Impact of Climate Variation on Plant Diseases

Dr. Isha Rana, Scientific Professional
Dr.S.S.Randhawa, Sr.Scientific Officer
State Centre on Climate Change
(H.P State Council for Science Technology & Environment)
Block-34, SDA Complex, Kusumpti, Shimla (H.P)-71009

TABLE OF CONTENT

S.No	Topic	Page No.
1	Introduction	2-6
	Plant Disease Epidemiology	
	Biotic Plant Diseases and Environment	
	Abiotic Diseases and Environment	
	Interactions between Biotic and Abiotic Diseases	
2	Climate variations and Plant Disease	6-10
	Temperature and Precipitation	
	Carbon Dioxide	
	Ultraviolet Light	
	Ozone	
	Insects	
3	Impact of climatic variation on plant diseases in Himachal Pradesh	10-16
4	References	17-19

Introduction:

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. Plant diseases are estimated to cause yield reduction of almost 20% in the principal food and cash crops worldwide. 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. In Asia, 14.2% of the potential production costing about US$ 43.8 billion is lost due to diseases.

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.

Plant diseases are considered an important component of plant and environmental health and can be caused by infectious or *biotic* pathogens and non infectious or *abiotic* factors. *Biotic* plant diseases are caused by organisms such as fungi, bacteria, viruses, nematodes, phytoplasmas, and parasitic plants. *Abiotic* diseases are associated with chemical and physical factors, such as temperature or moisture extremes, nutrient deficiencies, mineral toxicities, and pollution.

Biotic Diseases

- *Fungi* cause most biotic plant diseases. Members of this group of non-motile, filamentous organisms lack nchlorophyll and absorb nutrients from dead or living organisms. Over 100,000 species of fungi are known, and over 10,000 can cause diseases in plants.
- *Bacteria* are single-celled organisms, most of which decompose organic matter. However, about 100 of the known 1,600 species of bacteria can cause disease in plants.
- *Viruses* are nucleoproteins that are parasitic in plant cells and cause host cells to produce more virus particles. These viruses interfere with host metabolism, causing

disease in the host. About 2,000 different viruses have been identified, and about 500 of these cause disease in plants.

- *Nematodes* are microscopic worm-like animals. Several thousand species of nematodes have been identified, and several hundred of these cause plant diseases. Root-feeding species often decrease the ability of plants to take up water and nutrients, and others produce biochemical reactions when injecting their saliva into the host plant. Removal of nutrients by nematodes typically becomes important only when the nematode population is high. However, wounds caused by feeding nematodes can also act as entry points for other pathogens.
- *Phytoplasmas* are microorganisms without cell walls that live in infected plants and insect vectors. They cause over 200 plant diseases.

Plant Disease Epidemiology

When considering the potential influence of climate change on plant diseases, it is important to understand some of the epidemiological factors that influence how biotic plant diseases initiate, develop, and spread. In general, *primary inoculum is* the initial inoculum that starts an epidemic in each crop or year. The different types of primary inoculums are often classified by method of survival or overwintering (soil borne, debris- or host borne, vector borne, introduced). Some pathogens have more than 1 type of primary inoculum. Soil borne plant pathogens survive in soil apart from their host or host debris, and soil is the source of primary inoculum. Debris or host borne pathogens overwinter in infected tissues of perennial plants and/or in plant debris of annual plants. Primary inoculum of these pathogens is produced from these locations in the next growing season. Vector borne pathogens are carried and transmitted to host plants by organisms such as insects and nematodes, which are often an integral component of the pathogen's life cycle. Introduced pathogens typically do not overwinter in Ontario's climate and are introduced in seed or on air currents from the south. *Monocyclic* diseases produce only primary inoculum and thus typically have only one infection cycle each year. However, many of the more economically important pathogens produce secondary inoculums during the growing season, resulting in multiple infection cycles each season. With these *polycyclic* diseases, the number of cycles each year is restricted by the pathogen, duration of the season, and prevailing environmental conditions. Secondary inoculum is produced by many pathogens from existing diseased tissues, and this inoculum continues to spread the epidemic within a particular crop. The amount of secondary inoculum produced and subsequent infection can be summarized by calculating the rate of disease spread within each crop during a growing season.

A diagram of the disease cycle for biotic plant diseases is provided in Figure 1. After the primary inoculum infects the host, the plant begins to exhibit disease symptoms. The pathogen, in the case of polycyclic diseases, produces secondary inoculum, and then (or near the end of the growing season) produces survival structures. These structures allow the pathogen to survive winter dormancy, and they produce primary inoculums the next season.

