**Effect of Climate Change on Plant Disease Management**

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**Introduction**

Climate change is the concern of human being. The recurrent droughts and floods threaten seriously the livelihood of billions of people who depend on land for most of their needs. The global economy is adversely affected due to natural hazards such as droughts and floods, forest fires, landslips etc. Increase in aerosols due to emission of greenhouse gases such as carbon dioxide due to burning of fossil fuels, chlorofluorocarbons (CFCs), hydro chlorofluorocarbons (HCFCs), hydro fluorocarbons (HFCs), per fluorocarbons (PFCs) etc., Ozone depletion and UV-B filtered radiation, eruption of volcanoes, deforestation due to human beings and loss of wet lands are causal factors for weather extremes. The loss of forest cover which normally intercepts rainfall and allows it to be absorbed by the soil, causes precipitation to reach across the land eroding top soil and causes floods and droughts. Paradoxically, lack of trees also exacerbates drought in dry years by making the soil dry more quickly. Among the greenhouse gases, CO2 is the predominant gas leading to global warming as it traps long wave radiation and emits it back to the earth’s surface. The global warming is nothing but heating of surface atmosphere due to emission of greenhouse gases, thereby increasing global atmospheric temperature over a long period of time.

Change in surface air temperature and consequent adverse effect on rainfall over a long period of time is known as climate change. If these parameters show year-to-year variations or cyclic trends, it is known as climate variability. However, the official definition by the United Nations Framework Convention on Climate Change (UNFCCC) is that climate change is the change that can be attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. However, scientists often use the term for any change in the climate, whether arising naturally or from human causes. In particular, the Intergovernmental Panel on Climate Change (IPCC) defines climate change as a change in the state of the climate that can be identified by changes in the mean or the variability of its properties and that persists for an extended period. According to a study (McKinnon, 2012), climate change 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 CO2 concentration over the last 100 years. During the period, the global mean temperature has increased by 0.74oC and atmospheric CO2 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 3.4oC and CO2 concentration to 1250 ppm by 2095 under the A2 scenario, accompanied by much greater variability in climate and more extreme weather-related events (Savary *et al.,* 2012).

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 (Gautam, 2009). 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 production and productivity of crops. Temperature increase of 1oC, 2oC and 3oC in Punjab, reduced the grain yield of rice by 5.4%, 7.4% and 25.1% respectively (Aggarwal, 2009). Cooling trends have also been observed in northwest India and parts of South India. 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 CO2, CH4, N2O and O3 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 (IPCC, 2007). 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 oil seed, cereal and fruit crops etc. But when we combine these losses with the post-harvest spoilage and deterioration in quality; the losses become critical particularly for resource poor countries of the world (Oerke, 2006). Further, plant diseases are estimated to cause yield reduction of around 20% worldwide (Thind, 2012). In the last 40 years, effective management of pests and diseases has played a key role in doubling food production, but pathogens still claim 10–16% of the global harvest (Chakraborty and Newton, 2011). In Asia, 14.2% of the potential production costing about US$ 43.8 billion is lost due to diseases (Oerke *et al.,* 1994). Climate models predict a gradual rise in CO2 concentration and temperature all over the world, but are not precise in predicting future changes in local weather conditions. Local prediction about the 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.

Insects, weeds and pathogen-mediated plant diseases are affected by climate and atmospheric constituents. Resultant changes in the geographic distribution of these pests and their vigor in current ranges will likely affect the crops. Globally, the net effect of climate change has been predicted to increase pest damage to crops and trees (Karuppaiah and Sujayanad. 2012). The introduction and distribution of alien insect pests are also likely to be driven by climate change which would accelerate the spread of viruses by migrating vectors like aphids. Climate change will affect the distribution and degree of infestation of insect pests through both direct effects on the life cycle of insects and indirectly through climatic effects on hosts, predators, competitors and insect pathogens. There is some evidence that the risk of crop loss can increase due to pole ward expansion of insect pests. Climate change is likely to involve a higher frequency of abiotic disturbance also. Climate change can also cause new patterns of pests and diseases to emerge, affecting plants and human health.

