Global change and plant diseases

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1. Introduction

The importance of the environment on the development of plant diseases has been known for centuries (Colhoun, 1973). It is known that the environment can influence the growth and susceptibility of the host plant, the reproduction, dispersal, survival, and activities of the pathogen, as well as the interaction between the host plant and the pathogen. For this reason, global change represents a serious threat to agriculture, because they can promote significant alterations in the occurrence and severity of plant diseases. Such alterations may represent serious economic, social, and environmental consequences. Analyzing these effects is essential for the adoption of mitigating measures, in order to avoid future damages (Ghini, 2005). In the past, several epidemics that occurred in Brazilian agriculture could have been avoided or have their damages reduced if studies would have been carried out for the adoption of preventive measures.

Plant pathogens are ubiquitous, both in natural and managed systems, and may change the structure and functioning of ecosystems (Agrios, 1988; Malmström & Field, 1997). They are among the first organisms to show effects of climatic change due to their large populations, ease of multiplication and dispersion, and short time between generations (Scherm *et al.*, 2000). Thus, they form an essential group of bioindicators that need to be evaluated with regard to the impacts of climatic change, since they are one of the most important factors responsible for yield reductions, and may jeopardize the sustainability of the agroecosystem.

Global change may alter the current phytosanitary problems of Brazilian agriculture. Certainly, in the near future, modifications will occur in the relative importance of each plant disease. The economical impact could be positive, negative, or neutral, because changes may decrease, increase, or have no effect on different pathosystems, in each region. Mitigation strategies must take all these possibilities into consideration. For crops with higher loss risks, obtaining resistant varieties should be started as soon as possible, since this strategy requires long time for development. In addition, in face of global change effects on biological and chemical control, new strategies must be studied (Chakraborty, 2001).

There are few published papers about the effects of global change on plant diseases. Tests conducted in controlled environments may characterize isolated effects of certain environmental factors on pathogen-host interactions. With respect to assays conducted under field conditions, the few available papers have been conducted in the Northern Hemisphere. Little is known about effects on polycyclic diseases, which are responsible for significant losses in agriculture due to the occurrence of severe epidemics. In general, these diseases cannot be studied in controlled environments, because results are generally not representative.

In face of the threats represented by global change to plant protection, in the coming years it will become necessary to study this subject in detail. The main focus to be approached will be how global change manifested by the increased concentration of carbon dioxide (CO_2), increase in temperature, and alterations in precipitation could affect plant diseases.

2. Effects of climatic change on the cycle of pathogen-host relationships

The classic disease triangle illustrates one of the paradigms of Plant Pathology, which establishes the conditions for the development of diseases, i.e., the interaction between the susceptible host, the virulent pathogen, and the favorable environment (Fig. 1). Consequently, the disease does not occur if one of the components is eliminated. This triangular relationship is an exclusive trait of Plant Pathology, in comparison with the Veterinary and Medicine segments, because terrestrial plants possess little thermal storage capacity, and immobility prevents them from escaping from adverse environments (Francl, 2001).

Another aspect to be considered is that the alteration of a given climatic factor may have positive effects on one part of the disease triangle, and a negative effect on another. In addition, the effects may also have contrary behaviors in the various stages of the pathogen's life cycle (Coakley, 1995). Therefore, only a complete analysis of the system can define whether the disease will be stimulated or not.

The environment can influence all stages of development, both of the pathogen and of the host plant, as well as of the disease, at the various steps of the pathogen-host relationships cycle. In addition to these, it may also affect other organisms with which the plant and the pathogen interact, like endophytic, saprophytic, or antagonistic microorganisms. Thus, in an area where both the host plant and the pathogen are present, the appearance and development of the disease are determined by the environment. Important diseases can become secondary if the environmental conditions are not favorable. The relations between climate and diseases are so intense that they are routinely used for forecasting and managing epidemics, because fluctuations in the severity of diseases are determined, through the years, mainly by climatic variations.

The global change may have direct and indirect effects both on pathogens and on host plants and on the interaction between both. With regard to plant pathogens, their geographic distribution, for example, is determined by the temperature ranges over which the microorganism can grow, but many species prevail only in regions where temperature and other climatic factors are close to optimal values to allow rapid development (Lonsdale & Gibbs, 1994). Temporal distribution may be affected as well. Several pathogens, especially those that infect leaves, show fluctuations with regard to their incidence and severity throughout the year, which can be frequently attributed to climatic variations. Many of these pathogens are favored by increased moisture during the growth season, due to an increase in the production of spores. On the other hand, diseases such as powdery mildews are favored by low humidity conditions. The favorable conditions are specific for each pathosystem, and thus cannot be generalized.

