana longiflora* Cav., found that approximately 20% of the gene sequences represented on the array showed differential expression in response to solar UV-B and the expression response had parallels with those elicited by simulated insect herbivory. Both UV-B and UV-A radiation are able to induce the synthesis/accumulation of leaf phenolic compounds (Kotilainen et al., 2010). Ultraviolet radiation induces production of compounds linked to the pathogenesis process, such as chitinase and β 1–3 glucanase (Kunz et al., 2008). According to Kucera et al. (2003), UV-B supplementation in plants induces higher production of β 1–3 glucanase. However, production of pyrimidine dimers can also occur, demonstrating the damage sustained by the DNA. The same authors concluded that the response induced in bean plant leaves by UV-B radiation was only local. Plant responses to UV-B and their interactive effects with others climate change components can result in decreased productivity of important crops, such as soybean (Koti et al., 2005), rice (Mohammed & Tarpley, 2010), and cotton (Zhao et al., 2004). However, there are cultivars with higher tolerance to UV-B. Enhanced UV-B can affect genetic stability of plants causing long term heritable effects, with a high frequency of mutations, even after possible recovery of the ozone layer (Caldwell et al., 2007). Feng et al. (2007) found that UV-B, similarly to water stress, can decrease the net photosynthetic capacity of wheat and thus reduce the biomass of the roots, stems, and leaves, as well as yield. Paul (2005) suggests that artificially increasing UV-B radiation using special lamps can have positive effects, such as inhibiting plant growth (offering potential alternative to chemical growth regulators), improving leaf color, altering pigments, and increasing the amount of some essential oils (Johnson, 1999). However, UV-B radiation has not yet been used in commercial agriculture (Paul, 2005).

Action of UV-B radiation on pathogens

Elevated UV-B levels can harm microorganisms, including fungi and bacteria. High doses, larger than those recorded in nature, can be lethal (Johnson, 2003). Ultraviolet radiation regulates sporulation in many phytopathogenic fungi (Ensminger, 1993). Thus, UV radiation can be used for controlling certain diseases in greenhouse system. This fact is important in producing vegetables and flowers, where replacing conventional plastic that transmits UV with plastic that does not transmits UV may reduce disease incidence, as sporulation of many pathogens is reduced in the absence of UV radiation (Honda & Yunoki, 1977). For example, some *Botrytis cinerea* Pers. & F. isolates exhibited reduced sporulation in greenhouses containing polyethylene films that retained 280 – 380 nm wavelength

radiation (near-ultraviolet light) (Nicot et al., 1996; West et al., 2000). However, Manning & Tiedemann (1995) have suggested that the reduction of the ozone layer has had little effect on plant diseases.

Studies assessing the effects of UV-B radiation on plant diseases have mainly been conducted under controlled conditions or in greenhouses. Thus, the results may overestimate the effect of UV-B on plants, as under these conditions, UV-B radiation is high and constant (Caldwell & Flint, 1994). Raviv & Antignus (2004) revised the effects of UV radiation on pathogens and insect pests of greenhouse-grown crops.

Wavelengths that induce sporulation at low doses can inhibit sporulation at high doses (Leach & Trione, 1966). Ultraviolet radiation can inactivate pathogen spores quickly, as certain wavelengths inhibit spore germination or germ tube growth (Maddison & Manners, 1973; Aylor & Sanogo, 1997). As an example, using filters that exclude UV-B region increased the incidence and severity of blister blight disease of tea [*Camellia sinensis* (L.) Kuntze], caused by *Exobasidium vexans* Masee, in the field in Sri Lanka (Gunasekera et al., 1997). Another pathogen that was shown to be sensitive to UV-B radiation is *Uncinula necator* (Schw.) Burril, the causal agent of grape powdery mildew (Willoquet et al., 1996). However, not all plant pathogens are vulnerable to this type of damage. We must consider that there is enormous genetic diversity among fungi; therefore, pathogens will be affected differently by these changes (Paul et al., 1997).

Biggs & Webb (1986) observed that in a wheat cultivar moderately resistant to *Puccinia recondita* Rob. ex Desm., disease severity remained unaltered with increased UV-B. However, leaf rust severity significantly increased in a susceptible cultivar with increasing UV-B radiation. A similar result was found by Orth et al. (1990) for *Cladosporium cucumerinum* Ell. & Arth in cucumber, where a susceptible cultivar showed higher disease severity with increasing UV-B. Finckh et al. (1995), studying the effect of UV-B radiation on *Pyricularia grisea* (Cooke) Sacc. in rice, found that although the effects of UV-B radiation on disease severity may be small, there is evidence that plant tolerance to disease decreases because of UV-B radiation.