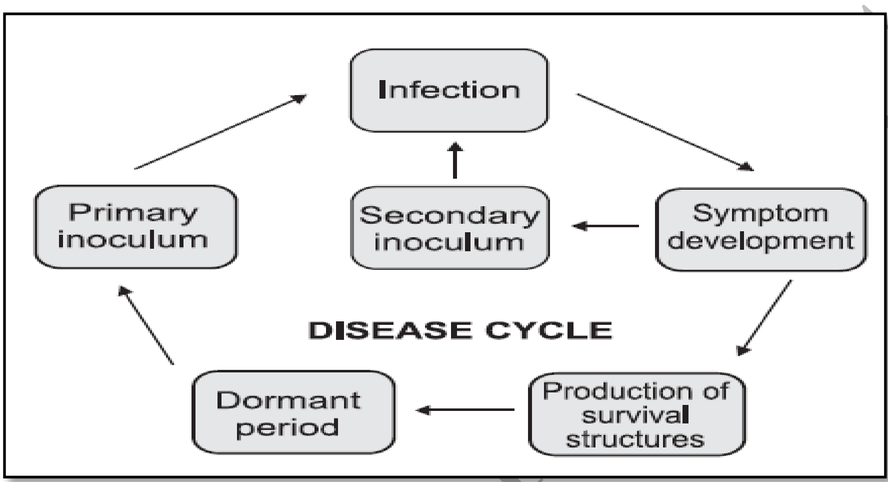

Figure 1: *A typical disease cycle of a plant pathogen, illustrating the relationships between survival and production of primary and secondary inoculum (adapted from Agrois 1997).*

Biotic Plant Diseases and Environment

Environmental factors dramatically affect the development of plant diseases. Plant pathologists often use a disease triangle (Figure 2) to illustrate the intimate relationship among plants, pathogens and the environment. For a plant disease to develop, a susceptible host, a virulent pathogen, and a suitable environment must occur simultaneously. Because of this intimate relationship among plants, pathogens, the environment, climate change is expected to affect the incidence and severity of plant diseases.

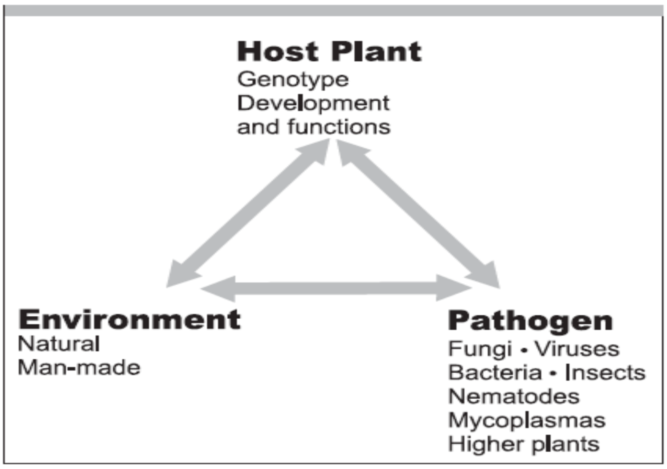

Figure 2. *The disease triangle, illustrating the relationships among host, pathogen and environment in the development of plant disease.*

Typically, the two most important environmental factors in the development of plant disease epidemics are temperature and moisture. In temperate regions most plant pathogens are not active in late rainfall, winter, and early spring because of low temperatures. Some diseases are favoured by cool temperatures, while others are favoured by moderate or hot conditions. Disease often occurs when temperatures are more stressful for the plant than for the pathogen. Moisture, in the form of free water or high humidity, is necessary for many pathogens to infect, reproduce, and spread, although some can cause disease in dry conditions. Plant diseases require varying environmental conditions to develop; thus, it is vital to understand the environmental requirements of individual plant pathogens before predicting responses to climate change.

Abiotic Diseases and Environment

Abiotic plant diseases are caused by non-infectious factors such as nutrient deficiencies, air pollutants, and temperature and moisture extremes. Abiotic diseases can affect plant health directly and indirectly.

Direct effects include the development of symptoms related to a deficiency or excess of a physical factor such as moisture, heat, or nutrients, as well as toxic effects caused by inappropriate use of pesticides or chemical pollutants to which plants are intentionally or unintentionally exposed. Abiotic diseases can indirectly affect plant health by weakening their defence mechanisms, thereby predisposing plants to infection by pathogens.