In many cases, an increase in precipitation allows greater dispersion of propagules by raindrops. A reduction in the number of days with rain during summer, for example, can decrease the dispersion of several pathogens. Winds also play an important role on the dissemination of propagules, in both the short and the long range. Factors related to air turbulence, intensity, and direction of winds can also influence the release, transport, and deposition of inoculum.

The direct effects of climatic change can also be observed on the survival stage of pathogens. Pathogens of annual or perennial plants with deciduous leaves, for example, have to withstand long periods of time in the absence of available host plant tissues. In such cases, the survival stage is essential to ensure the presence of inoculum for the following cycle of the disease. Conditions during the winter season, for example, are important to determine the success of saprophytic survival.

Climatic change can also have direct effects on the host plant. One of the mechanisms involved is a change in plant predisposition, which consists in the modification of its susceptibility to diseases by external factors, i.e., non-genetic factors, which act before infection (Schoeneweiss, 1975).

The development of a plant results from the interaction between its genotype and the environment. Thus, climate change interfers with the morphology, physiology, and metabolism of plants, resulting in alterations in the occurrence and severity of diseases. Certainly the nature of the host plant (for example, annual or perennial; C3 or C4) and the pathogen (soil-borne or shoot-infecting; biotrophic or necrotrophic) determines what the impacts of climatic change will be: positive, negative, or without effect. Supposed morphological and physiological alterations that may occur and affect pathogen-host interactions include a reduction in the density of stomata, greater accumulation of carbohydrates in leaves, greater layer of waxes and epidermal cells, with an increase in fiber content, production of papillae and silicon accumulation in appressoria penetration sites, and increase in the number of mesophyll cells (Chakraborty *et al.*, 2000a). Elevated CO_2 changes the onset and duration of stages in pathogen life cycles. The latent period, i.e., the period between inoculation and sporulation, can be changed, as well as the reproduction capacity of some pathogens. Therefore, the mechanisms of resistance of host plants can be more easily overcome, as a result of accelerated development of pathogen populations (Chakraborty, 2001).

Manning & Tiedemann (1995) analyzed the potential effects of increased atmospheric CO_2 on plant diseases, based on the responses of plants in this new environment. An increase in the production of plant biomass, i.e., increases in shoots, leaves, flowers, and fruits, represent a higher amount of tissue that can be infected by plant pathogens. Increased carbohydrate contents may stimulate the development of pathogens that depend on sugars, such as rusts and powdery mildews. Increases in canopy density and plant size can promote greater growth, sporulation, and dissemination of leaf infecting fungi, which require high air humidity, but not rain, such as rusts, powdery mildews, and necrotrophic fungi. An increase in crop residues could mean better conditions for the survival of necrotrophic pathogens. A reduction in the openings of stomata can inibit stomata-invading pathogens, such as rusts, downy mildews, and some necrotrophic pathogens. Reductions in the vegetative period of plants, with early harvest and senescence, can reduce the infection period of biotrophic pathogens and increase that of necrotrophics. Increases in root biomass increase the amount of tissue to be infected by mycorrhizae or soil-borne pathogens, but can compensate losses caused by pathogens. Greater root exudation can stimulate both pathogens and antagonists (plant growth promoters). Such alterations may have great influence on the development of epidemics.

Other organisms that interact with the pathogen and the host plant can also be affected by climatic change, resulting in modifications in the incidence of diseases. Diseases that require insects or other vectors may undergo a new geographic or temporal distribution, which will be the result of the environment-plant-pathogen-vector interaction (Sutherst *et al.*, 1998). Increases in temperature or the incidence of droughts can extend the area of occurrence of the disease into regions where the pathogen and the plant are present but the vector still has not exerted its action. Mycorrhizal fungi, endophytic microorganisms, and nitrogen-fixing microorganisms can also suffer the effects of climatic change, ensuing alterations in the severity of diseases.

Most papers dealing with the effects of the environment on plant diseases have been conducted with pathogens that attack the aerial part of the plant, but soil-borne pathogens can also undergo significant changes. Soil temperature, for example, affects the activity of rhizobacteria that induces soil suppressiveness to *Fusarium oxysporum* f. sp. *ciceris*, the causal agent of wilt in chickpea (*Cicer arietinum*), in addition to affecting the inoculum potential of the pathogen (Landa *et al.*, 2001).