Changes in ultraviolet radiation affect not only pathogens and plants but also biological control agents. According to Paul (2005), *Botrytis cinerea* was more tolerant to UV-B radiation than *Trichoderma harzianum* Rifai isolates in the laboratory. Thus, the author concluded that greenhouses covered with plastic films that filter UV-B radiation improve the biological control agent's action against pathogens. Costa (2011) found that UV-B radiation had a strong deleterious effect on conidia of *Trichoderma* spp. and *Clonostachys rosea* (Link) Schroers, which are taxa that include relevant biological control agents of plant diseases. In laboratory trials, *Trichoderma* was less sensitive than *Clonostachys*. However, on leaf discs, conidia of *Clonostachys* were less sensitive to radiation (Figures 5

and 6A). In field trials (Figure 6B), an increase of UV-B radiation significantly reduced *C. rosea* growth on bean leaves. This information indicates the need to add protectors against UV-B to biological control agent formulations. The effects of radiation on other growth stages of biological control agents and pathogens should also be evaluated.

An important aspect to consider is the interaction between increased CO₂ concentration, temperature, and UV-B radiation, as there may be synergy or compensation between these factors (Alvarado-Gutierrez et al., 2008). However, these interactions are rarely studied, and there are also methodological difficulties in such complex studies. Caldwell et al. (2007) and Wu et al. (2009) discussed the interactions between UV-B radiation and other climatic variables, such as elevated CO₂, drought, temperature, nitrogen availability, and nutrient cycling. Another important aspect discussed by Johnson (2003) is that most studies are conducted during a short period whereas organisms adapt to environments over long periods of time.

Geographic and temporal distribution of diseases: considerations for projecting future scenarios and forecasting methodology

The geographic distribution of pathogens results from distribution, susceptibility, and management of the crop, presence of vectors and other organisms related to diseases, and environmental conditions. Thus, it is likely that climate change may modify the geographic distribution of diseases; however, due to the dynamic and complex processes involved, it is still difficult to predict with great confidence how these alterations will occur. Predictions of many variables required to estimate changes in pathogen distribution are still uncertain, and the tools to predict such changes based on environmental correlations depend on good primary data, which are often absent, and must be verified with historical records, which, to date, are scarce for almost all pathosystems (Shaw & Osborne, 2011).

Climate models are used as a research tool for studying and simulating the effects of climate change. Climate models are based on well-established physical principles and describe attributes of the current climate and past changes in the climate with considerable confidence, providing good quantitative estimates of future climate change, particularly at a continental scale and below (Randall et al., 2007). Since the Third Report of the IPCC (2001), progress has been made in understanding how climate is changing in space and time, due to improved analysis of numerous data sets, broader geographical coverage, better understanding of uncertainties, and wider ranges of measurements (Pachauri & Resinger, 2007). The incorporation of this considerable increase in knowledge of climatic processes into climate models has increased the complexity and reliability of these models over the past decades. This improvement can be observed in the finer average spatial resolution of the projections from climate models and in the number of models provided by the Assessment Reports of the IPCC

(Figure 7), as highlighted in the Fourth Assessment Report of the IPCC (2007) (IPCC AR4), providing a quantitative basis to estimate the probabilities of many aspects of future climate change.

Thus, the information required to evaluate the impacts of climate change can be derived from projections of these climate models, which can be global (GCMs) or regional (RCMs). Numerical simulations used in the IPCC AR4 to define scenarios for future climate on Earth have a typical resolution of 100 km. The first impact of this low resolution is on boundary conditions on the surface in terms of topography for defining regions covered by water (ocean, lakes, and rivers) and vegetation (Silva Dias & Silva Dias, 2007). Depending on the regional uncertainties of global climate scenarios, several initiatives have led to the development of more detailed scenarios by focusing on larger-scale RCMs that use low-resolution scenarios as boundary conditions; however, unless resolutions much finer than 10 km are achieved, it is unlikely that these high-resolution scenarios will reduce the uncertainties in the results. Also, it is noteworthy that RCM performance substantially depends on the original GCM's performance; if the GCM does not adequately simulate important processes on a small scale, then the RCM cannot properly capture the climate at higher resolution (Betts et al., 2011).

Climate change is not only projected considering the altered temperature values but also considering the pace of change expected for the other climatic variables (e.g., rainfall, humidity, and wind), although temperature projections are considered to be more reliable. The IPCC AR4 presents the simulations of more than 20 sophisticated models that were developed by renowned institutions and executed according to different Special Report on Emissions Scenarios (SRES). All of the models simulate an elevated global temperature for the next century, with certain general patterns of change that are common in all emission scenarios but differ in intensity. For future rainfall projections, the models diverge in terms of patterns or even the trend of change in some places (Nobre et al., 2011). Under the A2 scenario, the mean temperature projections for Brazil for the period 2071-2100 indicate an increase or positive anomalies for the entire country in all months of the year compared to the period 1961-1990 (Figure 8), considering the average of 15 climate models and the statistical variability among the models' projections (Figure 9). In particular, projections from the GCMs on extreme events in tropical regions remain uncertain. Certain models tend to overestimate, while others underestimate the amplitude of the El Niño-Southern Oscillation (ENSO); therefore, over- or underestimating the most important source of inter-annual variability in the tropics (Christensen et al., 2007). Thus, in Brazil's case, the projections from the models may have more uncertainty for such regions as the North, Northeast, and South, where the effect of the ENSO is most evident.

