Climate change and its impact on plant diseases

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Climate change is the biggest threat to mankind, and is the cause of nearly 0.4 million deaths a year worldwide and costing the world more than US$ 1.2 trillion. Climate change is affecting our agriculture due to 0.74°C average global increase in temperature in the last 100 years and atmospheric CO_2 concentration increase from 280 ppm in 1750 to 400 ppm in 2013. Such changes will have a drastic effect on the growth and cultivation of the different crops on the Earth. Simultaneously, these changes will also affect the reproduction, spread and severity of many plant pathogens, thus posing a threat to our food security. Climate change is also putting stem rust resistance due to Sr31 under threat of Ug99 race of stem rust caused by Puccinia graminis f. sp. tritici. Elevated temperature and CO_2 concentration are also posing higher threat perception of late blight (Phytophthora infestans) disease of potato and important diseases of rice, namely blast (Pyricularia oryzae) and sheath blight (Rhizoctonia solani). Changing disease scenario due to climate change has highlighted the need for future studies on such models which can predict the severity of important pathogens of major crops in real-field conditions. Simultaneously, disease management strategies should be reoriented in changing conditions with amalgamation of new strategies for sustainable food production.

Keywords: Climate change, disease threat, food security, plant pathogens.

CLIMATE change is the biggest threat of the present century. According to a study[1], it is already contributing to the death of nearly 400,000 people a year and costing the world more than US$ 1.2 trillion, thus wiping 1.6% annually from the global GDP. Climate change is the result of the acceleration in the increase in temperature and CO_2 concentration over the last 100 years. During the period[2], the global mean temperature has increased by 0.74°C and atmospheric CO_2 concentration has increased from 280 ppm in 1750 to 400 ppm in 2013. Changes in climate are still going unabated and temperature is projected to increase by 3.4°C and CO_2 concentration to 1250 ppm by 2095 under the A2 scenario, accompanied by much greater variability in climate and more extreme weather-related events[3]. The impacts are being felt most keenly in developing countries, where damage to agricultural production from extreme weather linked to climate change is contributing to deaths from malnutrition, poverty and their associated diseases[4]. Throughout the 21st century, India is projected to experience warming above the global mean. A warming trend has been observed along the west coast, in central India, the interior peninsula and Northeast India. A single factor of climate change like temperature can have a catastrophic effect on crop yield. Temperature increases of 1°C, 2°C and 3°C in Punjab, would reduce the grain yield of rice by 5.4%, 7.4% and 25.1% respectively[5]. However, cooling trends have been observed in northwest India and parts of South India[6]. Rainfall data for the last 100 years at the all-India level do not show any significant trend. However, at the regional level, increasing monsoon seasonal rainfall has been found along the west coast, northern Andhra Pradesh and northwestern India, while a trend of decreasing monsoon seasonal rainfall has been observed over eastern Madhya Pradesh, NE India and some parts of Gujarat and Kerala. The possible changes in temperature, precipitation, concentration of CO_2, CH_4, nitrous oxide (N_2O) and O_3 are expected to have significant impact on crop growth.

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[7]. Combined infestation of pests and diseases in plants could result up to 82% losses in attainable yield in case of cotton and over 50% losses for other major crops and if we combine these losses with post-harvest spoilage and deterioration in quality; these losses become critical particularly for resource poor regions of the world[8]. Further, plant diseases are estimated to cause yield reduction of almost 20% in the principal food and cash crops worldwide[9]. In the last 40 years, effective management of pests

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and diseases has played a key role in doubling food production, but pathogens still claim 10–16% of the global harvest[10]. It covered eight crops that together occupy half the world's cropland. In Asia, 14.2% of the potential production costing about US$ 43.8 billion is lost due to diseases[11]. Climate models predict a gradual rise in CO_2 concentration and temperature all over the world, but are not precise in predicting future changes in local weather conditions. Local weather conditions such as rain, temperature, sunshine and wind in combination with locally adapted plant varieties, cropping systems and soil conditions can maximize food production as long as plant diseases can be controlled. Currently, we are able to secure food supplies under these varying conditions. However, all climate models predict that there will be more extreme weather conditions, with more droughts, heavy rainfall and storms in agricultural production regions. Such extreme weather events will influence where and when diseases will occur, and therefore impose severe risks on crop failure.