3. Impacts of climatic change on plant diseases

The impacts of climatic change on plant diseases can be expressed under different aspects. The most likely effects of climate change are on damages caused by diseases, on the geographical distribution of diseases, on the efficacy of control methods, and on other organisms that interact with the plant, such as mycorrhizae, rhizobacteria, antagonists, and endophytic organisms, among others (Chakraborty *et al.*, 2000a; Chakraborty, 2001).

3.1. Damages caused by diseases

The effects of climatic change on the damages caused by diseases are determined by the interactions of a large number of factors which, directly or indirectly, influence the occurrence and severity of diseases. However, an increase in the severity of a given disease, caused by a climatic change, does not necessarily implicate increased losses (Luo *et al.*, 1995).

In seven out of fourteen reports found involving necrotrophic phytopathogenic fungi, the disease increased as CO_2 concentration increased (*Fusarium nivale,* in rye; *Fusarium oxysporum* f. sp. *cyclaminis,* in cyclamen; *Fusarium* sp., in wheat; *Cladosporium fulvum*, in tomato; *Colletotrichum gloeosporioides*, in *Stylosanthes scabra*; *Seiridium cardinale*, in *Cupressus sempervirens*; and *Plasmodiophora brassicae*, in cabbage, according to Osozawa *et al.*, 1994; Manning & Tiedemann, 1995; Chakraborty *et al.*, 1998; Chakraborty *et al.*, 2000b; Paoletti & Lonardo, 2001); in four, the disease was not affected (*Pythium splendens* and *Thielaviopsis basicola,* in *Poinsettia*; *Botrytis cinerea,* in cyclamen; and *Sclerotinia minor,* in lettuce, according to Manning & Tiedemann, 1995); and in two there was a reduction (*Rhizoctonia solani,* in sugar beet and

Phytophthora parasitica, in tomato, according to Manning & Tiedemann, 1995 and Jwa & Walling, 2001); however, in one the results were contradictory (*Rhizoctonia solani*, in cotton, according to Runion *et al.*, 1994). For biotrophic fungi, of ten papers published, seven reported that the disease increased (*Ustilago hordei,* in barley; *Ustilago maydis*, in corn; *Puccinia striiformis, Puccinia graminis tritici*, and *Puccinia recondita tritici*, in wheat; *Puccinia coronata*, in oat; and *Puccinia dispersed*, in rye, according to Manning & Tiedemann, 1995); disease reduction was reported in only one (*Sphaerotheca pannosa,* in rose plants, according to Manning & Tiedemann, 1995), and different results were reported in two (*Erysiphe graminis*, in wheat and barley, according to Thompson *et al.*, 1993, and Hibberd *et al.*, 1996, respectively). These results demonstrate the lack of information on the subject, although fungi are the most studied group. In addition, the effects of CO_2 on the increase or reduction of diseases depend on specific characteristics of the pathosystems.

Open-top chambers (OTC) were installed at Embrapa Meio Ambiente to evaluate the effects of increases in the concentration of CO_2 on epidemiological parameters of plant diseases (Fig. 2). Six open-top chambers were constructed, having circular aluminium structure (2m diameter X 2m tall), sides covered with transparent plastic, and automated CO_2 concentration control. In three of them CO_2 is injected until it reaches twice the concentration in the environment, as evaluated inside the other three chambers. The monocyclic components evaluated are incubation period, latent period, percentage of leaf area with lesions, frequency of infection, infectious period, and sporulation.

4.2. Changes in the geographical distribution of diseases

The increase in the planet's temperature alters the agroclimatic zones and directly interferes with the geographic distribution of plant diseases. A few scant examples of this type of study can be found in the literature (Carter *et al.*, 1996; Boag *et al.*, 1991; Brasier & Scott, 1994; Brasier, 1996).

In Brazil, Ghini *et al.* (2005) and Hamada *et al.* (2005) obtained maps of the spatial distribution of nematodes (races 1, 2, and 4 of *Meloidogyne incognita* in coffee) and the coffee leaf miner (*Leucoptera coffeella*) for current and future scenarios focused on the 2020's, 2050's, and 2080's (extreme scenarios A2 and B2). The future scenarios were obtained from the average of five models (ECHAM4, HadCM3, CGCM1, CSIRO-Mk2b, and CCSR/NIES), made available by IPCC-DDC (2004). The maps were prepared by means of models for the prediction of the number of annual generations of the nematode and leaf miner (Jaehn, 1991; and Parra, 1985), with a spatial resolution of 0.5 × 0.5 degrees of latitude and longitude, using a Geographic Information System (GIS).