In addition, increased incidence of water-borne diseases in wood-prone areas, changes in vectors for climate responsive pests and diseases and the emergence of new diseases could affect both the food chain and people’s physiological capacity to obtain the necessary nutrients from the foods they consume (Debay, 2010). Pests and diseases that were once minor problems can turn into major constraints and change their range of distribution with climate change. For example, projections illustrate these effects for three major cassava pests: the mealy-bug, the cassava green mite and the whitefly (Herrera *et al*., 2011). Environmental conditions have a major influence on the survival, propagation and dispersal of plant pathogens. The effects of the climate are perhaps most obvious for diversity in fungal pathogens, which require suitable temperatures and minimum amounts of moisture to survive and reproduce and to initiate the infection process in plants. Most pathogens complete part of this life cycle on this host plants and the remaining part in the soil or on plant residues in the soil. Thus, temperature and moisture conditions in both air and soil are important for pathogen survival and development (Chaneallor and Kubiriba, 2006). Climate is a prime determinant of the geographical distribution of plants, and climate variables have a major effect on the development of plant diseases. Anthropogenic climate change will impact directly on crops and natural vegetation as well as on their interaction with plant pathogens (Rosenzwieig *et al.,* 2000).

**Environmental factors influencing crop disease epidemics**

Disease triangle recognizes the role of climate in plant diseases as no virulent pathogen can induce disease on a highly susceptible host if climatic conditions are not favourable. Climate influences all stages of host and pathogen life cycles as well as development of disease. Disease severity over a period can fluctuate according to climatic variation. Climate factors that influence the growth, spread and survival of crop diseases include temperature, precipitation, humidity, dew, radiation, wind speed, circulation patterns and the occurrence of extreme events. Higher temperature and humidity and greater precipitation result in the spread of plant diseases, as wet vegetation promotes the germination of spores and proliferation of fungi and bacteria and influences the life cycle of soil nematodes. In regions that suffer aridity disease infestation lessens, although some diseases such as the powdery mildews thrive in hot dry conditions (Haggag *et al.,* 2006). Fungal and bacterial pathogens are likely to increase in severity in areas where precipitation increases. Under warmer and more humid conditions cereals and vegetables would be more vulnerable to diseases such as *Septoria*. In addition, increase in population levels of disease vectors could lead to increased epidemics of the diseases they carry (Figure 1).



**Fig. 1 Climate change and the disease triangle**

Globally, farmers are able to reduce inoculum of plant pathogens by using a range of integrated crop protection practices, such as crop debris management (by removal, grazing, burning or burial by tillage) , paddy-field creation, crop rotation, intercropping and companion planting to reduce inoculum production or separate crops from sources of inoculum including insect vectors. Choice of varieties that are resistant to certain pathogens affects host susceptibility, while the main agronomic factor altered by the farmer’s actions is application of crop protection products, such as fungicides, to protect the crop at particular growth stages. Changes in the weather likely result in changes in the occurrence and severity of crop diseases.

Climate change may also have indirect effects due to the inclusion in arable rotations of alternative crops that can act as hosts for certain pathogens, e.g. maize, a host to *Fusarium graminearum*, which also affects wheat, as maize is likely to increase in crop area in western Europe due to (i) use of cultivars that are adapted to cooler climates than those where maize was traditionally grown, (ii) climate change and (iii) demand for animal feed and biofuel (West *et al.*, 2011). In addition to altering climate, changes in atmospheric gas concentrations can encourage diseases since increasing ozone and CO2 can reduce resistance expression (Gregory *et al.,* 2009) and elevated CO2 can increase pathogen fecundity, leading to enhanced rates of pathogen evolution (Chakraborty and Datta, 2003). In contrast, increased CO2 was reported to increase pathogen latent periods, which would reduce epidemic rates. Increased CO2 was also reported to increase resistance of barley to *Blumeria graminis* (*hordei*) (Coakley *et al.,* 1999). Environment and particularly climate-change, has been predicted to lead to an altered geographic distribution of hosts and their pathogens as well as changes in host pathogen interactions and yield-loss relationships. These environmental changes are likely to affect both polycyclic and monocyclic pathogens. Consideration of climate change effects on crop diseases and particularly newly emerging infectious diseases (EIDs), should be put into context alongside a brief review of other factors that influence the emergence of new diseases. According to Anderson *et al.* (2004), introduction is the most important driver for emergence of new diseases in different pathogen groups. Weather conditions were found to be a major influencing factor for bacterial and fungal plant EIDs and although direct effects of climate were reported as relatively unimportant for plant EIDs that are caused by viruses, changes in vector populations were reported as the most important influence after pathogen introduction. Interestingly, although agricultural changes were identified as important driving factors of plant EIDs caused by fungi and viruses, they were not mentioned as drivers of bacterial diseases. Anderson *et al.* (2004) have introduced the term ‘pathogen pollution’ to describe the anthropogenic movement of pathogens resulting in a pathogen crossing a boundary that previously provided geographical or ecological separation. As a result, there may be heightened impact of introduced pathogens on native susceptible host populations. Given the predicted continued increase in global air travel and trade volume, the number of introduced emerging diseases is also likely to increase. Because climate change will enable plants and pathogens to survive outside their historic ranges, Harvell *et al.* (2002) predicted an increase in the number of invasive pathogens. For example, range expansion of grey leaf blight of maize, caused by the fungus *Cercospora zeae-maydis*, was first noted during the 1970s and subsequently became the major cause of maize yield loss in the USA. If key climatic conditions for survival and establishment of a disease are known, it is possible to use climate-matching tools such as NAPPFAST, BIOCLIM, HABITAT or CLIMEX to map locations where those conditions are met in order to identify locations where increased surveillance is advised and mitigating control measures researched. For example, Karnal bunt, caused by *Tilletia indica*, which infects wheat, rye and triticale, is favoured by cool weather, rainfall and high humidity at the time of wheat ear emergence. The risk of establishment in Europe was estimated by applying a published karnal bunt disease model; they showed that conditions during the ear emergence or heading period were favourable for infection and disease development in many places in Europe.