Interactions between Biotic and Abiotic Diseases

Several important plant diseases are initiated by abiotic stress. Forest decline diseases, for example, are caused by a combination of plant predisposition and a repetitive sequence of plant stresses that weaken a plant until it becomes susceptible to weak pathogens that often infect and kill the plant. In temperate climates, plants that are stressed by biotic or Abiotic factors during a growing season are often predisposed to freezing damage during the subsequent winter.

Climate variations and Plant Disease:

The scientific literature provides some background on the potential impact of climate variations on plant diseases. Much of the literature focuses on diseases of agricultural crops and includes discussion of the influence of temperature, precipitation, CO_2, ozone, ultraviolet light, and insects on plant disease.

Temperature and Precipitation: Changes in temperature and precipitation regimes due to climate variation may alter the growth stage, development rate and pathogenicity of infectious agents, and the physiology and resistance of the host plant (Mboup *et.al*, 2012) The large population size and short generation time of plant pathogens are expected to make them the first organisms to show effects of climate change (Chakraborty *et al*. 1998b). In northern latitudes, the impacts of plant pathogens are expected to increase with warming, because low temperatures and long winters currently reduce the survival, generations per year, reproduction rate, and activity of most pathogens attacking crops during the growing season (Harvell *et al*. 2002, Kaukoranta 1996). However, climate variation may bring positive and neutral as well as negative impacts on plant diseases (Coakley 1995, Chakraborty *et al*. 1998a). Changes will occur in the type, amount, and relative economic importance of pathogens and diseases, altering the disease spectrum, particularly for pathogens with alternate and alternative hosts. Impacts will vary depending on host, pathogen, and changes in climate (Chakraborty *et al.* 1998a).

Harvell *et al*. (2002) considered the consequences of warmer temperatures on host-pathogen interactions and concluded that there will be 3 main effects: 1) increases in pathogen development rate, transmission, and generations per year, 2) increases in overwintering of pathogens, and 3) changes in host susceptibility to infection. Furthermore, they suggested that the most severe and unpredictable consequences would occur if populations of pathogen and host, which were formerly geographically separated due to climate constraints, converged.

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 (Coakley *et.al*.1999). Other pathogens like the powdery mildew species tend to thrive under conditions with lower (but not low) moisture. Drought stress has been found to affect the incidence and severity of viruses such as *Maize dwarf mosaic virus* (Olsen *et.al.* 1990).

With changes in climate, plants will migrate to new areas, and their pathogens will follow. How quickly pathogens migrate to follow host plants will depend on factors such as their dispersal mechanisms, suitability of the environment for dispersal to occur, survival between seasons, and changes in host physiology and ecology in the new environment. If a host is chronically stressed due to less than optimum conditions, its health would deteriorate and its susceptibility to disease would increase, particularly in perennials (Chakraborty *et al*. 1998a). New diseases may establish in a region, while some established diseases may cease to be economically important. Although climate changes may reduce the suitability of a crop for a region, it may continue to be grown for agro-ecological or economic reasons.

Climate change can modify host physiology and resistance and alter stages and rates of pathogen development (Coakley *et al*. 1999). It can also affect disease management by altering efficacy of biological and chemical control options (Chakraborty *et al*. 1998a, Coakley *et al*. 1999). For example, heavy rains reduce fungicide residue. Crop plants growing under elevated CO_2 could be altered morphologically or physiologically, affecting uptake, translocation, and metabolism of systemic fungicides. For example, increased thickness of the epicuticular wax layer on leaves could result in slower and/or reduced uptake by the host, while increased canopy size could negatively affect spray coverage. Conversely, if higher temperatures increase plants' metabolic rates, they may take up chemicals more quickly, which may result in greater toxicity (Coakley *et al*. 1999).

The nature and magnitude of global climate change could influence plant diseases and the efficacy of management options, in turn affecting the productivity and sustainability of agricultural systems. While a shift in the mean temperature or rainfall may appear to affect plants marginally, the effects are greatly magnified at extreme values. Thus, the impact of such events is particularly important to understand. With this shift, the hydrological cycle will likely intensify and climate variability will likely increase. An increase in rainfall intensity could greatly affect agriculture and plant pathogens in particular. Such effects will interact with changes in plant morphology and chemistry brought about by enhanced CO_2 concentrations (Chakraborty *et al*. 1998a).