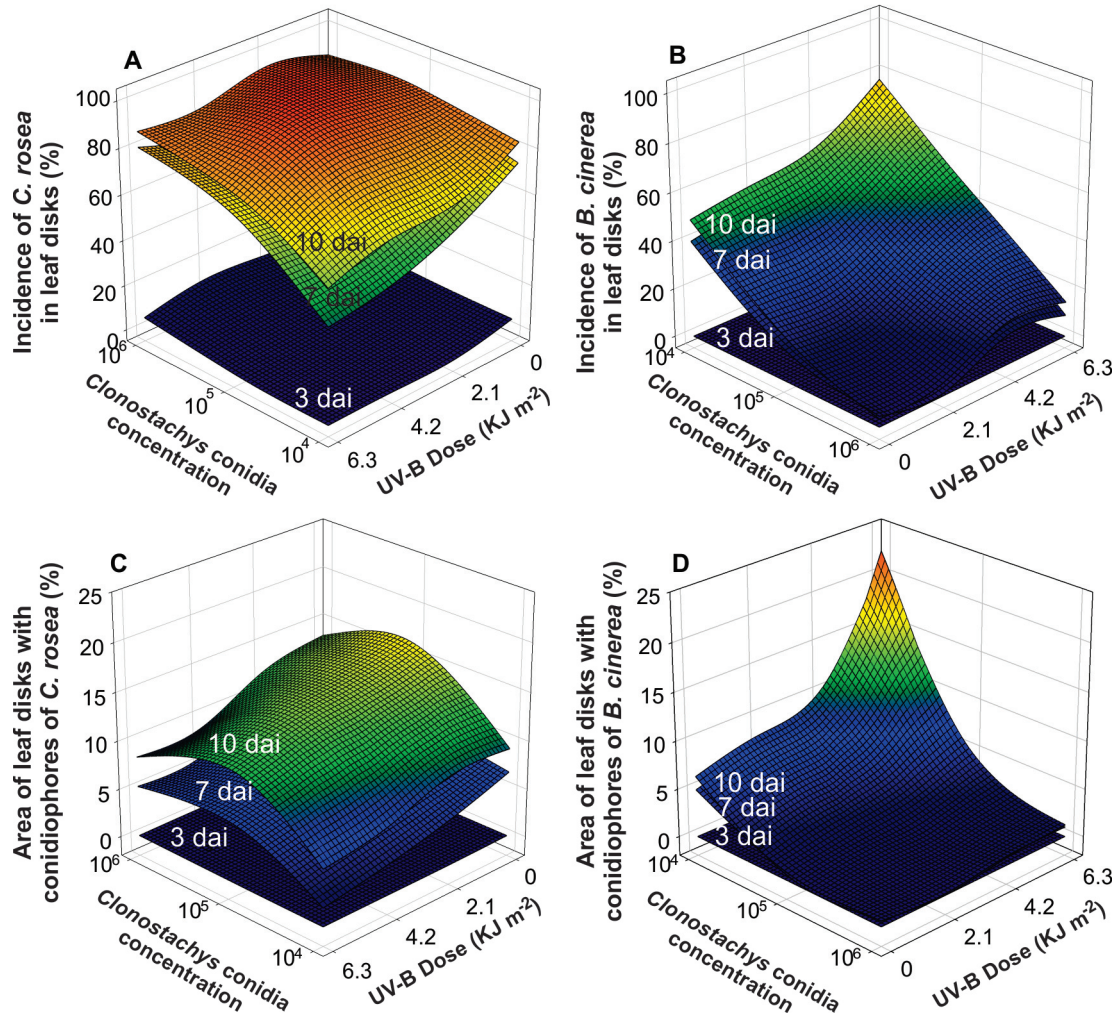


FIGURE 5 - *Clonostachys rosea* on strawberry leaf discs exposed to doses of UV-B radiation and challenged by *Botrytis cinerea*, 3, 7, and 10 days after inoculation (dai). **A.** Incidence of *C. rosea* with different inoculum concentrations at several doses of UV-B radiation; **B.** Incidence of *B. cinerea* on leaf discs challenged by *C. rosea*; **C.** Leaf disc area with *C. rosea* conidiophores; **D.** Leaf disk area with *B. cinerea* conidiophores. Source: adapted from Costa (2011).