**Elevated CO2 levels**

The concentration of CO2 in the atmosphere reached 379 ppm in 2005, which exceeds the natural range of values of the past 650,000 years (Savary *et al*., 2012). An increase in CO2 level 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 (Chakraborty *et al.,* 2002). 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 (Yanez-Lopez *et al.,* 2012). Some workers suggest that elevated CO2 concentration and climate change may accelerate plant pathogen evolution, which can affect virulence. Under elevated CO2 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 (Mcelrone *et al.,* 2005). Changes brought by high CO2 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 (Hibberd *et al.,* 1996). The severity of downy mildew damage was significantly reduced at high levels of CO2.

Elevated CO2 would increase canopy size and density of plants, resulting in a greater biomass production and microclimates may become more conducive for foliar pathogens (rusts, mildews, leaf spots and blights) development. Because of high C: N ratio of litter as a consequence of plant growth under elevated CO2, decomposition will be slower. Increased plant biomass, slower decomposition of litter and higher winter temperature could increase pathogen survival on overwintering crop residues and increase the amount of initial inoculum available for subsequent infection. Research on rice leaf blast and sheath blight in the temperate climates of Japan showed that elevated CO2 increased the potential risks for infection from leaf blast and epidemics of sheath blight (Kobayashi *et al*., 2006). In soybeans, elevated CO2 alone or in combination with ozone (O3) significantly reduced downy mildew (*Peronospora manshurica*) disease severity by 39.66%. In contrast, elevated CO2 alone or in combination with O3 significantly increased brown spot (*Septoria glycines*) severity (Eastburn *et al*., 2010). In wheat, grown at elevated atmospheric CO2 (700 ppm), the mean per cent leaf area infected with mildew was significantly reduced under elevated atmospheric CO2, compared to ambient CO2. The enlarged canopy of *Stylosanthes scabra* plants grown under elevated CO2 trapped more conidia of *Colletotrichum gloeosporioides* that, together with increased humidity in the denser canopy, led to more severe anthracnose than on plants grown under lower CO2 (Chakraborty *et al*., 2000). Following penetration, established colonies of *Erysiphe graminis* grew faster and sporulation per unit area of infected tissue was increased several-fold under elevated CO2*.* It has been also observed that under elevated CO2 out of the 10 biotrophic pathogens studied, disease severity was enhanced in six and reduced in four and out of 15 necrotrophic pathogens, disease severity increased in nine, reduced in four and remained unchanged in the other two.