Carbon Dioxide**:** CO_2 concentrations in the troposphere are projected to increase from 355 ppm to 710 ppm by 2050. Higher CO_2 concentrations will likely result in increased biomass production due to increased water use efficiency. Little is known about the effect of higher CO_2 concentration on incidence and severity of plant diseases. Increases in CO_2 from 0.03 to 0.07% may have a slightly stimulatory effect on growth of pathogens (Manning and Tiedemann 1995).

The impact of increased CO_2 concentrations on plant diseases will likely be through changes in host physiology and anatomy. Some significant changes that will likely influence plant disease severity under elevated CO_2 are lowered nutrient concentration, leading to partitioning of nitrogen from photosynthetic proteins to metabolism that is limiting to plant growth; greater carbohydrate accumulation in leaves; more waxes, layers of epidermal cells, and fibre content; production of papillae and accumulation of silicon at the sites of appressorial penetration; and increased mesophyll cells (Chakraborty *et al*. 1998a).

Elevated CO_2 is expected to increase canopy size and density (Coakley *et al*. 1999), resulting in greater biomass of high nutritional quality, combined with higher microclimate humidity (Manning and Tiedemann 1995). These changes will likely promote foliar diseases such as rusts, powdery mildews, leaf spots, and blights (Coakley *et al*. 1999, Manning and Tiedemann 1995); however, Karnovsky *et al*. (2002) did not observe an increase in infection by poplar leaf rust under elevated CO_2 except in the presence of high ozone. Under elevated CO_2, increased partitioning of assimilates to roots occurs consistently in crops such as carrot (*Daucus carota*), sugar beet (*Beta vulgaris*), and radish (*Rhaphanus sativus*). If more carbon is stored in roots, losses from soilborne diseases of root crops may be reduced under climate change (Coakley *et al*. 1999). The inoculum potential of nonbiotrophs, from more abundant crop debris, would increase (Manning and Tiedemann 1995). Evidence indicates that high-CO_2 leaf litter decomposes at a slower rate (Coakley *et. al* 1999). Increased plant biomass, slower litter decomposition, and higher winter temperatures could increase pathogen survival on overwintering crop residues and increase the amount of initial inoculum available to infect subsequent crops (Coakley *et al*. 1999).

Normal soils may contain as much as 6-18% CO_2, depending on organic matter decomposition, microbial and root respiration, and other factors. Most soil-inhabiting fungi tolerate more than 10 or 20 fold increases in atmospheric CO_2 concentration. Some typical soilborne plant pathogens, such as species of *Phytophthora*, *Aphanomyces*, and *Sclerotium*, and pathotypes of *Fusarium oxysporum* are well adapted to and even multiply better at high CO_2 and low oxygen levels (Manning and Tiedemann 1995).

In recent studies on host-pathogen interactions in selected fungal patho-systems, two important trends have emerged related to the effects of elevated CO_2. First, initial pathogen establishment may be delayed because of changes in pathogen aggressiveness and/or host susceptibility. Second, pathogens were more fecund under elevated CO_2 (Coakley *et al*. 1999). The combination of increased fecundity and conducive microclimate within enlarged canopies may provide more opportunities for severe infection. For genetically diverse pathogens, an increase in population size and number of generations in conducive microclimates may lead to the development and proliferation of well adapted and possibly more destructive sub-populations (Chakraborty *et al*. 1998a).

Ultraviolet Light: Ultraviolet (UV) light has long been known to influence plant pathogenic fungi. This light may stimulate spore production in a wide range of fungi, but may also reduce spore survival during dispersal or early stages of infection (Paul *et al*. 1998). Although an increase in solar UV-B radiation due to ozone depletion could promote sporulation of pathogenic fungi in a way that could greatly increase the frequency and intensity of epidemics, normal daylight already contains enough UV light to stimulate sporulation of light-dependent fungi. Provided that this stimulation is mainly a qualitative effect of specific wavelengths, a slight quantitative increase in UV-B radiation is not likely to influence the life cycle of pathogenic fungi greatly (Manning and Tiedemann 1995).