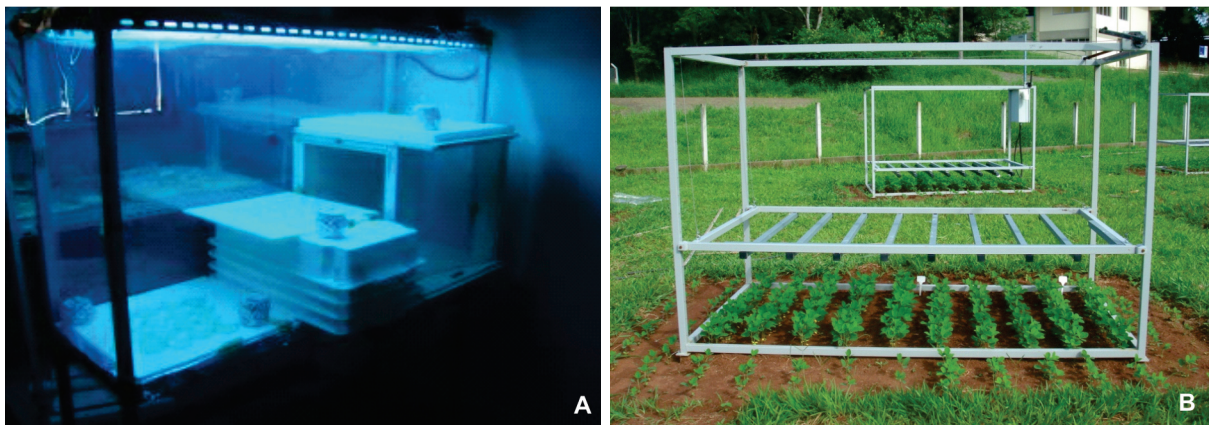


FIGURE 6 - **A.** Laboratory and **B.** field facilities to study the effects of increased UV-B radiation on plant diseases and biological control agents (Jaguariúna SP, Brazil).

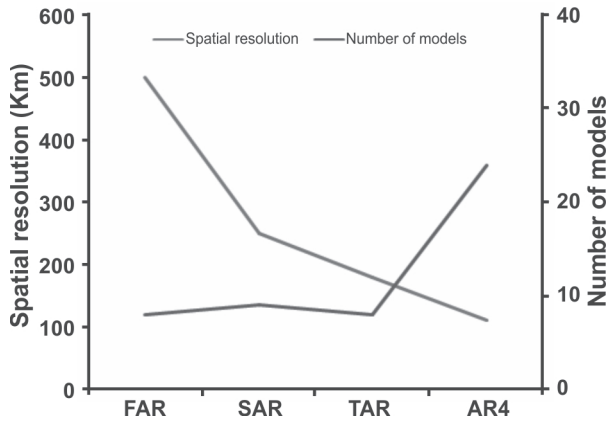


FIGURE 7 - Evolution of average spatial resolution and number of global climate models from the IPCC Assessment Reports: First Assessment Report (FAR), Second Assessment Report (SAR), Third Assessment Report (TAR), and Fourth Assessment Report (AR4).

Although the GCMs show projections of many climatic variables, not all variables are equally available in the models. Data is not available for one particularly important variable for studying the effect of climate change on the geographic distribution of diseases, namely, the leaf wetness duration. In this case, one option is to estimate the leaf wetness duration in relation to another parameter, such as relative humidity (Hamada et al., 2008a), allowing for its application, for example, in downy mildew (Hamada et al., 2008b).

The characteristic spatial and temporal resolutions of the GCMs make it difficult to reconcile these models with the plant disease models. Disease models, generally

require inputs of climate data with the same high temporal and spatial resolution used for their calibration and parameterization, generally meteorological records with a daily or hourly temporal resolution and plot- or field-level spatial resolution; however, climate change is assessed over large temporal and spatial units, and reliability decreases in the context of high-resolution analyses (Garrett et al., 2011). According to these authors, although there are procedures that can be adopted to circumvent this difficulty, all methods introduce uncertainties in the assessments, and the increased uncertainty of the climate change scenarios at finer resolutions may be more significant for evaluating the average of future long-term impacts of climate change, for example, over 30 years than when making transient assessments.

Climate change is expected to alter numerous attributes of abiotic and biotic environments, for example, temperature, CO₂ levels, nutrient levels, and species diversity, where the impacts of these alterations are probably dependent on species and location (Alexander, 2010). It is important to observe that the SRES set and its respective projections from the models are associated with greenhouse gas emission levels, and therefore possible interactions between the attributes of abiotic and biotic environments should be considered as additive effects.

Specific predictions of the geographic distributions of diseases often rely on identification of places where the climate models predict possible shifts in niches, derived from information in the literature or laboratory studies of pathogen-environment relationships (Shaw & Osborne, 2011). Table 1 presents examples of studies that applied relatively simple disease models and projections from GCMs on both regional or lower scales. These applications can be considered as first approximations

