International Journal of Chemical Studies

P-ISSN: 2349–8528
E-ISSN: 2321–4902
www.chemijournal.com
IJCS 2020; 8(2): 2968-2973

Received: 10-01-2020
Accepted: 12-02-2020

Priyanka
PhD Scholar, Division of Plant Pathology, RARI, Durgapura, SKNAU, Jobner, Rajasthan, India

Anand Kumar Meena
Assistant Professor, Department of Plant Pathology, SKNAU, Jobner, Rajasthan, India

Sunaina Varma
PhD Scholar, Department of Plant Pathology, SKRAU, Bikaner, Rajasthan, India

Virendra Kumar
Assistant Professor, Department of Plant Pathology, Carrier Point University, Kota, Rajasthan, India

RS Sharma
Assistant Professor, Division of Plant Pathology, RARI, Durgapura, SKNAU, Jobner, Rajasthan, India

Corresponding Author:
Priyanka
PhD Scholar, Division of Plant Pathology, RARI, Durgapura, SKNAU, Jobner, Rajasthan, India

Impact of climate change on plant diseases and management strategies: A review

Priyanka, Anand Kumar Meena, Sunaina Varma, Virendra Kumar and RS Sharma

DOI: https://doi.org/10.22271/chemi.2020.v8.i2at.9203

Abstract
Climate change is a major environmental challenge worldwide. Over the past century, human activities have dramatically altered the Earth's atmospheric composition, with significant consequences for the planet's climate, biogeochemistry, ecosystems and societies. Plant diseases are already causing extensive crop losses throughout the world and these extreme weather conditions along with warmer temperature will aggravate these impacts. Change in climate also affect disease management with regard to timing, preference, and efficacy of chemical, physical, and biological measures of control and their utilization within integrated pest management strategies. Climate change is just one of the many ways in which the environment can move in the long term from disease-suppressive to disease-conducive or vice versa. Therefore, plant diseases could be even used as indicators of climate change. Climate change is indeed not only going to threaten plant health, but may in some cases enhance it 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. A limited amount of information on the potential impacts of climate change on plant diseases is available. This overview addresses the need for review of this burgeoning literature by summarizing opinions of previous reviews and trends in recent studies on the impacts of climate change on plant health.

Keywords: Climate change, plant diseases, pathogens, temperature, elevated Co_2

Introduction

Human population size has grown enormously over the last hundred years. This means increase in demand for food, water, home, automobiles and numerous other commodities, these demands are exerting tremendous pressure on our natural resources and also contributing in climate change, which is emerging as a major threat on agriculture, food security and livelihood of millions of people in many places throughout the world (IPCC, 2014). Increasing climate variability with the change in climate is recognized unequivocally. Even with minor deviations from the normal weather, the efficiency of applied inputs and food production is seriously impaired (Rotter *et al*., 1999) [31]. Elevated greenhouse gases, temperature and moisture are the major variables of climate change. The most apparent effect of climate change is on the global mean temperature which is expected to rise between 0.9 and 3.5 ºC by the year 2100 (IPCC, 2007). Variability in rainfall pattern and intensity is expected to be high. Greenhouse gases (CO2 and O3) would result in increase in global precipitation of 2 ± 0.5 ºC per 1ºC warming. Underlying these trends is much spatial and temporal heterogeneity with projections of climate change impacts differing among various regions on the globe. Agriculture production of rainfed regions, which constitute about 65% of the area under cultivation and account for about 40-45% of the total production in India, is expected to suffer severe as a result of climate change (Agarwal, 2003) [1]. Plant diseases are one of the important factors which have a direct impact on global agricultural productivity and climate change will further aggravate the situation. Climate changes affect plant diseases together with anthropogenic processes such as air, water and soil pollution, long-distance introduction of exotic species and urbanization (Regniere, 2012) [30]. With the changing climate patterns and cropping systems, host, pathogen and favorable environment interactions are leading to diseases epidemics in a range of crops. Three essential components are required simultaneously for a disease to occur which include, a virulent pathogen, a susceptible host and favorable environment and the effect over time of the evolutionary forces on living populations leading to new disease epidemics often referred as "disease tetrahedron". Some authors agree that when plants become weakened or stressed by environmental factors, microorganisms can easily colonize plants thereby causing plant death (Moricca and Ragazzi, 2008; Moricca *et al.*, 2016) [20, 21].