Ozone: Ozone is considered to be the most phytotoxic of the common air pollutants. It can cause chlorotic and necrotic lesions on sensitive plant species, and even in the absence of visible symptoms, photosynthesis and growth can be inhibited. Ozone damage can lead to reduced competitive fitness of plants, and reduced vitality makes plants more susceptible to plant pathogens (Sandermann 2000). Direct effects of ozone on fungal pathogens are not significant (Manning and Tiedemann 1995), although interactions between ozone damage and infection by *Alternaria solani*, the causal agent of early blight of potato, have been reported (Holley *et al*. 1985a, 1985b). Ozone induced metabolic changes can apparently persist in plants over days or months. Researchers have reported both increased (Sandermann 2000) and decreased (Coleman *et al*. 1988) disease susceptibility in plants after ozone exposure. According to Tiedemann and Firsching (1998), ozone effects on plant disease susceptibility may be strongly altered by interfering factors such as plant developmental stage, nutrient supply, and other atmospheric trace gases.

***Insects*:** Insects are important vectors of many plant diseases. The potential effects of climate change on agricultural insect pests have been explored by Porter *et al*. (1991). Temperature is the most critical climatic variable, with low temperatures often being more important than high temperatures in determining global insect species' distributions. Winter is the most critical time for many insect pests because low temperature extremes can significantly increase mortality, thereby reducing population levels in the following season. Information from general circulation models indicates that future temperature changes will be greatest in winter. Predicted higher winter temperatures could increase the survival of many overwintering species and allow them to overwinter even farther north. For example, in northern temperate zones, aphid (Aphididae) damage is expected to increase due to earlier aphid activity in the spring, increased development rate, and greater survival over winter. Serious outbreaks of aphid vectored viruses have been observed following mild winters (Harrington *et al*. 1995).

For all insect species, higher temperatures that are below the species' upper lethal limit could reduce the time it takes to reach reproductive maturity and, therefore, increase pest populations more quickly. Such effects would be particularly important at higher latitudes, where current temperatures, particularly in the spring, limit insect development and distribution. Increases in food availability as a result of plant stress could dramatically affect how quickly pest populations develop. Pest outbreaks are more likely to occur if plants are stressed (e.g., drought stress) because their defensive systems are compromised and resistance to pest infestation lower. Drought may become more frequent and severe in the future if increased evapo-transpiration rates associated with predicted higher temperatures are not compensated sufficiently by increases in precipitation.

Impact of climatic variation on plant diseases in Himachal Pradesh

Agriculture/Horticulture is the main occupation of the people of Himachal Pradesh. It has an important place in the economy of the State. The state of Himachal Pradesh is the only state in the country whose 89.96 percent as per 2011 census of population lives in rural areas. Therefore dependency on Agriculture/ Horticulture is eminent as it provides direct employment to about 70 percent of total workers of the State. The agro-climatic conditions in the state are congenial for the production of cash crops like seed potato, off-season vegetables and ginger. During the Eleventh Five Year Plan, 2007-12 emphasis has been laid on production of off-season vegetables, potato, pulses and oilseeds besides cereal crops through timely and adequate supply of inputs, bringing more area under irrigation, approach of watershed development, demonstration and effective dissemination of improved farm technology etc. The production of vegetables during the year 2012-13 was 13.80 lakh M.Ts as against 13.57 lakh M.Ts in 2011-12.

The productivity of crops in the country is much lower as compared to other countries. One of the major factors contributing towards it is the prevalence of diseases which sometimes may lead to even zero harvest. In order to increase the production of crops, adoption of plant protection measures is of paramount importance. During each season, campaigns are organised to fight the menace of crop disease, insects and pest etc.

The coverage of area under plant protection measures and distribution of chemicals from the year 2007 to 2013 in Himachal Pradesh (as per economic survey of Himachal Pradesh 2013-2014) is as follows:

YEAR	Coverage of area under plant protection measures ('000 hec)	Distribution of Chemicals (M.T.)
2007-08	440	135
2008-09	435	135
2009-10	442	169
2010-11	438	141
2011-12	315	120
2012-13	320	121

Climate variation 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 (Brasier, 2001). For example Stewart's wilt, a bacterial (*Erwinia stewartii*) disease of generally sporadic importance in sweet corn in the northeast, is vectored by the corn flea beetle (*Chaetocnema pulicaria*). Climate variations 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. Similarly Late blight (*Phytopthora infestans*) infects both potatoes and tomatoes. Infection from this disease is triggered by high moisture conditions within a fairly specific temperature range. In wheat the survival of rusts depends on hosts being continuously available. Increased rain over summer will enable more growth of 'volunteer' wheat and other grass hosts and result in more rust inoculum being available to infect early sown crops (Chakraborty *et.al.*, 1998).

