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Impact of Climate Change on Diseases of Crops and Their Management—A Review

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Abstract: Change in global climate is primarily due to rising concentrations of greenhouse gases in the atmosphere that is mostly caused by human activities. The important factors affecting the occurrence and spread of the plant diseases are temperature, moisture, light, and CO_2 concentration. These factors cause physiological changes in plants that result in increase in intensity of crop diseases. Climate change causes a significant impact on germination, reproduction, sporulation and spore dispersal of pathogens. Climate change affects all life stages of the pathogen as well as its host to cause impact on host-pathogen interaction which facilitates the emergence of new races of the pathogen ultimately breakdowns the host resistance. It also affects the microbial community in the soil which is beneficial to the plants in various aspects. The minor diseases become major ones due to alteration in climatic parameters thus posing a threat to the food security.

Key words: Climate change, greenhouse gases, temperature, elevated CO_2, pathogens, sporulation.

1. Introduction

Climate change is a long-term shift in the statistics of the weather. Worldwide climate change is a major concern of discussion within both scientific and political forums. According to World Meteorological Organization (WMO) the decade (2010-2020) is the warmest decade on record. Changes in climate are still going unstopped and temperature is projected to increase by 3.4 ℃ and CO_2 concentration to 1,250 ppm by 2095, along with much greater variability in climate and more extreme weather-related events [1] accompanied by more climatic variability and adverse weather events [2]. In India, it is likely to experience a temperature rise of 1-4 ℃; rainfall will increase by 9%-16% by 2050. This change in the earth's atmospheric composition is mostly due to the unscrupulous activities of the human beings. The changes in the earth's climate are the result of changes in the cryosphere, biosphere, hydrosphere, and other interacting factors. Greenhouse gases like water vapor (H_2O), methane (CH_4), carbon dioxide (CO_2), nitrous oxide (N_2O), hydrofluorocarbons (HFCs) and ozone (O_3) present in the earth's atmosphere trap the reflected radiation; and in turn warm the earth surface [3]. Biological processes are strongly influenced by temperature and water availability. Climate change is affecting all the four pillars of food security: availability (yield and production), access (prices and ability to obtain food), utilization (nutrition and cooking), and stability (disruptions to availability) [4].

Many environmental factors affect plant disease development viz., temperature, light and water availability, soil fertility, wind speeds, and atmospheric ozone, methane and CO_2 concentrations. Among these, three factors viz., CO_2 concentration,

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temperature, and water availability are mostly changed and affect the environment. Climate change affects crop pest and disease susceptibility which affects crop health, and these changes result in a shift in farming practices to manage the effects of these changes and to prevent a reduction in productivity. It can impact food security and thus human health [5]. The popular "disease triangle" concept in plant pathology underlines the interaction of both pathogens and plants with the environment. For a disease to occur, a susceptible plant host, a virulent pathogen, and the optimum environmental conditions are required, as lack of any of these three factors fails in disease development [6]. Variation in any of these three factors results in non-occurrence of disease and when these factors coincide for a conducive time period, only then the disease occurs. Changing weather parameters can induce severe plant disease epidemics [7]. The effect of environmental factors on plants and pathogens can have favorable, neutral or negative outcomes on plant disease development. Both pathogens and plants need an optimal environmental condition for their growth and reproduction, which is best for disease outbreaks. Few works have been done to model the effects of climate change on plant disease epidemics. Severe plant disease epidemics can be induced by changing weather, which threatens food security if they affect staple crops [8]. There is an exemplar shift in nature, time and type of occurrence of viral and other diseases of various horticultural crops due to climate change [9]. Several reports indicate that plant pathogens cause significant economic crop yield losses every year [10, 11]. Cereal, spices and vegetables are most affected by the disease due to changing climate parameters *i.e.*, high incidence of colocasia leaf blight and moderate incidence of blast and brown spot of paddy, bacterial blight and false smut of paddy, stripe rust of wheat, curvularia leaf spot of maize, leaf blotch and leaf spot of turmeric, tomato leaf curl, citrus canker, downy mildew and powdery mildew of cucurbits, fruit rot, and anthracnose of king chili, banana and Sigatoka diseases [12].