Climate variability is also adding a new dimension to managing plant diseases by altering the equilibrium of host-pathogen interactions resulting in either increased epidemic outbreaks or new pathogens surfacing as threats or less known pathogens causing severe yield losses. The purpose of this review paper is to discuss the climate variables and how they affect the plant diseases, crop growth, development and production.

Climate change as a driver for plant diseases emergence

Plant diseases are one of the important factors which have a direct impact on global agricultural productivity and climate change will further aggravate the situation. The complexities of climate change and the biotic responses to this, makes prediction of the future impact of climate change on emerging infectious diseases of plants difficult. Climate change may affect plant pathosystems at various levels *viz*. from genes to populations, from ecosystem to distributional ranges; from environmental conditions to host vigour or susceptibility; and from pathogen virulence to infection rates. In general, climate variability has shown positive and negative impacts on host-pathogen interactions. However, in general climatic changes could result in following changes in diseases or pathogens, extension of geographical range, increased over-wintering, growth rates changes in population, increased number of generations, loss of resistance in cultivars, crop development season extension, crop diseases synchrony changes and changes in inter-specific interactions etc. For example, Spot blotch disease is particularly important under conditions of high relative humidity and high temperature and has become a major production constraint of wheat in South Asia and Latin America. This increase has been linked to climate change and increased temperature (Sharma *et al*., 2007) [35], dry root rot of chickpea caused by *Rhizoctonia bataticola* is becoming more severe in rainfed environments as the host plant is predisposed by moisture stress and higher temperatures during the flowering to pod filling stage (Pande *et al*., 2010) [25]. Weather and dry root rot disease data collected in India for one decade showed higher incidence of dry root rot in chickpea varieties that resist Fusarium wilt in years when temperatures exceed 33 ºC (Pande *et al.*, 2010; Sharma *et al*., 2010) [25, 36]. On the contrary, cooler temperature and wetter conditions are associated with increased incidence of stem rot on soybean (*Sclerotinia sclerotiorum*), blights (*Ascochyta* spp.) in chickpea, lentil, pea; and anthracnose in chickpea and lentil (Pande *et al*. 2010, Panagga *et al.*, 2004) [25, 26].

Another climate variable, moisture can impact both host plants and pathogens in various ways. For example high moisture favors most of the foliar diseases and some soil borne pathogens such as, *Pythium, Phytophthora, Sclerotium rolfsii* and *Rhizoctonia solani* etc. An outbreak of Phytophthora blight of pigeonpea (*Phythophthora drechsleri* f. sp. *cajani*) in Deccan Plateau of India is attributed to erratic and heavy rainfall (>300mm in 6-7 days) leading to temporary flooding (Sharma *et al*., 2006; Pande *et al*., 2011). Alternaria blight of pigeonpea is being seen more frequently in recent years in semi-arid tropic regions due to the untimely rainfall (Sharma and Pande, unpublished). The bacterium has been linked to nosocomial outbreaks (Gaston, 1988; Van den Berg *et al*., 2000) [12, 39] but was reported as a plant pathogen causing disease on onion (*Allium cepa* L.) in the USA (Bishop and Davis, 1990). Later, this bacterium affected many hosts including, macadamia (*Macadamia integrifolia* Maiden & Betche) in Hawaii (Nishijima *et al*., 2007) [23]; dragon fruit (*Hylocereus* spp.) in Malaysia (Masyahit *et al*., 2009) [18]; mulberry (*Morus* L.) in China (Wang *et al*., 2010) [41]; lucerne (*Medicago sativa* L.) seeds in China (Zhang and Nan, 2013) [42]; cassava (*Manihot esculenta* Crantz) in Venezuela (Santana *et al*., 2012); and chili pepper (*Capsicum annuum* L.) in Mexico (Garcia-Gonzalez *et al*., 2018, to be published.