There has been only limited research on impact of climate change on plant diseases under field conditions or disease management under climate change. Emphasis should shift from impact assessment to developing adaptation and mitigation strategies and options. There is need to evaluate under climate variations the efficacy of current physical, chemical and biological control tactics, including disease-resistant cultivars. Future climate scenarios in all research should be 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.

Some of the plant diseases influenced by climate variations are as follows:

Diseases	Pathogen	[1] Anticipated effect of climate change(↑,-,↓)		Time[2]	[3] Remarks	[4]Estimated effect (+, -)	References
		1^o inoculums / disease establishment	Rate of disease progress				
Root rot	*Phytophthora* spp.	-	↑	-	B/EK	--	Stuteville, andErwin , 1990
Wilt	*Erwinia* spp.	↑	↑	↑	C/GH	+	White, 1999
Powdery mildew	*Oidium* spp.	↑	↓	↑	BE	-	Hartman *et.al.*, 1999
Angular leaf spot	*Phaeoisariopsis* spp.	↑	↓	-	BD/E	-	Hall, 1991
Early blight	*Alternaria* spp.	↑	↓	↑	AB/EL	-	Howard , 1994; Hooker, 1981
Late blight	*Phytophthora* spp.	↑	↓	↑	BD	-	Howard , 1994; Hooker, 1981
Collar rot	*Phytophthora* spp.	↑	↓	-	AB/KN	-	Jones and Aldwinckle, 1990
Apple scab	*Venturia* spp.	↓	↓	-	B/EM	-	Jones and Aldwinckle, 1990
Soft rot	*Erwinia* spp.	-	↑	-	AB/LM	+	Howard , 1994; Schwartz and Mohan,1995
Black rot	*Botryoshpaeria* spp.	↑	↓	-	B/EM	-	Jones and Aldwinckle, 1990
Bacterial blight	*Xantomonas* spp.	-	-	-	D/EFM	o	Hall, 1991

White rot	*Selerotium* spp.	-	↓	-	A/EK	-	Howard , 1994; Schwartz and Mohan,1995
Common smut in corn	*Ustilago* spp.	↑	↑	↑	FL	++	White, 1999
Ear rot in corn	*Fusarium* spp	↑	↑	↑	B/FL	+	White, 1999
Grey leaf spot	*Cercospora* spp	↑	↑	↑	B/EM	+	White, 1999
Stalk rot in sweet corn	*Fusarium* spp	↑	↑	↑	B/L	+	White, 1999; Howard , 1994
Bean yellow mosaic virus	*virus*	↑	↑	-	C/HIO	++	Hall, 1991
Aster yellow in carrot	*Phytoplasma*	↑	↑	-	BC/GIJ	+	Howard , 1994
Basal rot in onion	*Fusarium* spp	↑	↑	-	A/F	+	Howard , 1994; Schwartz and Mohan,1995
Damping off in onion	*Fusarium* spp	↑	↑	-	ABC/G	+	Howard , 1994; Schwartz and Mohan,1995
Pink rot in onion	*Phoma* spp	↑	↑	-	A/FGH	+	Howard , 1994; Schwartz and Mohan,1995
Verticillium wilt in potato	*Verticillium* spp	↑	↑	↑	A/G	+	Howard , 1994; Hooker, 1981
Common scab on potato	*Streptomyces* spp	-	↑	↑	BD/K	+	Howard , 1994; Hooker, 1981

Potato leaf roll virus	*virus*	-	↑	↑	BC/HI	++	Howard , 1994; Hooker, 1981
Cucumber mosaic virus	*virus*	↑	↑	-	C/GHI	++	Howard , 1994; Hooker, 1981
Powdery mildew in apple	*Podosphaera* spp	↑	↑	-	B/FL	+	Jones and Aldwinckle, 1990
Powdery mildew in grape	*Uncinula* spp	↑	↑	-	F	+	Pearson and Goheen, 1988
Powdery mildew in strawberries	*Sphaerotheca* spp	↑	↑	-	B/F	+	Maas, 1984
Root lesion in strawberries	*Pratylenchus* spp	-	↑	-	A/G	+	Maas, 1984
Anthracnose in turf	*Calletotrichum* spp	↑	↑	-	B/G	+	Smiley *et.al.*, 1992
Brown patch in turf	*Rizoctonia* spp	-	↑	-	B/GF	+	Smiley *et.al.*, 1992
Rust in wheat	*Puccinia* spp	↑	↑	-		+	Chakraborty *et.al.*, 1998
Maize dwarf mosaic virus	*Virus*	↑	↑	↑	P	++	Olesn *et.al.* 1990

[1] "↑" = Anticipated increase, "↓"= decrease and " – "= no change.

