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 CO2

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 cm 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 surfaceing 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 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 °C (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 (Phytophthora drechsleri f. sp. cajanii) 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 & Betchè) in Hawaii (Nishijima et al., 2007) [23]; dragon fruit (Hylocereus spp.) in Malaysia (Masyahat 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. Bebb (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 CO2 and O3 concentration on diseases

The concentration of CO2 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 CO2 are fossil fuel burning and deforestation (Paterson and Lima, 2010). This increase in CO2 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 CO2 levels can impact both the host and the pathogen in multiple ways. An increase in CO2 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 sleepy 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 disease 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 (Chakraborty 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 CO$_2$ 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 CO$_2$ combination compared with control temperature combinations in particular with higher CO$_2$ 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 avenue 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
**Effect of changed moisture on the disease**

Moisture also plays significant role in disease development. It has 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. However, it is also seen that in some cases of fungal diseases, condition of host that has increased moisture can affect the disease development. For example, some disease symptoms that appear in leaf wetness may be reduced when the leaf is dry. In these cases, the climate conditions that are favorable for disease development are not always the same as the ones that are favorable for disease control. Therefore, it is important to consider both climate and host factors when developing disease management strategies.

In addition, other changes like concentration of CH4, 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 CO2. 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. Thus, bacteria 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) [29]. 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, 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.

References

1. Aggarwal PK. Impact of climate change on Indian agriculture, J Plant Biology. 2003; 30(2):189-198

2. Anonymous. Annual report on assessment of vulnerability of crop yield to pest damage in global climate change, Directorate of Maize Research, Pusa, New Delhi, 2008.

3. Bebber PD. Climate change effects on Black Sigatoka disease of banana. Phil. Trans. R. Soc. 2019, B374: 20180269. http://dx.doi.org/10.1098/rstb.2018.0269.

4. Bishop AL, Davis RM. Internal decay of onions caused by Enterobacter cloaceae. Plant Dis. 1990; 74(9):692-694.

5. Chakraborty S. Migrate or evolve: Options for plant pathogens under climate change. Glob Chang Biol. 2013; 19:1985-2000.

6. Chakraborty S, Datta S. How will plant pathogens adapt to host plant resistance at elevated CO2 under a changing climate? New Phytol. 2003; 159:733-742.

7. Challinor AJ, Ewert F, Arnold S, Simelton E, Fraser E. Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. J Exp. Bot. 2009; 60(10):2775-2789.

8. Coakley SM. Variation in climate and prediction of disease in plants. Ann. Rev. Phytopath. 1999; 26:163-8

9. Debela C, Tola M. Effect of Elevated CO2 and Temperature on Crop-Disease Interactions under Rapid Climate Change. Int J Environ Sci Nat Res. 2018; 13(1):555851. DOI: 10.19080/IJESNR.2018.12.555851.

10. EPPO (European and Mediterranean Plant Protection Organization) PQR-EPPO database on quarantine pest, 2016. Available from: http://www.eppo.int/DATABASES/pqr/pqr.htm.

11. FAO. Climate change, Agriculture and Food Security [Internet]. Agriculture Organization, 2008. Available from: http://www.fao.org/faostat/en/#data/RF

12. Gaston MA. Enterobacter: An emerging nosocomial pathogen. J Hosp. Infect. 1988; 11(3):197-208.

13. Hibberd JM, Whitbread R, Farrar JF. Effect of elevated concentrations of CO2 on infection of barley by Erysiphe graminis. Physiological and Molecular Plant Pathology 48:37-53 seedlings. Plant Pathol. J. 1996; 34(1):1-10.

14. Huot B, Castroverde MDC, Velásquez CA, Hubbard E, Jane A, Yao JP et al. Dual impact of elevated temperature on plant defence and bacterial virulence in Arabidopsis. Nature Communications. 2017; 8:1808 DOI: 10.1038/s41467-017-01674-2.

15. IPCC Climate Change. The Physical Science Basis Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK: Cambridge University Press, 2013.

16. Kobayashi T, Nakajima T, Hamasaki T, Ishiguro K. A method for artificial inoculation of rice blast fungus using clear cover materials in the field. Annu. Rep. Plant Prot. North Jpn. 2006; 52:21-23

17. Kudela V. Potential impact of climate change on geographic distribution of plant pathogenic bacteria in Central Europe. Plant Protect. Sci. 2009; 45:S27-332.

18. Masyahit M, Sijam Y, Ghazali M. First report on bacterial soft rot disease on dragon fruit (Hylocereus spp.) caused by Enterobacter cloacae in peninsular Malaysia. Int. J Agric. Biol. 2009; 11:659-666.

19. Milus EA, Seyran E, McNew R. Aggressiveness of Puccinia striiformis f. sp. tritici isolates in the south-central United States. Pl. Dis. 2006; 90(7):847-852.

20. Moricca S, Ragazzi A. Fungal endophytes in Mediterranean oak forests: A lesson from Discalia quercina. Phytopathol. 2008; 98(4):380-386.
21. Moricca S, Linaldeddu BT, Ginetti B, Scanu B, Franceschini A, Ragazzi A. Endemic and emerging pathogens threatening cork oak trees: Management options for conserving a unique forest ecosystem. Plant Dis. 2016; 100(11):2184-2193.