Most of the available data clearly suggests that increased CO2 would affect the physiology, morphology and biomass of crops (Challinor *et al.*, 2009) [7]. Elevated CO2 and associated climate change have the potential to accelerate plant pathogen evolution, which may, in turn, affect virulence. Pathogens fecundity increased due to altered canopy environment and was attributed to the enhanced canopy growth that resulted in conducive microclimate for pathogen's multiplication (Pangga *et al*., 2004) [26]. Foliar diseases like Ascochyta blights, Stemphylium blights and Botrytis gray mold can become a serious threat in pulses under the higher canopy density. Increased CO2 will lead to less decomposition of crop residues and as a result soil borne pathogens would multiply faster on the crop residues. The close relationship between the environment and diseases also suggests that climate change will cause modifications in the current phytosanitary scenario. Bebber (2019) [3] analysis report showed that Black Sigatoka infection risk has increased significantly across the banana-growing regions of Latin America and the Caribbean, increasing by a median of 44.2% per pixel from the 1960s to the 2010s and this increase in risk was caused by climate change that improved the temperature conditions for spore germination and growth and made crop canopies wetter.

Changing scenario of plant diseases and pathogens

Climate change is just one of the many ways in which the environment can move in the long term from disease-suppressive to disease-conducive or vice versa (IPCC, 2013) [15]. Climate change will allow survival of plants and pathogens outside their existing geographical range. Parameters like elevated temperatures, carbon dioxide concentration, and rainfall pattern, altogether climate change influence the development of both hosts, pathogen which ultimate impact can be seen in disease development.

Effect of elevated Co_2 and o_3 concentration on diseases

The concentration of Co_2 in the atmosphere has continuously increased from pre-industrial levels at 280 ppm to about 395 ppm at present, and is expected to reach above 700 ppm by the end of the century (IPCC, 2013) [15], which exceeds the natural range of values of the past 650,000 years. The main causes of this global increase of Co_2 are fossil fuel burning and deforestation (Paterson and Lima, 2010). This increase in Co_2 concentration along with other green house gases contributing in increase in the global average temperature of 0.6–0.7 °C over the last century (Walther *et al.*, 2002) [40]. Increased Co_2 levels can impact both the host and the pathogen in multiple ways. An increase in Co_2 levels may encourage the production of plant biomass. However, productivity is regulated by the availability of water and nutrients, competition against weeds and damage by pests and diseases. Elevated temperature, Co_2 concentration with other changed climatic factors which favouring plant pathogens to grow well and also outbreak of various sleeper pathogens to cause heavy damage to our crop plants. New races of the pathogen may evolve rapidly under elevated temperature and Co_2, as evolutionary forces act on massive pathogen populations boosted by a combination of increased infection cycles and fecundity under favourable microclimate within enlarged canopy (Chakraborty, 2013) [5]. Consequently, a high concentration of carbohydrates in the host tissue promotes the development of biotrophic fungi such as rust. Thus, an increase in biomass can modify the microclimate and affect the risk of infection. In general, increased plant density will tend to increase leaf surface wetness duration and regulate temperature, and thus make infection by foliar pathogens more likely. Some workers also suggest that elevated Co_2 concentration and climate change may accelerate plant pathogen evolution, which can affect virulence. According to Braga *et al*. (2006), the exposure to Co_2-enriched atmospheres can change inducible defensive responses in plants against pathogens. Some of the other observed Co_2 effects on disease may counteract others. Lesser plant decomposition rates observed in high Co_2 situations could increase the crop residue on which disease causing pathogen can overwinter, resulting in higher inoculum potential at the beginning of the growing season which results into earlier and faster disease epidemics. Kobayashi *et al*., 2006 [16] also reported that rice plants grown in an elevated Co_2 concentration were more susceptible to leaf blast than those in ambient Co_2 concentration. Fungicide and bactericide efficacy may change with increased Co_2, moisture, and temperature.