Effect of increased CO_2 concentration on pathogens

The concentration of CO_2 in the atmosphere reached 379 ppm in 2005, which exceeds the natural range of values of the past 650,000 years[3]. 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. Consequently, a high concentration of carbohydrates in the host tissue promotes the development of biotrophic fungi such as rust[12]. 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[13]. Some workers suggest that elevated CO_2 concentration and climate change may accelerate plant pathogen evolution, which can affect virulence. 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[14]. 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[15]. 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[16]. The severity of downy mildew damage was significantly reduced at high levels of CO_2. In contrast, high levels of CO_2 alone or in combination with high concentration of O_3, increased the severity of *Septoria* leaf spots. The concentration of CO_2 and O_3 did not have an effect on sudden death syndrome. The workers concluded that high levels of CO_2 and O_3 induced changes in the soybean canopy density and leaf age, which likely contributed to disease expression modification. 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[17]. 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*)[16,18]. 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[19].

Effect of increase in temperature

Changes in temperature and precipitation regimes due to climate change may alter the growth stage, development rate and pathogenicity of infectious agents, and the physiology and resistance of the host plant[20,21]. A change in temperature could directly affect the spread of infectious diseases and their survival between seasons. 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[22]. Climate change is also reported to cause a shift in the geographical distribution of host pathogens[23]. A change in temperature may favour the development of different dormant pathogens, which could induce an epidemic. 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[14]. Diseases such as common bunt (*Tilletia caries*) and Karnal bunt (*Tilletia indica*) in wheat can be of importance under changing climatic conditions in regions with low productivity if proper seed treatment is not followed in this crop[24]. In India, in the last decade the disease scenario of chickpea and pigeon pea has changed drastically; dry root rot (*Rhizoctonia bataticola*) of chickpea and *Phytophthora* blight (*Phytophthora drechsleri* f. sp. *cajani*) of pigeon pea have emerged as a potential threat to the production of these pulses[25]. Higher risk of dry root rot has been reported in *Fusarium* wilt chickpea-resistant varieties in those years when the temperature exceed 33°C (ref. 26). In North America, needle blight (*Dothistroma septosporum*) is reported to be spreading northwards with increasing temperature and precipitation[27]. 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[28]. 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[29]. Similarly, the incidence of most of the virus and other vector-borne diseases will be altered. This is because climate can substantially influence the development and distribution of vectors. Genetic changes in the virus through mutation and recombination, changes in the vector populations and long-distance transportation of plant material or vector insects due to trade of vegetables and ornamental plants have resulted in the emergence of tomato yellow leaf curl disease, African cassava mosaic disease, diseases caused by bipartite begomoviruses in Latin America, *Ipomovirus* diseases of cucurbits, tomato chlorosis caused by criniviruses, and the torrado-like diseases of tomato[30]. Temperature can also affect disease resistance in plants, thus affecting the incidence and severity of the diseases. Temperature sensitivity to resistance has been reported for leaf rust (*Puccinia recondita*) in wheat, broomrape (*Orobanche cumana*) in sunflower, black shank (*Phytophthora nicotianae*) in tobacco and bacterial blight (*Xanthomonas oryzae* pv. *oryzae*) in rice[31].