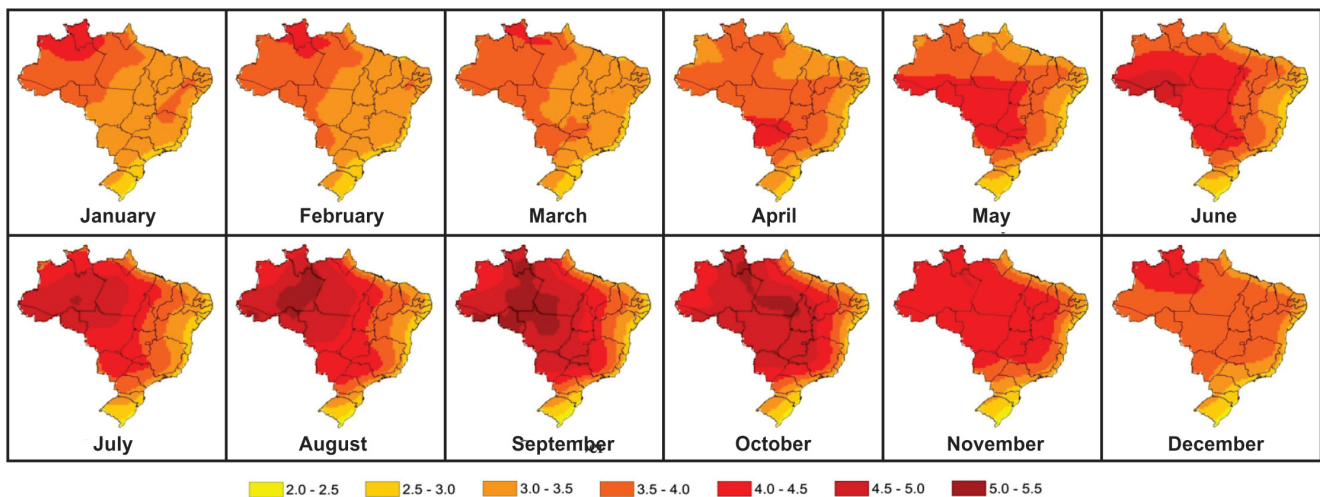


FIGURE 8 - Anomaly of mean temperature (°C) projected for the period 2071-2100 under the A2 scenario using the average of 15 global climate models from the Fourth Report of the IPCC, compared to the period 1961-1990.

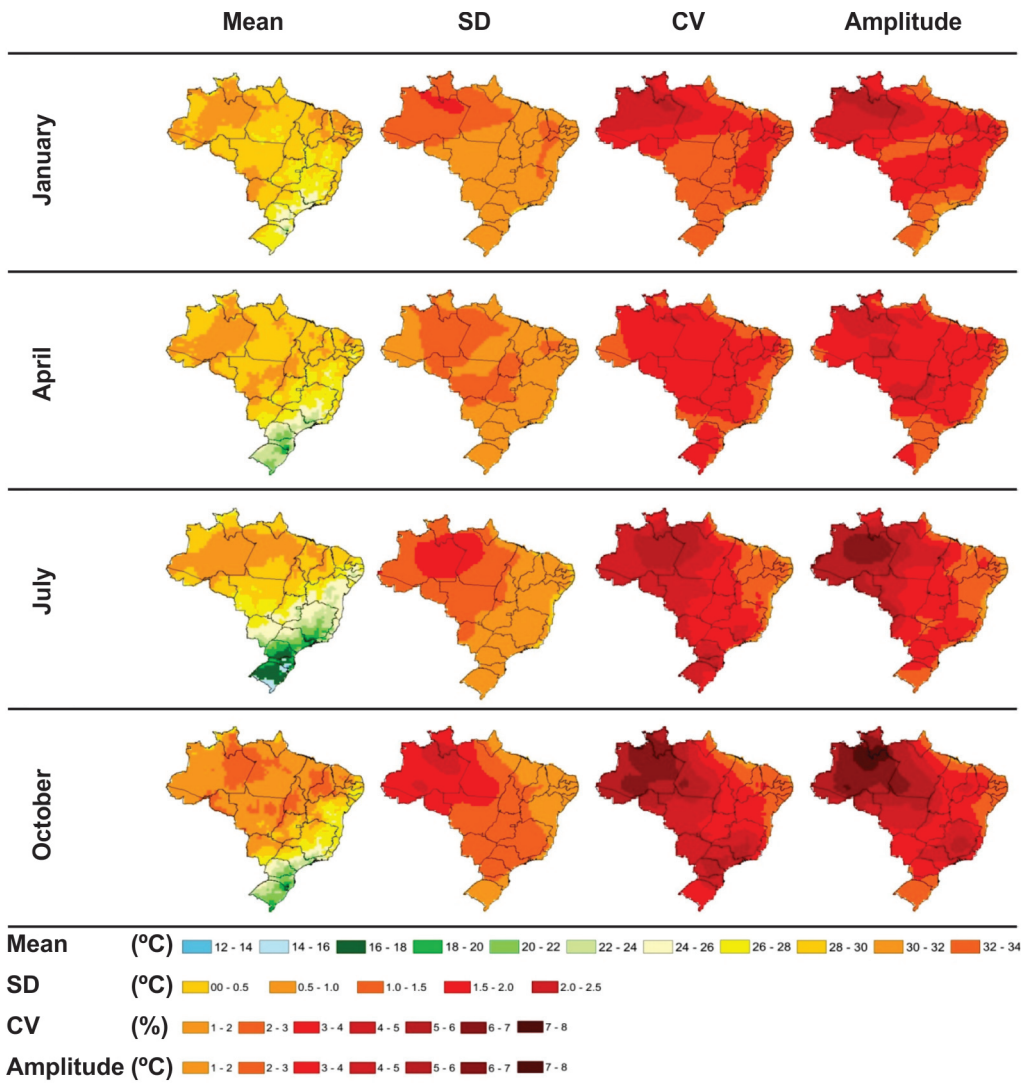


FIGURE 9 - Mean monthly temperature (°C) projected by the average of 15 global climatic models from the Fourth Report of the IPCC for the period 2071-2100 under the A2 scenario for Brazil. The standard deviation, coefficient of variation, and range between the maximum and minimum values in each month, considering the 15 models, are shown for January, April, July, and October.