Under elevated Co_2 conditions, potential dual mechanism of reduced stomata opening and altered leaf chemistry results in reduced disease incidence and severity in many plant pathosystems where the pathogen targets the stomata. In soybean, elevated concentration of Co_2 and O_3 altered the expression of three soybean diseases, namely downy mildew (*Peronospora manshurica*), brown spots (*Septoria glycines*) and sudden death syndrome (*Fusarium virguliforme*) and plant response to the diseases varied considerably. Changes brought by high Co_2 concentration like reduced stomatal density, production of papillae and accumulation of silicon at the sites of appressorial penetration and changed leaf chemistry increased resistance to powdery mildew (*Blumeria graminis*) in barley.

Effect of elevated concentrations of Co_2 has also been evaluated on two important diseases of rice, namely blast (*Pyricularia oryzae*) and sheath blight (*Rhizoctonia solani*) and rice plants were found more susceptible to injury. In addition to high disease incidence and severity due to changes in host, reproduction of the pathogens has also been reported to increase at high Co_2 levels in barley powdery mildew and anthracnose (*Colletotrichum gloeosporioides*). Overall, the effects of elevated Co_2 concentration on plant diseases can be positive or negative, although in a majority of the cases disease severity increased (Zhou *et al.*, 2017) [43].

Effect of increase in temperature on plant diseases

Temperature has potential impacts on plant disease through both the host crop plant and the pathogen. A change in temperature may favor the development of different inactive pathogens, which could induce an epidemic. Plant pathogens require a ranges of optimum temperature that affect the various steps in disease infection cycles such as penetration, pathogen survival, dispersal, epidemic development, survival and sexual reproduction. Many studies indicated that colony area, number of hyphal tips, conidiophores and conidia per colony were significantly greater at temperature ranging from 22 to 28 °C compared to standard conditions. Due to changes in temperature and precipitation regimes, climate change may alter the development rate, growth stage, pathogenicity of infectious agents, and the physiology and resistance of the host plant (Charkraborty and Datta, 2003) [6]. Few studies have shown that wheat and oats become more susceptible to rust diseases with increased temperature (Coakley *et al.*, 1999) [8]. Change in temperature might lead to appearance of new races of pathogens until now not active, but which might cause a sudden epidemic (Reddy, 2013) [29]. In India report of Singh *et al*., 1988 in red rot of sugarcane (*Colletotrichum falcatum*), reaction of cultivars shift towards resistance under low temperature of January conditions and cultivars shift to susceptibility under higher temperature of August. Again report of Williamson, 1998 in his root knot disease found that root knot resistance gene Mi (Mi-1) derived from *Lycopersicum peruvianum* is not effective at temperatures above 30 °C, but some other genes may express at other temperature conditions like 32 °C, 25 °C. Debela and Tola (2018) [9] noted that elevated temperature and CO2 significantly stimulated disease index. There was a clear increment of growth of the pathogen, fecundity and severity of the disease observed at the higher temperature-higher CO2 combination compared with control temperature combinations in particular with higher CO2 at standard temperatures. A change in temperature could directly affect the spread of infectious diseases and their survival between seasons. Some evidence suggests that sunlight affects plant pathogens due to the accumulation of phytoalexins or protective pigments in host tissue. There are indications of increased aggressiveness at higher temperatures of stripe rust isolates (*Puccinia striiformis*), suggesting that rust fungi can adapt to and benefit from higher temperatures (Milus *et al*. 2006) [19]. The general trend of the response of soil-borne pathogens shows increasing growth in the coldest areas of Europe; however, a larger rate of increase is predicted from 2020 to 2030 compared to that of 2000 to 2020. Climate change is also reported to cause a shift in the geographical distribution of host pathogens. A change in temperature may favour the development of different dormant pathogens, which could induce an epidemic. Like the effect of elevated temperature on late blight at global level revealed that with rise in global temperature of 2 °C, there will be lower risk of late blight in warmer areas (<22 °C) and higher risk in cooler areas (>13 °C) with early onset of the epidemics (Singh *et al*., 2013). Increase in temperature with sufficient soil moisture may increase evapotranspiration resulting in humid microclimate in crops and may lead to incidence of diseases favoured under these conditions. Considering the consequences of warmer temperatures on host-pathogen interactions and it is concluded that there will be three main effects occurs which are increases in pathogen development rate, transmission, and generations per year, Increases in overwintering of pathogens, and Changes in host susceptibility to infection. Most heat-loving plant pathogenic bacteria like, *Acidovorax avenae* subsp. *aveane*, *Ralstonia solanacearum* and *Burkholderia glumea* have emerged as serious problem worldwide (Schaad 2008). Thus, bacteria could proliferate more in areas where temperature-dependent diseases have not been previously observed (Kudela, 2009) [17]. Anon. (2008) [2] reported that