[2] Anticipated effect of increased growing season length on disease.

[3] Reason(s) for anticipated effect:

A. Initial or primary inoculum is soil borne and expected to remain at the same levels, or possibly decrease, due to milder winters, longer growing season, and increased microbial competition.
B. Initial or primary inoculum is debris borne or survives on host and is expected to increase due to increased survival over milder winters.
C. Initial or primary inoculum is insect borne and is expected to increase due to increased survival of insect vectors.
D. Initial or primary inoculum is introduced each year from outside sources i.e., seed borne, airborne. The influence of climate change is difficult to assess without knowledge of the pathogen, host, and source of inoculum.
E. Warmer and/or drier growing season slows rate of disease progress.
F. Warmer and/or drier growing season increases rate of disease progress.
G. Increased severity of disease symptoms due to stress of drier and/or warmer summer growing conditions.
H. Increased survival of insect vectors due to milder winter.
I. Increased rate of development of insect vectors due to warmer temperatures.
J. Earlier introduction of vectors or pathogens from southern regions.
K. Reduced soil moisture due to increased evapo-transpiration, sporadic precipitation, etc., affects pathogen.
L. Increased wound sites on hosts due to increased extreme weather events (i.e., thunderstorms, high winds, hail) and /or increased insect damage increases infection sites.
M. Reduced disease development and spread due to decrease in rain and/or length of time of leaf wetness.
N. Fruiting bodies on trees have a longer active growth period in both fall and spring, hence more primary inoculum.
O. On non-woody perennials, pathogens have longer to grow on roots or overwintering leaves so more damage and perhaps increased primary inoculum in spring.
P. Due to drought stress.
Q. Due to increase rains in summer.

[4] Net anticipated effect on a particular plant disease. From a significant increase (++) to a significant decrease (--) in importance (--, -, o, +, ++).

References:

- Agrios, G.N. 1997. Plant Pathology 4th ed., Academic Press, San Diego, CA. 635 pp.
- Brasier, C. M. 2001. Rapid evolution of introduced plant pathogens via interspecific hybridization. *BioScience*, **51**: 123–133.
- Chakraborty, S., Murray, G.M., Magarey, P.A., Yonow, T., O'Brien, R.G., Croft, B.J., Barbetti, M.J., Sivasithamparam, K., Old, K.M., Dudzinski, M.J., Sutherst, R.W., Penrose, L.J., Archer, C. and Emmett, R.W. 1998. Potential impact of climate change on plant diseases of economic significance to Australia. *Australian Plant Pathology*, **27**:15-35.
- Chakraborty, S., Tiedemann, A.V. and Teng, P.S. 1998b. Climate change and air pollution: Potential impact on plant diseases. *In* 7th *International Congress of Plant Pathology*. Edinburgh, Scotland. Aug. 9-16, 1998. British Society for Plant Pathology, Birmingham, UK. Invited Papers Abstracts **1**: 4.2.1S.
- Coakley, S.M. 1995. Biospheric change: Will it matter in plant pathology? *Canadian Journal of Plant Pathology*, **17**:147-153.
- Coakley, S.M., Scherm, H. and Chakraborty, S. 1999. Climate change and plant disease management. *Annual Review of Phytopathology*, **37**:399-426.
- Coleman, J.S., Jones, C.G., and Smith, W.H. 1988. Interaction between an acute ozone dose, eastern cottonwood and Marssonia leaf spot: Implications for pathogen community dynamics. *Canadian Journal of Forest Research*, **66**: 863-868.
- Hall, R. (ed.). 1991. Compendium of Bean Diseases. APS Press, St. Paul, MN. 73 pp.
- Harrington, R., Bale, J.S. and Tatchell, G.M. 1995. Aphids in a changing climate. Pp. 125-155 *in* R. Harrington and N.E. Stork, (eds.). Insects in a Changing Environment. Academic Press, San Diego, CA. 535 pp.
- Hartman, G.L., J.B. Sinclair and J.C. Rupe (eds.). 1999. Compendium of Soybean Diseases, 4th ed. APS Press, St. Paul, MN. 100 pp.
- Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S. and Samuel, M.D. 2002. Climate warming and disease risks for terrestrial and marine biota. *Science*, **296**:2158-2162.
- Holley, J.D., Hofstra, G. and Hall, R. 1985a. Appearance and fine structure of lesions caused by the interaction of ozone and *Alternaria solani* in potato leaves. *Canadian Journal of Plant Pathology*, **7**: 277-282.
- Holley, J.D., Hofstra, G. and Hall, R. 1985b. Effect of reducing oxidant injury and early blight on fresh weight and tuber density of potato. *Phytopathology*, **75**: 529-532.