Effect of changed moisture regime on the disease scenario

Moisture can impact both host plants and pathogens in various ways. Some pathogens such as apple scab, late blight and several vegetable root pathogens are more likely to infect plants with increased moisture content because forecast models for these diseases are based on leaf wetness, relative humidity and precipitation measurements. Other pathogens like the powdery mildew species tend to thrive under conditions with lower (but not low) moisture[32]. Condition of drought is also expected to lead to increased frequency of tree pathogens due to indirect effects on host physiology[33]. 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[34]. Drought stress has been found to affect the incidence and severity of viruses such as *Maize dwarf mosaic virus* and *Beet yellows virus*[35,36]. 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[32]. Salinari *et al.*[37] used two climate-change models to simulate future scenarios of downy mildew on grapevine (*Plasmopara viticola*). These empirical models predicted an increase of the disease pressure in each decade and more severe epidemics were a direct consequence of more favourable air temperature and rainfall reduction conditions during May and June. The simulation analysis suggests that the impact of increased temperature on enhancing disease pressure exceeded the limiting effect of reduced rainfall. From a biological point of view, this result can be explained by considering that temperature and wetness act together on the pathogen. Thus, the production of grapes in northwestern Italy would decrease. Some climate change models predict higher atmospheric water vapour concentrations with increased temperature and this would also favour pathogen and disease development. While physiological changes in host plants may result in higher disease resistance under climate change scenarios, host resistance to disease may be overcome quickly by more rapid disease cycles, resulting in a greater chance of pathogens evolving to overcome host-plant resistance. Some modelling studies predict changes in incidence and severity with rising temperature and other weather variables for important crop pathogens such as those for black sigatoka (*Mycosphaerella fijiensis*) in banana, grapevine downy mildew and phoma stem canker (*Leptosphaeria maculans*) on oilseed rape[38–40]. Similarly, a model was developed for the risk assessment of early outbreak or increases in the intensity of potato late blight (*Phytophthora infestans*) under climate change in central Europe[40]. Recently, a conceptual design for modelling approaches has been developed that could be a useful tool to agronomists to integrate airborne fungal pathogens and the diseases they cause in their crop models in order to estimate future crop productivity, including disease impact[41]. Fungicide and bactericide efficacy may change with increased CO_2, moisture and temperature[42]. The more frequent rainfall events predicted by climate change models could result in farmers finding it difficult to keep residues of contact fungicides on plants, triggering more frequent applications. Systemic fungicides could be affected negatively by physiological changes that slow down uptake rates, such as smaller stomatal opening or thicker epicuticular waxes in crop plants grown under higher temperatures. The same fungicides could be affected positively by increased plant metabolic rates that could increase fungicide uptake.

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 (ref. 18). Effect of UV-B radiation has been reported to be inconsistent[19]. Evidence suggests that sunlight affects pathogens due to the accumulation of phytoalexins or protective pigments in host tissue[20,21].