Rhizoctonia solani produced symptoms in the form of scattered lesions after 3 days of inoculation at temperature range 26.0- 33.3 °C and relative humidity 84- 86 per cent as compared to temperature range 8.8-20 °C and relative humidity 86-92 per cent after 20 days of inoculation. In general, increase in temperature would significantly raise the severity and spread of plant diseases but quantity of precipitation could act as regulator in deciding the increase or decrease in disease severity and spread. 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 (Perkins *et al*., 2011) [28]. Huot *et al*. (2017) [14] show that elevated temperature significantly increases the susceptibility of Arabidopsis to *Pseudomonas syringae* pv. Tomato (Pst) DC3000 independently of the phyB/PIF thermo sensing pathway. Instead, elevated temperature promotes translocation of bacterial effectors proteins into plant cells and causes a loss of ICS1-mediated salicylic acid (SA) biosynthesis. Soil temperature profiles will also have a specific impact on soil-borne diseases, such as clubroot (*Plasmodiophora brassicae*) and *Verticillium longisporum*.

Effect of changed moisture on the disease

Moisture also plays significant role in disease development. It have impact on both host plants and pathogen in various ways and generally it is seen that in most of the foliar diseases temperature and moisture together plays very important role in disease occurrence and development, like Some pathogens such as apple scab, late blight, and several vegetable root pathogens are more likely to infect plants with increased moisture – forecast models for these diseases are based on leaf wetness, relative humidity and precipitation measurements. Some pathogens are unable to infect its host without sufficient surface moisture as seen in oomycetes because these fungi are greatly dependent on high humidity levels for all stages of the life cycle, including sporangia formation (Sanogo and Ji, 2013) [32], and especially so for the indirect germination of sporangia in the form of zoospores, and other pathogens like the powdery mildew species tend to thrive in conditions with lower moisture. Condition of drought is also expected to lead to increased frequency of tree pathogens due to indirect effects on host physiology. In Italy, the invasive exotic species *Heterobasidion irregulare* appears to be well adapted to dispersal in the Mediterranean climate than the native *H. annosum* species. Drought stress has been found to affect the incidence and severity of viruses such as *Maize dwarf mosaic virus* and *Beet yellows virus*. More frequent and extreme precipitation events that are predicted by some climate change models could result in longer periods with favourable pathogen environments. Host crops with canopy size limited by lack of moisture might no longer be so limited and may produce canopies that hold moisture in the form of leaf wetness or high-canopy relative humidity for longer periods, thus increasing the risk from pathogen infection.

In addition, other changes like concentration of CH_4, other greenhouse gases, UV light and sunshine hours will also have different impacts on pathogens and host– pathogen interactions, resulting in varied response in incidence and severity of diseases. Ultraviolet radiation plays an important role in natural regulation of diseases. Evolution of pathogen populations may accelerate from enhanced UV-B radiation and/or increased reproduction in elevated CO_2. Effect of UV-B radiation has been reported to be inconsistent. Evidence suggests that sunlight affects pathogens due to the accumulation of phytoalexins or protective pigments in host tissue.