**Elevated temperatures**

In most locations, temperature changes had significant effect on disease development. However, these effects varied between different agro-ecological zones. In cool sub-tropical zones such as Japan and northern China, elevation of ambient temperature resulted in greater risk of rice blast epidemics. Situations in the humid tropics and warm humid subtropics were opposite to those in cool areas. A lower temperature resulted in greater risk of blast epidemics. Temperature change might lead to appearance of different races of the pathogens hitherto not active but might cause sudden epidemic. Change in temperature will directly influence infection, reproduction, dispersal and survival between seasons and other critical stages in the life cycle of a pathogen. At higher temperature, lignification of cell walls increased in forage species and enhanced resistance to fungal pathogens. Research has shown that host plants such as wheat and oats become more susceptible to rust diseases with increased temperature (Coakley *et al*., 1999). Predictive models for potato and tomato late blight show that the fungus infects and reproduces most successfully during periods of high moisture that occur when temperatures are between 7.2oC and 26.8oC (Wallin and Waggoner, 1950). Earlier onset of warm temperatures could result in an earlier threat from late blight with the potential for more severe epidemics and increase in the number of fungicide applications needed for control. In mild winters, high intensity of aphid movement during spring and a high frequency of PVY-infected potatoes have been reported. Aphid vectors are expected to have increased survival with milder winter temperatures and higher spring and summer temperatures will increase their development and reproductive rates and lead to more severe disease. Systemic fungicides could be affected negatively by physiological changes that slow uptake rates, such as smaller stomatal opening or thicker epicuticular waxes in crop plants grown under higher temperatures.

Changes in temperature 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. 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 (Mboup *et al.,* 2012). Climate change is also reported to cause a shift in the geographical distribution of host pathogens (Mina and Sinha, 2008). 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 (Mcelrone *et al.,* 2005). 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 (Oerke, 2006). 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 (Pande and Shanna, 2005). Higher risk of dry root rot has been reported in *Fusarium* wilt chickpea-resistant varieties in those years when the temperature exceeds 33oC (Dixon, 2012). In North America, needle blight (*Dothistroma septosporum*) is reported to be spreading northwards with increasing temperature and precipitation (Madden *et al.,* 2007). 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 (Woods *et al.,* 2005). 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 (Kudela, 2009). 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 (Navas-Castillo *et al.,* 2011). 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 (Gregory *et al.*, 2009).

**Precipitation patterns**

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. Other pathogens like powdery mildew species tend to thrive in conditions with low moisture. Bacteria are spread to their host plants mainly by water, usually in the form of rain splash and insects. In humid wet conditions, infected plant tissues can exude masses of bacteria that are spread from host to host by rain splash and insects. Therefore, the warmer drier summers expected with climate change should limit bacterial diseases. Precipitation following fungicide application may improve its distribution (Schepers, 1996) but an increase in rainfall intensity can deplete fungicide residue on the foliage. 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.

**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 (Baker *et al.,* 2000). 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 (Garrett *et al.,* 2006). 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 over-summering 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 (Pfender and Vollmer, 1999). Under climate change, due to increased biomass of crops, necrotrophic pathogens 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. 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. Effect of elevated CO2 and O3 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 (Eastburn, 2010). While high levels of CO2, alone or in combination with high concentrations of O3, 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 CO2 on plants are fairly well understood, such as reduced stomatal opening and changes in leaf chemistry. In such situations, diseases caused by pathogens that infect through stomata such as *Phyllosticta minima* (*Phyllosticta* leaf spot of maple) may be reduced. 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. 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 (Sharma *et al.,* 2010). 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. 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 India 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. 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, Sr31stem 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. 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 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– 27.5oC than at 10–25oC recorded in earlier years (Luck *et al.,* 2012). 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. 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 (Juroszek and Tiedemann, 2013). 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. 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. 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 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. Under higher concentration of CO2, the risk of potato blight has been predicted to be significantly higher in all regions of Finland. Increased spread is likely for diseases like rice blast (*Magnaporthe grisea*), wheat scab (*Fusarium* spp.), stripe rust (*P. striiformis*) and powdery mildew (*Blumeria graminis*). In USA, recent epidemics of wheat stripe rust 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(Garrett *et al.,* 2009). 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. 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 sexual spores and spread of the disease.

There are two methods for making predictions as to how geographic ranges and average severity of a disease may change. The more widely used method assumes that climate and host currently limit the pathogen and attempt to match the current geographic range with suitable climatic measures. Future range is then matched to predictions of future climate (Desprez-Loustau *et al.* 2007); this is widely used in predicting the possible limits to expansion of newly invasive diseases. The second approach applies if we believe that we know the basic factors limiting the abundance of a pathogen and understand quantitatively their relation to weather. It may then be appropriate to use a weather-based prediction system (Semenov, 2007) to predict future abundance. For example, Evans *et al*. (2008) used an analysis of key features of the monocyclic pathogen *Leptosphaeria maculans*, coupled to a weather generator parameterized by predicted future climate, to predict the future levels of the pathogen.