Effect of climate change on plant disease scenario

Climate change is predicted to have a direct impact on the occurrence and severity of diseases in crops, which will have a serious impact on our food security. Climate change will result in rise in temperature and carbon dioxide levels and will also have a varied effect on moisture. In many cases, temperature increases are predicted to lead to the geographic expansion of pathogen and vector distributions, bringing pathogens into contact with more potential hosts and providing new opportunities for pathogen hybridization[43–45]. Pathogen evolution rates are determined by the number of generations of pathogen reproduction per time interval, along with other characteristics such as heritability of traits[46]. Temperature governs the rate of reproduction for many pathogens. Longer seasons that result from higher temperatures will allow more time for pathogen evolution. Pathogen evolution may also be more rapid when large pathogen populations are present, so increased overwintering and oversummering rates will contribute as well. Climate change may also influence whether pathogen populations reproduce sexually or asexually; in some cases, altered temperatures may favour overwintering of sexual propagules, thus increasing the evolutionary potential of a population[47]. In case of biotrophic fungi, an increase in disease severity has been found for six of ten fungi studied, and a decrease for the other four[18]. Similarly, in case of 15 necrotrophic fungi studied, 9 exhibited an increase in disease severity, 4 exhibited a decrease, and 2 remained unchanged[20]. Under climate change, due to increased biomass of crops and alternative host plants, necrotrophic pathogen will produce large quantities of inoculum that can infect subsequent crops, thereby often losing the advantage of using a partially resistant variety to reduce inoculums[48]. Change in temperature regimes will provide wider opportunities for overwintering of sexual stages, thereby accelerating gene recombination and opportunities for the development of more aggressive pathogen strains[49]. Effect of elevated CO_2 and O_3 levels has been evaluated on three soybean diseases, namely downy mildew (*P. manshurica*), brown spots (*Septoria glycines*) and sudden death syndrome (*F. virguliforme*). It was found that the composition of the atmosphere altered the expression of the disease and simultaneously plant responses to the diseases varied considerably[15]. While high levels of CO_2, alone or in combination with high concentrations of O_3, increased the severity of *S. glycines*, it did not have an effect on sudden death syndrome. This suggests that predicting effects for unstudied pathosystems will be quite challenging. Some mechanisms of effects of elevated CO_2 on plants are fairly well understood, such as reduced stomatal opening and changes in leaf chemistry. In such situations, diseases caused by the pathogens that infect through stomata such as *Phyllosticta minima* (*Phyllosticta* leaf spot of maple) may be reduced[49]. In soil-borne pathogens, increase in disease development for autumn and winter-infecting root and stem pathogens has been predicted due to increased thermal time[38,50]. Pathogens such as *Sclerotinia sclerotiorum*, which causes stem or white rot of oilseed rape and a wide range of vegetable crops, are likely to release spores in synchrony with earlier flowering of crops like oilseed rape. Excess moisture on the other hand, favours some dreaded soil-borne diseases caused by *Phytophthora*, *Pythium*, *R. solani* and *Sclerotium rolfsii*, especially in pulses[51]. Different climate change variables will have different effects on different soil microorganisms and associated biological processes as the soil is a highly complex ecosystem. Further, such changes are highly dependent on the particular soil conditions and few generalizations attributable to climate change can be made[52].

In India, wheat, rice and potato are important crops. Analysis of the last 30 year historical weather data from different locations of Punjab has indicated that significant changes have occurred in the weather causing early warming in February. Such climatic changes will influence wheat crop, which is of importance in the region. Temperature affects the growth of the crop, host–pathogen interactions and will alter the susceptibility window. Temperature rise above normal and increased humidity will predispose the crop to severe brown rust (*P. recondita*) infection and abet facultative pathogens. In wheat belt of Indian in Punjab, while change in temperature and humidity will reduce the importance of yellow rust (*P. striiformis*) and Karnal bunt (*T. indica*); the importance of leaf rust, foliar blights, *Fusarium* head blight and stem rust may increase in the future, particularly in the absence of resistance in wheat cultivars[53]. On the other hand, the importance of leaf rust, foliar blights *Fusarium* head blight and stem rust may increase in Punjab in the future. In plant diseases, there are some pathogens of major crops which have a huge potential to cause losses in those crops. In wheat, *Sr31* stem rust resistance has been effective in cultivars for over 30 years, which can be overcome by new races of *Puccinia graminis* f. sp. *tritici* like Ug99. According to estimates, Ug99 race of the stem rust can result in up to 10% yield loss in Asia alone, amounting to US$ 1–2 billion per year[54]. Similarly, banana wilt caused by *Xanthomonas* affects the food security of 70 million people in Uganda. In potato, economic production is often impossible without the application of pesticides. Late blight of potato caused by *P. infestans*, is considered to be the most economically important disease of potato worldwide. The disease can destroy a potato crop within a few weeks. Estimates of losses to late blight in developing countries vary between US$ 3 and US$ 10 billion each year, and about US$ 750 million is spent on pesticides alone. In the temperate Indian hills which occupy about 20% of the acreage, a severe epiphytotic (epidemic) of late blight recurs every year resulting in 40–85% yield loss. The disease now appears earlier in the northern part (November) and later in the eastern part (February) and within a wider temperature range, i.e. 14–27.5°C than at 10–25°C recorded in earlier years[55]. In effective disease management strategy in potato, pesticide usage may increase if changing crop physiology interferes with the uptake and translocation of pesticides or changes in other climatic factors (e.g. more frequent rainfall, washing away residues of contact pesticides) indicate that there is a need for more frequent applications. Faster crop development at increased temperature could also increase the need for application of pesticides.