The geographic distribution maps obtained for the probable number of generations of *M. incognita* and coffee leaf miner under the future scenarios demonstrate that there could be an increase in infestation when these are compared with the present climatic condition, based on the average of the last 30 years (Fig. 3 and 4). In general, for the 2020's and 2050's, there is little difference between the probable number of annual generations of coffee leaf miner obtained for the A2 and B2 scenarios. These differences are pronounced for the 2080 period, i.e., there is a larger area of the country with a higher number of generations under the A2 scenario than under B2.

A similar tendency was obtained for the coffee *M. incognita* strains, i.e., an increase in the number of annual generations will occur in future scenarios. Races 1 and 2 showed more intense development than race 4, as can also be observed in the current scenario. Because this is a soil-borne plant pathogen, the most important control method consists in the adoption of preventive measures, avoiding the introduction of the nematode in the area. However, after its establishment, a control strategy must be organized, because infestation seriously compromises productivity.

4.3. Effectiveness of control methods

All types of plant disease control are affected by climatic conditions. Changes in precipitation, for example, relative to the duration, intensity, and frequency of rains, have an effect on chemical control. If intense rains occur during the post-application period, many fungicides, for example, could have their effectiveness compromised.

Alterations in the composition of the atmosphere, and in temperature and precipitation, among others, could modify the phyllosphere and rhizosphere microbiota communities that act on the natural biological control of plant diseases. This mode of control can hardly be quantified; however, it is a known fact that it is frequent and its effects are significant.

A direct consequence of the modifications caused by climatic change on pathogen-host relationships occurs in plant genetic resistance to diseases. Many modifications in plant physiology may change the mechanisms of resistance of cultivars obtained both by traditional methods and by genetic engineering. Some forms of resistance can be more affected than others. However, the greatest threat to genetic resistance consists in the acceleration of pathogen cycles, which may undergo changes in all life stages as CO_2 increases. Some papers have verified that, despite the occurrence of a delay in initial development and a reduction in host penetration, established colonies develop at a greater rate, and an increase occurs in the multiplication of the pathogen in the tissues of the plant (Hibberd *et al.*, 1996; Chakraborty *et al.*, 2000a). A more intense multiplication of the pathogen, in connection with a favorable microclimate, due to greater development of plants, favors the occurrence of epidemics.

5. Final considerations

Maintaining the sustainability of agricultural systems directly depends upon plant protection. In a few years, climatic change may alter the present scenario of plant diseases and their management. These changes will certainly have effects on productivity. Therefore, studying the impacts on important plant diseases is essential to minimize yield and quality losses, helping in the selection of strategies to work around problems (Chakraborty *et al.*, 2000a).

Another important aspect is that diseases constitute one of the components of the agroecosystem that can be managed. An immediate necessity exists for determining the impacts of changes on economically important diseases. Plant pathogenic bacteria, for example, are responsible for serious damages in several crops, and there is only one paper in the literature evaluating the effects of increases in CO_2 concentration on diseases caused by this group (Jiao *et al.*, 1999). Secondary diseases must also be studied, since they can assume greater importance. However, in addition to this, plant disease specialists must go beyond their own subject matters and situate the impacts on diseases within a wider context that would involve the entire system.

The zoning of diseases by using climate parameters allows the evaluation of their possible geographic distributions within predicted climatic scenarios. This type of study can be particularly apropriate for exotic pathogens, since it allows an evaluation of their geographic distribution in new regions and the intensity of the importance that the pathogen may take on (Coakley, 1995). However, the lack of available information about the effects of the environment on the occurrence of diseases makes it difficult to use this type of work. Little is known about the environmental factors governing secondary pathogen communities, which could assume a significant importance in future scenarios (Clifford *et al.*, 1996).

Coakley & Scherm (1996) listed some of the most important difficulties found in studies on the effects of global climatic change and plant diseases. Among them, the following are worth noting: the continuous uncertainty about the precise magnitude of the climatic change that will occur in the next 25 to 50 years; the possibility that complex interactions will occur between climatic change components; a limitation of the knowledge about how these changes on a large scale and in the long term will affect the biological processes that take place at the regional and local scales, in a short period of time; and the issue of separating direct effects (for example, on the pathogen) from indirect effects (for example, by the effect on biological control agents or changes in the physiology of the host plant).

Researches intended to assess the effects of global climatic change on plant diseases must be carried out in an interdisciplinary fashion, preferably by means of international programs. The complexity of the processes involved and their interrelations require communication between professionals in the various areas concerned. Communication networks via the Internet have been formed among persons interested on this subject; as a consequence, several direct and indirect benefits have been accomplished (Scherm *et al.*, 2000). Thus, duplicated efforts are avoided and the spread of information and the establishment of partnerships are facilitated.