Disease management strategies

Disease management strategies depend upon climate conditions. Change in climate will cause alterations in the disease geographical and temporal distributions and consequently control methods will have to be adapted to climate change scenarios. Since regional impacts of climate change on plant diseases will be more, disease management strategies will require adjustments. As a consequence of all these potential impacts of climate change on the health of plants and their associated organisms, there is increasing recognition that we need to develop strategies for long-term adaptation. Although physiological changes in host plants may result in higher disease resistance under climate change scenarios, the durability of resistance may be threatened and may lead to more rapid evolution of aggressive pathogen races (Hibberd *et al*., 1996) [13]. Key soil aspects for microbial activity will also be modified due to climate change, such as the population dynamics of beneficial microorganisms such as rhizobia, biocontrol agents and mycorrhizal fungi. In addition, the amount of nitrogen introduced into natural and agricultural systems through fertilizers and pollutants can cause significant impacts on the microbiota (Nosengo, 2003) [24]. Smith and Read (2008) suggested that arbuscular mycorrhizal fungi can modulate plant responses to elevated CO2 by increasing resistance/tolerance of plants against an array of environmental stresses. Under elevated CO2 conditions, mobilization of resources into host resistance through various mechanisms such as reduced stomata density and conductance (Hibberd *et al*., 1996) [13]; greater accumulation of carbohydrates in leaves; more waxes, extra layers of epidermal cells and increased fiber content and increased biosynthesis of phenols (Hartley *et al*., 2000), increased tannin content (Parsons *et al*., 2003) [27] have been reported. Changes in temperature and high precipitation can alter fungicide residue dynamics in the foliage and the degradation of products can be modified. The efficacy of fungicides may change with changes in climate variables. For example more frequent rainfall events could make it difficult for farmers to use the fungicides on plants leading to more frequent applications.

In addition to refinement in the existing management practices, there is a need for simulation models to assess the potential of emerging pathogens for a given crop production system and also shift in pathogen populations/fitness that may demand modifications in current production systems. Forecasting models which allows investigating multiple scenarios and interactions simultaneously will become most important for disease prediction, impact assessment and application of disease management measures. Many weather driven epidemiological models have been developed and used to predict plant disease epidemics under variable climate (Serge *et al,* 2011) [34]. Most forecasting models are meant for tactical and strategic decisions (Garret *et al.*, 2010). Another modeling is ecological niche modeling or species distribution models to anticipate the potential geographical range (Serge *et al.,* 2011) [34]. Recently, Geographic information system (GIS) is commonly used to evaluate and model the spatial distribution of plant disease in relation to environmental factors. Using GIS, Phytophthora blight of pigeonpea was monitored in the major pigeonpea growing areas in India indicating that Phytophthora blight occurs on improved as well as local cultivars of pigeonpea irrespective of soil types and cropping systems (Pande *et al*., 2010) [25]. Biological control agents are ecologically and environmentally safe option for disease management. Biological control agents (BCAs) may be effective either upon introduction by application or through strengthening their natural occurrence because their effectiveness requires specific, conducive environmental conditions. If appropriate temperature and moisture are not consistently available due to changing climate change, BCA populations may fail to reduce disease incidence and severity, and may not recover as rapidly as pathogen populations when conducive conditions reoccur. Vulnerability of BCAs will be higher under climate change, because if climate variability becomes greater it would impose difficulties on the survival and activity of applied antagonists. In spite of potential problems when applying BCAs research efforts must be strengthened to develop biocontrol measures with more tolerance to variable conditions.

Adaptation Measure for Climate Change

- Integrated pest management
- Using available early warning system for diseases.
- Biological control measures.
- Utilization of indigenous traditional knowledge base for disease control.
- Soil solarization technique
- Breeding for disease, pest and drought resistance varieties.
- Careful tracking of geographical distribution of plant virus diseases and their vectors.
- Phytosanitary regulations to prevent or limit the introduction to risky plant pathogens.

Conclusion

Regional impacts of climate change on plant disease management strategies need a relook using forecasting models and biotechnological approaches in understanding the emerging scenario of host pathogen interactions. Models of plant disease have now been developed to incorporate more sophisticated climate predictions from general circulation models.

Epidemiological knowledge, combined with biophysical and socio-economical understanding are required to deploy resistances and achieve sustainable disease management. There is a need for a greater understanding of the effect of climate variables on the efficacy of synthetic fungicides, their persistence in the environment, and development of resistance in pathogens populations to the fungicides. Recently, national and international net work is also actively anticipating and responding to biological complexity in the effects of climate change on agriculture and crop diseases (Serge *et al*., 2011) [34]. The primary benefit of such studies to growers will be their ability to control the diseases that become severe as result of climate change, select varieties that are less vulnerable for diseases, and reduce fungicide application. The information will be useful to the crop growers, scientists and extension agencies, NGOs, research planners, and administrators.

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