- Hooker, W.J. (ed.). 1981. Compendium of Potato Diseases. APS Press, St. Paul, MN. 125 pp.
- Howard, R.J., J.A. Garland and W.L. Seaman (eds.). 1994. Diseases and Pests of Vegetable Crops in Canada. The Canadian Phytopathological Society and Entomological Society of Canada, Ottawa, ON. 554 pp.
- Jones, A.L. and H.S. Aldwinckle (eds.). 1990. Compendium of Apple and Pear Diseases. APS Press, St. Paul, MN. 100 pp.
- Karnosky, D.F., Percy, K.E., Xiang, B., Callan, B., Noormets, A., Mankovska, B., Hopkin, A., Sober, J., Jones, W., Dickson, R.E. and Isebrands, J.G. 2002. Interacting elevated CO_2 and tropospheric O_3 predisposes aspen (*Populus tremuloides* Michx.) to infection by rust (*Melampsora medusae* f.sp. *tremuloidae*). *Global Change Biology*, **8**:329-338.
- Kaukoranta, T. 1996. Impact of global warming on potato late blight: Risk, yield loss and control. Agricultural and Food Science in Finland, **5**:311-327.
- Maas, J.L. (ed.). 1984. Compendium of Strawberry Diseases. APS Press, St. Paul, MN. 138 pp.
- Manning, W.J. and Tiedemann, A.V. 1995. Climate change: Potential effects of increased atmospheric carbon dioxide (CO_2), ozone (O_3) and ultraviolet-B (UV-B) radiation on plant diseases. *Environmental Pollution*, **88**:219-245.
- Mboup, M., Bahri, B., Leconte, M., De Vallavieille-Pope, C., Kaltz, O. and Enjalbert, J. 2012. Genetic structure and local adaptation of European wheat yellow rust populations: the role of temperature-specific adaptation. *Evol. Appl*., **5**: 341–352.
- Olsen, A. J., Pataky, J. K., D'arcy, C. J. and Ford, R. E. 1990. Effects of drought stress and infection by maize dwarf mosaic virus in sweet corn. *Plant Dis*., **74**: 147–151.
- Paul, N.D., Ayres, P.G., Rasanayagam, S. and Royle, D.J. 1998. Stratospheric ozone depletion, UVB radiation and *Septoria tritici* infection of wheat. *In* 7th International Congress of Plant Pathology. Edinburgh, Scotland. Aug. 9-16, 1998. British Society for Plant Pathology, Birmingham, UK. Invited Papers Abstracts **1**: 4.2.6.S.
- Pearson, R.C. and A.C. Goheen (eds.). 1988. Compendium of Grape Diseases. APS Press, St. Paul, MN. 93 pp.
- Porter, J.H., Parry, M.L. and Carter, T.R. 1991. The potential effects of climatic change on agricultural insect pests. *Agricultural and Forest Meteorology*, **57**:221-240.
- Sandermann Jr., H. 2000. Ozone/biotic disease interactions: Molecular biomarkers as a new experimental tool. *Environmental Pollution,* **108**:327- 332.

- Schwartz, H.F. and S.K. Mohan (eds.). 1995. Compendium of Onion and Garlic Diseases. APS Press, St. Paul, MN. 54 pp.
- Smiley, R.W., P.H. Dernoeden, and B.B. Clarke (eds.). 1992. Compendium of Turfgrass Diseases, 2nd ed. APS Press, St. Paul, MN. 98 pp.
- Stuteville, D.L. and D.C. Erwin (eds.). 1990. Compendium of Alfalfa Diseases, 2nd ed. APS Press, St. Paul, MN. 84 pp.
- Tiedemann, A.V. and Firsching, K.H. 1998. Hostpathogen systems in a changing atmosphere: Case studies with fungal pathogens on wheat. *In* 7th International Congress of Plant Pathology. Edinburgh, Scotland. Aug. 9-16, 1998. British Society for Plant Pathology, Birmingham, UK. Invited Papers Abstracts **1**: 4.2.7S.
- White, D.G. (ed.). 1999. Compendium of Corn Diseases, 3rd ed. APS Press, St. Paul, MN. 78 pp.