because in many cases, other factors, such as altered plant development, metabolism, and morphology, that can influence pathogen-host interactions should ideally be considered and incorporated into the results. Another factor not included in the models is pathogen adaptation to the new climate, which may aggravate epidemics. Evans et al. (2008) applied an approach based on a complete system, empirically developing a disease model using data from 40 field experiments collected over 15 years and executed a predictive model under altered climate conditions for which the required input data were obtained by downscaling or reducing the time scale of the forecasts from the GCMs using stochastic weather generators. This methodological approach, however, is not easy to apply broadly for all of the pathogens, and there is doubt that a process that is thoroughly understood on a regional scale for a specific location can be generalized to other locations and at smaller scales. Thus, depending on the complexity and the many factors to consider, Garrett et al. (2011) proposed

a framework for analyzing the complexity of effects of climate change mediated by plant disease, indicating that in practice, it may be necessary to expand the models to include more components, identify those that are more important, and summarize these models to include an optimal level of complexity for planning and prioritizing research.

In summary, increasing the experimental results enabling the development and improvement of plant-pathogen linked models, fitting information provided by climate models, and reducing the uncertainty in projections from climate models will greatly improve our ability to assess impacts of future climate scenarios on pathogens. Improved understanding of the functioning of the abiotic and biotic processes involved will lead to increasingly reliable findings. Under current conditions, considering the possible impacts of climate change on the occurrence of plant diseases under the “worst” or “most likely” scenarios, even using still limited knowledge, will allow us to elaborate adaptation strategies with a greater margin of safety.

TABLE 1 - Examples of studies on the spatial distribution of plant disease, including the application of plant disease models and projections from global climate models, scope, and principal conclusions of the impacts of climate change

Crop	Pathogen/disease	Area	Impact of climate change	Reference
Banana (<i>Musa</i> spp.)	<i>Mycosphaerella fijiensis</i> Morelet / black Sigatoka	Global	Areas favorable for the disease will decrease.	Jesus Junior et al. (2008); Ghini et al. (2007)
Coffee (<i>Coffea arabica</i> L.)	<i>Hemileia vastatrix</i> Berk & Br. / coffee leaf rust	Brazil	Reduced incubation period.	Ghini et al. (2011)
Coffee (<i>Coffea arabica</i>)	<i>Meloidogyne incognita</i> (Kofoid & White) Chitwood	Brazil	Increased number of generations of the nematodes.	Ghini et al. (2008)
Eucalyptus (<i>Eucalyptus camaldulensis</i> Dehnh.)	<i>Cylindrocladum quinqueseptatum</i> Boedijn & Reitsma / leaf blight	Global	Indication of new high-risk areas.	Booth et al. (2000)
Forest species	Forest-pathogenic fungi	France	Predicted warming would be favorable to most of the studied species, especially those for which winter survival is a limiting factor linked to low temperature.	Desprez-Loustau et al. (2007)
Grapevine (<i>Vitis vinifera</i> L.)	<i>Plasmopara viticola</i> (Berk. & Curtis) Berl & de Toni / downy mildew	North-west of Italy.	More severe epidemics and increased number of fungicide sprays to control the disease.	Salinari et al. (2006)
Maize (<i>Zea mays</i> L.)	<i>Puccinia polysora</i> Underw. / rust	Brazil	Reduction of the most favorable period.	Moraes et al. (2011)
Oak (<i>Quercus</i> spp.)	<i>Phytophthora cinnamomi</i> / root disease	Euro-Mediterranean region	Spread to new areas, increased favorable period for inoculum production and infection, increased pathogen survival on soil and roots and plant predisposition.	Brasier & Scott (1994); Brasier (1996)
Oak (<i>Quercus</i> spp.)	<i>Phytophthora cinnamomi</i> Rands / soil-borne pathogen	France	Increased annual rates of pathogen survival and spread to new areas from the Atlantic coast.	Bergot et al. (2004)
Oilseed rape (<i>Brassica</i> spp.)	<i>Leptosphaeria maculans</i> / phoma stem canker	Scotland and England	Despite high complexity interaction, the disease will increase in severity and spread.	Butterworth et al. (2010); Evans et al. (2008)
Potato (<i>Solanum tuberosum</i> L.)	<i>Phytophthora infestans</i> /late blight	Finland	Disease occurrence increased in all regions.	Carter et al. (1996)
Potato (<i>Solanum tuberosum</i>)	<i>Phytophthora infestans</i> / late blight	Global	Strong differences between potato production zones.	Hijmans et al. (2000)
Rice (<i>Oryza sativa</i> L.)	<i>Magnaporthe grisea</i> / rice leaf blast	Asia	Effects varied between different agroecological zones.	Luo et al. (1995)
Several crops	<i>Xiphinema</i> , <i>Longidorus</i> spp., <i>Globodera rostochiensis</i> (Wollenweber), <i>Meloidogyne</i> sp.	Great Britain and Europe	Increased nematode population and spread to Northern Europe.	Boag et al. (1991); Carter et al. (1996)
Several crops	Several pathogens	Sweden	Dramatic change in crop health.	Roos et al. (2011)