The range of many pathogens is limited by climatic requirements for infection and development. Studies in this area have been carried out and in many cases have been predicted to lead to geographic expansion[12,37,56]. Shift in warming and other climatic conditions such as altered precipitation may result in over-wintering, survival, changes in the number of generations of polycyclic pathogens and the geographic distribution of important wheat diseases[57]. In the presence of susceptible hosts, pathogens with short life cycles, high reproduction rates and effective dispersion mechanisms respond quickly to climate change, resulting in faster adaptation to climatic conditions[32]. Warm winters with high night temperatures facilitate the survival of pathogens, accelerate life cycles of vectors and fungi, and increase sporulation and aerial fungal infection[58]. Thus, the results of the above mentioned study suggested that the number of pathogens moving northward will increase as increasing temperature makes the previously inclement areas more conducive. Climate change will also modify host physiology and resistance, and alter the stages and rates of development of pathogens. New disease complexes may arise, and some diseases may cease to be economically important. But, pathogens will follow migrating hosts and infect vegetation in natural plant communities not previously exposed to the often more aggressive strains from agricultural crops[23]. Under higher concentration of CO_2, the risk of potato blight (caused by *P. infestans*) has been predicted to be significantly higher in all regions of Finland[59]. Increased spread is likely for diseases like rice blast (*Magnaporthe grisea*), wheat scab (*Fusarium* spp.), stripe rust (*P. striiformis*) and powdery mildew (*Blumeria graminis*)[49]. In USA, recent epidemics of wheat stripe rust (yellow rust; *P. striiformis* f. sp. *tritici*) appear to have resulted from an increase in prevalence of strains adapted to warmer temperatures and the strains were found capable of overcoming the long-standing resistance genes *Yr8* and *Yr9* (ref. 60).

Effect of climate change has also been observed on different diseases in Himachal Pradesh. In apple, due to lesser rainfall in the rainy season and more severe summers, incidence of different canker diseases due to fungal pathogens is increasing[61]. Similarly, incidence of apple scab (*Venturia inaequalis*) has been reduced due to lesser rainfall in winter and also in March–April, which is necessary for maturation of the propagating sexual spores and spread of the disease.

Need for adoption of novel approaches

Changing disease scenario due to climate change has highlighted the need for better agricultural practices and use of ecofriendly methods in disease management for sustainable crop production[63]. In the changing climate and shift in seasons, choice of crop management practices based on the prevailing situation is important. In such scenarios, weather-based disease monitoring, inoculum monitoring, especially for soil-borne diseases and rapid diagnostics would play a significant role. There is need to adopt novel approaches to counter the resurgence of diseases under changed climatic scenario. Integrated disease management strategies should be developed to decrease dependence on fungicides[62]. Other multipronged approaches include healthy seeds with innate forms of broad and durable disease resistance, and intercropping systems that foster refuges for natural biocontrol organisms. In addition, monitoring and early warning systems for forecasting disease epidemics should be developed for important host–pathogens which have a direct bearing on the earnings of the farmers and food security at large. Such as diversified crop protection strategy has been highlighted in a comprehensive study on an integrated approach to control all foliar diseases in barley[63]. Use of botanical pesticides and plant-derived soil amendments such as neem oil, neem cake and karanja seed extract also help in mitigation of climate change because it helps in the reduction of nitrous oxide emission by nitrification inhibitors such as nitrapyrin and dicyandiamide[64].

Conclusion

There has been only limited research on impact of climate change on plant diseases under field conditions or disease management under climate change. However, some assessments are now available for a few countries, regions, crops and particular pathogens which concern with food security. Now, emphasis must shift from impact assessment to developing adaptation and mitigation strategies and options. First, there is need to evaluate under climate change the efficacy of current physical, chemical and biological control tactics, including disease-resistant cultivars, and secondly, to include future climate scenarios in all research aimed at developing new tools and tactics. Disease risk analyses based on host–pathogen interactions should be performed, and research on host response and adaptation should be conducted to understand how an imminent change in the climate could affect plant diseases.

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