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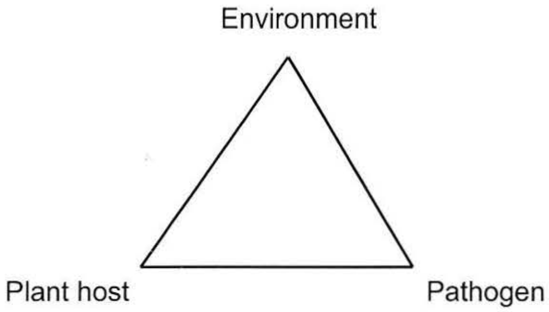

Fig. 1. Disease triangle showing the interaction between the essential elements that determine the occurrence of a plant disease.

Figure 2. Open-top chambers installed at Embrapa Meio Ambiente, Jaguariúna, SP, Brazil.

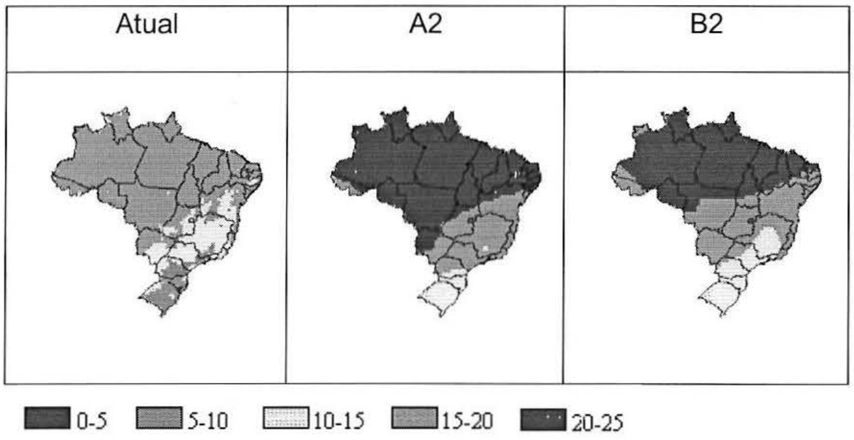

Figure 3. Maps for the likely number of annual generations of coffee leaf miner (*Leucoptera coffeella*) in current and future scenarios (A2 and B2 focused on the 2080's) in Brazil.

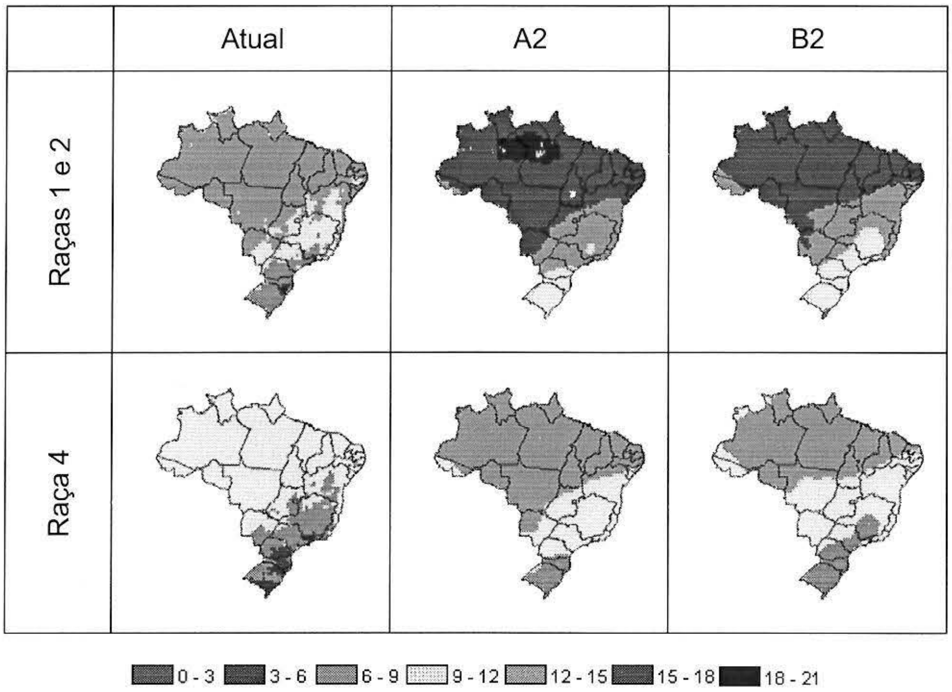

Figure 4. Maps for the likely number of annual generations of *Meloidogyne incognita* races 1, 2, and 4 in coffee in current and future scenarios (A2 and B2 focused on the 2080's) in Brazil.