Adaptation Strategies

According to the IPCC (2007), “adaptation is an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities”. Adaptation measures have received more attention in recent years, due to the greater certainty of occurrence of a number of the expected climate changes and the fact that productivity and food security are guaranteed only if we can elaborate a highly successful strategy to adapt agriculture to climate change (Barnes et al., 2010).

Since farmers are continually adapting cropping systems to new conditions caused by market, economic, political, social, and technical changes, Barnes et al. (2010) stated that climate change will become yet another new pressure to which they must adapt. However, climate change is an unprecedented situation, and thus there is no way to exploit the lessons learned in the past. The high speed at which the climate is changing is a serious threat to adaptation. In a review on disease management under the climate change scenario, Juroszek & Tiedemann (2011) stated that preventive control measures, such as the use of a diversity of crop species in cropping system, adjustment of sowing or planting dates, use of disease-resistant and/or abiotic stress-tolerant cultivars, use of reliable systems for forecasting epidemics, application of an integrated management strategy, and effective quarantine systems, may become particularly important in the future.

Another important point is the choice of locations where trials would be installed for breeding resistant cultivars, as these should include countries with hot climates (Butterworth et al., 2010). Given this context, the Brazilian Northeast may be a potential region for future trials because the average temperature of, for example, the Submedial region of the Vale do Rio São Francisco, state of Bahia, is around 26°C. In addition, companies that develop new varieties and hybrids of major cultivated crops, such as rice, sugarcane, and corn, are investing heavily in obtaining plants that are resistant to drought and higher temperature conditions.

Exotic pathogens are the main causes of emerging diseases (Anderson et al., 2004). Establishing and reinforcing barriers that prevent introductions of exotic pathogens and the development of techniques for fast diagnosis of new diseases and the training of technical teams able to readily use such techniques are key measures for adaptation. Roos et al. (2011) analyzed the impact of increased temperature on plant diseases and insect vectors in Sweden and found that the country’s climate will become more favorable for plant diseases. According to these authors, climate change will bring opportunities for cultivating new crops, but at the same time, there is a need to establish strategies for protecting plants to adapt to the new phytosanitary scenario.

Barnes et al. (2010) discussed the effectiveness of measures for adapting to increased risk of phoma stem canker caused by *Leptosphaeria maculans* in winter

oilseed rape in the UK. Autonomous adaptations by the private sector to solve the short-term problem (2020) were compared with planned adaptations of the long-term impact (2050), which will require investments in research and development from both the public and private sectors and more efforts toward adaptation by producers. The authors stated that most of the literature on adaptation to climate change has had a conceptual focus without quantifying the impacts, which is essential to provide clearer information to guide decision makers on the risks of climate change. For the same disease, Fitt et al. (2008) discussed the costs and benefits of strategies to prevent the spread of the pathogen in China. The concern that considerable damage could result, if the pathogen becomes established, was augmented because cultivars available in China are highly susceptible; the predicted future climate for the region is more favorable for the disease; moreover, the novel government policy to reduce air pollution in China banned the burning of these crops, which might be contributing to reducing the inoculums of *L. maculans*. The authors concluded that the costs involved in preventing the establishment and spread of the pathogen are low as compared with the cost of adaptation after its introduction.

In regions where the environment becomes more favorable for disease occurrence, intensive chemical control may be required. According to Hannukkala et al. (2007) such a situation may emerge in Finland with regards to the control of potato late-blight (*Phytophthora infestans*) as concluded from their study on this pathosystem from 1933 to 2002, and the possible changes in the climate and lack of crop rotation. The need for more fungicide sprays was predicted for controlling downy mildew in the Acqui Terzi region in northwestern Italy by Salinari et al. (2006) for the 2030s, 2050s, and 2080s. However, intensifying chemical control can result in an increased risk of resistance to fungicide, increased production costs, and more problems with residues in food and the environment. Fortunately we are already assisting major pressures in favor of the use of non-chemical methods to control plant diseases. In order to avoid the major environmental problems that are threatening the future of mankind major shifts in public habits and attitudes towards sustainability are urgently needed. After all the biggest threats for the future of mankind, ranging from food security to the conservation of biodiversity and the maintenance of the biosphere in favorable conditions for the survival of humans, are consequences of anthropogenic activities.