22. Mostert L, Bester W, Jensen T, Coertze S, van Hoorn A, Le Roux J et al. First report of leaf rust of blueberry caused by Thekopsora minima on Vaccinium corymbosum in the Western Cape, South Africa. Plant Dis. 2010; 94(4):478-478.

23. Nishijima KA, Wall MM, Siderhurst MS. Demonstrating pathogenicity of Enterobacter cloacae on macadamia and identifying associated volatiles of gray kernel of macadamia in Hawaii. Plant Dis. 2007; 91(10):1221-1228.

24. Nosengo N. Fertilized to death. Nature, 2003; 425:894-895.

25. Pande S, Sharma M, Mangala UN, Ghosh R, Sundaresan G. Phytophthora blight of Pigeonpea [Cajanus cajan (L.) Millsp.]: An updating review of biology, pathogenicity and disease management. Crop Protection. 2010; 30:951-957.

26. Panga IB, Chakraborty S, Yates D. Canopy size and induced resistance in, 2004.

27. Parsons WFJ, Kopper BJ, Lindroth RL. Altered growth and fine root chemistry of Betula papyrifera and Acer saccharum under elevated CO2. Canadian J Forest Res. 2003; 33:842-846.

28. Perkins LB, Leger EA, Nowak RS. Invasion triangle: an organizational framework for species invasion. Ecology and evolution. 2011; 1(4):610-625.

29. Reddy P. Impact of climate change on insect pests, pathogens and nematodes. Pest Management in Horticultural Ecosystems. 2013; 19(2):225-233.

30. Regniere J. Invasive Species, Climate Change and Forest Health. Natural Resource Canada. ISBN 978-94-007-2575-1, 2012

31. Rotter R, Van de Geijn SC. ‘Climate change effects on plant growth, crop yield and livestock’, Climate Change. 1999; 43(4):651-681.

32. Sanogo S, Ji P. Water management in relation to control of Phytophthora capsici in vegetable crops. Agricultural Water Management. 2013; 129:113-119

33. Sato S, Katsuya K, Hiratsuka Y. Morphology, taxonomy and nomenclature of Tsuga-Ericaceae rusts. Trans. Mycol. Soc. Japan. 1993; 34(1):47-62.

34. Serge S, Andrew N, Sparks A, Willocquet HL, Duveiller E, Mahuku G et al. International Agricultural Research Tackling the Effects of Global and Climate Changes on Plant Diseases in the Developing World. Plant Disease. 2011; 59:1204-1216

35. Sharma RC, Duveiller E, Ortiz-Ferrara G. Progress and challenge towards reducing wheat spot blotch threat in the Eastern Gangetic Plains of South Asia: is climate change already taking its toll? Field Crops Research 2007; 103:109-18.

36. Sharma M, Mangala UN, Krishnamurthy M, Vadez V, Pande S. Drought and dry root of chickpea. In: 5th International Food Legumes Research Conference (IFLRC V) & 7th European Conference on Grain Legumes (AEP VII) April 26-30, 2010- Antalya, Turkey, 2010.

37. Sharma M, Pande S, Pathak M, Rao IN, Kumar A, Reddy M et al. Prevalence of Phytophthora blight of pigeonpea in the Deccan Plateau of India. The Plant Pathology Journal. 2006; 22(4):309-313.

38. Tasmanian Government. Biosecurity Tasmania Fact Sheet. Blueberry Rust (Thekopsora minima P. Syd & Syd). 2014. Available from: http://www.dpipwe.tas.gov.au/Documents/BT_BlueberryRust_factsheet092014.pdf.

39. Van den Berg, Faulks R, Granado F, Hirschberg J, Olmedilla B, Sandmann G et al. The potential for the improvement of carotenoid levels in foods and the likely systemic effects. J Sci. Food Ag. 2000. https://doi.org/10.1002/(SICI)10970010(20000515)80:7<880::AID-JSFA646>3.0.CO;2-1

40. Walther GR, Post E, Convey P, Menzel A, Parmesank C, Beebee TJC et al. Ecological responses to recent climate change. Nature. 2002; 416:389-395.

41. Wang GF, Xie GL, Zhu B, Huang JS, Liu B, Kawicha P et al. Identification and characterization of Enterobacter complex causing mulberry (Morus alba) wilt disease in China. Eur. J Plant Pathol. 2010; 126(4):465-478.

42. Zhang ZF, Nan ZB. Occurrence of lucerne seedborne Enterobacter cloacae sprouts decay in Gansu Province of China. Eur. J Plant Pathol. 2013; 135(1):5-9.

43. Zhou Y, Vroeogp-Vos I, Schuurink RC, Pieterse CMJ, Wees SCV. Atmospheric CO2 alters resistance of arabidopsis to Pseudomonas syringae by affecting abscisic acid accumulation and stomatal responsiveness to coronatine. Frontier in Plant Sciences. 2017; 8: Article 700. DOI:10.3389/fpls.016.01680.