**Impact of climate change on plant disease management practices**

Climate change impacts on plant health are likely to be ubiquitous, both in terms of direct and indirect ones. Maintaining plant health across the planet, in turn, is a key requirement for climate change mitigation, as well as the conservation of biodiversity and provision of ecosystem services under global change as disease management strategies depend on climate conditions (Fig. 2: Haggag *et al.,* 2006).



**Fig. 2 Climate change, soil microbes and plant health**

While physiological changes in host plants may result in higher disease resistance under climate change scenarios, host resistance to disease may be overcome more quickly by more rapid disease cycles, resulting in a greater chance of pathogens evolving to overcome host plant resistance. Fungicide and bactericide efficacy may change with increased CO2, moisture and temperature. 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 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. Exclusion of pathogens through regulatory means may become more difficult for authorities as unexpected pathogens might appear more frequently on imported crops. Climate change would cause alterations in disease geographical and temporal distributions and consequently the control methods would have to be adapted to this new reality. There are few discussions on how chemical control could be affected by climate changes in temperature and precipitation that might alter fungicide residue dynamics in the foliage, and the degradation of products could also be modified (Fig. 3: Haggag *et al.,* 2006).



**Fig. 3 Plant Pathogens interactions**

**Effect on farmers**

Although the specific impacts of climate change on plant disease are difficult to predict, it seems possible to make several generalizations for farmers in the northeastern US: a) increased winter temperatures will likely mean higher populations of pathogens survive to initially infect plants; b) increased temperatures will likely result in northward expansion of the range of some diseases because of earlier appearance and more generations of pathogens per season; c) more frequent and more intense rainfall events will tend to favor some types of pathogens over others (Coakley *et al*., 1999). Two pathogens important in the northeastern US, Stewart’s wilt and late blight illustrate some of these effects. Stewart’s wilt, a bacterial (*Erwinia stewartii*) disease in sweet corn in the northeast, is vectored by the corn flea beetle (*Chaetocnema pulicaria*). Survival of the vector through winter is considered key to the severity of Stewart’s wilt infections the following year. Currently, a forecast model based on winter temperatures is used to predict severity for Stewart’s wilt. The model assumes the survival of the corn flea beetle is higher in warmer winters than colder winters (Castor *et al*., 1975). Climate change resulting in more winters that allow larger populations of flea beetles to survive would be expected to increase the frequency of growing seasons with severe Stewart’s wilt.

Farmers in the northeastern US now attempt to control Stewart’s wilt by planting resistant varieties and using in-furrow or foliar insecticides to control the flea beetle vector (Baniecki and Dabaam, 2000). Farmers would incur increased costs as a result of increased frequency of insecticide treatment and the accompanying negative environmental impacts would mount. Resistant varieties are the most effective method for Stewart’s wilt control, yet few varieties offer high levels of resistance and some popular varieties offer only moderate or low levels of resistance (Whitney *et al.,* 2000). Higher levels of Stewart’s wilt in more growing seasons could impact farmers’ variety selection forcing them to choose varieties based on Stewart’s wilt resistance rather than market qualities such as taste, texture and appearance. Farmers’ profitability could thus be impacted by the varieties they would be forced to grow to combat Stewart’s wilt. Late blight (*Phytopthora infestans*) infects both potatoes and tomatoes in the northeastern US. It can be a devastating disease for both crops and farmers, with complete crop loss if control measures are not employed. Infection is triggered by high moisture conditions within a fairly specific temperature range. Annually, 5-20 fungicide applications from as early as June through August are used in the northeastern US (Baniecki and Dabaam 2000). This represents a significant expense to farmers and a significant environmental risk. Work in Finland, which is considered to be in a similar late blight risk zone to the northeastern US (Hijmans 2000), has predicted that for each 1oC warming late blight would occur 4 to 7 days earlier and the susceptibility period extended by 10 to 20 days. This would likely translate into an additional 1 to 4 additional fungicide applications for northeastern US potato farmers – increasing both farmer costs and environmental risk.

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