Climate change, can force us to rely more heavily on chemical control as a plant disease management tool but the contrary is also possible. Certainly, altering the phytosanitary scenario by reducing the importance of some diseases and increasing that of others will result in changes to the pesticide market. In addition, individual fungicide products effectiveness may be altered (Ghini, 2008). Increased temperature is likely to cause more phytotoxicity problems, creating the need to adjust formulations and doses. Reduced

half-life of the active ingredients in the soil is also another likely consequence of increasing temperature. Increased rainfall will increase fungicide runoff. Despite being an extensively studied control method, there is no information in the literature on the effects of increased atmospheric CO₂ concentration on the translocation and effectiveness of systemic fungicides.

Climate change will also impact the biological control of plant diseases, but there is little information available on the subject (Ghini et al., 2008; Bettiol & Ghini, 2009). Modified microbial community composition and dynamics in the soil and phylloplane would result in altered plant health. To achieve success with biological control, organisms specifically adapted to each region must be selected.

According to Juroszek & Tiedemann (2011), in recent years, a large arsenal of tactics have been developed aimed at controlling plant diseases and at adapting crops to different regions and periods throughout the year, including the breeding of new cultivars and the development of novel biological and chemical methods. The authors argue that these same tools can be used for adapting to climate change. However, due to the uncertainties of new scenarios, there may be a need for new techniques for managing diseases, and these techniques must be widely discussed.

According to the IPCC (2007), “mitigation is an anthropogenic intervention to reduce the anthropogenic forcing of the climate system; it includes strategies to reduce greenhouse gas sources and emissions and enhancing greenhouse gas sinks”. Using this approach, Mahmuti et al. (2009) analyzed the control of diseases in winter oilseed rape in the UK and found that applying fungicides can contribute to climate change mitigation. However, other control methods may have the same effect and result in minor impacts to the environment.

Remaining Questions

Accurate assessment of the impacts of climate change on plant diseases is limited by the multiple interactions between agroecosystem processes, human interferences, uncertainties about future climate scenarios, attributes of species and cultivated varieties, and adaptability of pathogen populations. The lack of historical series on the incidence of plant diseases is another limiting factor for studying the impacts of climate change, as the lack of data reduces the reliability of the forecasts. Del Ponte et al. (2009) simulated the seasonal risk of *Fusarium* head blight epidemics in wheat over a 50-year period and suggested that the increased outbreaks of the disease in the 1990s may have been due to changes in climatic patterns that favored the disease. However, these researchers did not use observed data on the disease but data simulated by a model validated for the site studied (Passo Fundo, RS, Brazil).

Despite the large uncertainties, estimating disease-risk on a large scale is necessary for identifying research priorities, strategically orienting industry, and developing

public policies for establishing measures of adaptation that will allow the maintenance of food security. For diseases of tropical crops, Ghini et al. (2011) presented the little existing information and discussed the need for further studies due to the worldwide importance of the region in producing food.

The responses of different pathosystems to climate change vary widely. This variation makes it necessary to study each response of the species or plant variety and its diseases in relation to climate change on a case-by-case basis. Aspects related to pathogen dynamics and evolution are also largely neglected in studies, as are the effects on the relationship between pathogen dynamics and plant architecture. The information available on soil-borne pathogens is even more limited.

Advances in technology for monitoring genetic responses in plants have enabled more accurate determination of how climate change results in modified expression of diseases (Eastburn et al., 2011). These altered molecular mechanisms determine the ability of plants to respond to environmental stimuli and adjust to new conditions. An improved understanding of these mechanisms will allow their use in developing adaptation strategies.

Few studies under field conditions have addressed the combined effects of multiple climate variables and their interactions. For example, in a FACE experiment investigating the effects of increased CO₂ and O₃ concentrations, Percy et al. (2002) found that leaf rust in *Populus tremuloides* (caused by *Melampsora medusae*) remained unaltered in environments with high CO₂ concentrations but significantly increased with increasing O₃ concentrations. However, in an environment with high concentrations of both gases, the effects of O₃ were partially offset by CO₂. These results indicate that studying a single environmental variable can lead to conclusions lacking practical significance, due to the importance of the interactions between factors. This property should be further explored in both carrying experiments and studying the impacts of climate change through modeling. Altered CO₂ and O₃ concentrations, for example, are rarely included in models, despite their importance (Eastburn et al., 2011). In addition to this association, there is a need to verify the interactions between UV-B radiation, nitrogen availability, drought, and increased temperature, as all of these variables will simultaneously affect cultivated plants. These interactions need to be studied over a long-term in an interdisciplinary approach, as the short-term effects do not reflect the long-term evolutionary processes.

According to Long et al. (2004), plants are growing in a CO₂ concentration never experienced by terrestrial vegetation in the last 26 million years, and understanding of their responses to this new environmental condition can aid understanding how the increasing CO₂ concentrations in the atmosphere will

affect them. Ainsworth et al. (2008) highlight the need for traditional breeding to consider selection in an environment with a high CO₂ concentration.

The uncertainties concerning the effects of climate change on plant diseases will only be minimized over the years as more data is obtained. Thus, all predictions should be regularly updated in light of the emerging new knowledge.

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