2. Climate Change and Plant Pathosystems

Plant diseases play a key role in agriculture. Previously, many plant diseases considered minor emerged as a major ones as a result of changing climatic scenario. Plant pathologists continuously study the environmental effect on plant diseases. The disease triangle focuses on the relationship between plant hosts, pathogens, and the environment in causing disease. The global climate changes by various factors [13] change or influence all the three major elements of the disease triangle, *viz.*, host, pathogen and environment [14]. However, the disease triangle of any plant pathogen interaction may shift in response to climate change, favoring different climatic preferences and niche breadths in the future [15]. Furthermore, while some environmental changes, such as increasing temperature and changing precipitation, are linked directly to change in pathogen incidence and severity [16], others, such as increases in CO_2 levels, have more indirect effects by changing biomass production, the density of crop stands, and hence humidity within the canopies [17]. Plant health is commonly suffered under climate change through various mechanisms like rapid pathogen evolution. In the case of fungal pathogens, moisture is necessary for the germination and initiation of infection by spores as well as for dispersal in many species. In some cases, drought helps in enhancing fungal diseases of plants [18], especially in forest trees. Synergistic interaction between drought and infection has been shown on tree physiology and the severity of plant diseases [19].

3. Environmental Factors Affecting Plant Diseases

Many environmental parameters affect plant disease development *viz.*, temperature, light, CO_2 concentrations, water availability, soil fertility, wind speeds, etc. Among these, three factors are most likely to change and affect the climate: temperature, water availability and CO_2 concentrations which are discussed thoroughly in the next sections [20].

3.1 Effects of Changing Temperatures

Temperature plays an important role in the development of plant and plant-pathogen interaction. An alteration in temperature may facilitate the evolution of many avirulent plant pathogens, which can induce an epidemic. Temperature affects the chain of events in the disease cycle *viz*., survival, dispersal, penetration and development as well as reproduction rate of many pathogens. Due to continuous change in temperatures, climate change may affect the growth stage, development rate, physiology and resistance of the host plant [21, 22]. The change in ambient temperature [23] influences the microbial pathogens, host and simultaneously disease incidence [24, 25]. The effect of elevated temperature on pathogen aggressiveness is both high and low (Table 1). Rise in temperature with sufficient soil moisture may boost evapo-transpiration causing humid microclimate in crops which helps to increase in extent of diseases [26]. Generally, high moisture and temperature favor the initiation of disease development as well as germination and proliferation of fungal spores of various pathogens. Evidence suggests that temperature affects pathogens due to the accumulation of phytoalexins or protective pigments in the host tissues. A temperature rise facilitates spore germination of rust fungus *Puccinia* substrate [27]. For instance, Karnal bunt (*Tilletia indica*) and common bunt (*Tilletia caries*) in wheat can be of importance under changing climatic conditions in areas with low productivity, if proper treatment of seed is not followed in this crop [28]. Higher risk of dry root rot has been reported in Fusarium wilt chickpea-resistant varieties when the temperature increased beyond 33 ℃ [29]. In North America, needle blight (*Dothistroma septosporum*) is reported to be spreading northwards with increase in temperature and precipitation [30]. Oil seed pathogens *viz*., *Alternaria brassicae*, *Sclerotinia sclerotiorum*, and *Verticillium longisporum* in Northern Germany are anticipated to be benefited by average warmer temperatures, especially when taking a long-term (2071-2100) view [31].

Owing to continuous change in temperature, the plant pathogenic bacteria (heat loving) like *Ralstonia solanacearum*, *Acidovorax avenae* and *Burkholderia glumae* have emerged as a serious problem worldwide [32]. Singh *et al.* [33] reported that bacterial wilt disease intensity incited by *R. solanacearum* was found maximum 8.73% and 95.9% in injured roots of Pusa Ruby and N-5 cultivars of tomato at 35 ℃ on 11th d of inoculation respectively. However, no wilt disease was observed in both the cultivars at 20 ℃ up to 60 d. Climate can have a significant impact on the development and dispersal of vectors. It can result in geographical distribution, increases in the number of generations, overwintering, changes in population growth rates, crop-pest synchrony of phenology, changes in inter-specific interactions and increased risk of attack by migratory insects. The rise in temperature with enough soil moisture may increase evapotranspiration which creates humid conditions in the crop which leads to an elevated incidence of diseases [34, 35].

The temperature has a significant impact on plant diseases by affecting both hosts as well as the pathogens. Scientists reported that the increase in temperature above 20 ℃ can disable temperature-sensitive resistance genes like Pg3 and Pg4 in oat [36]. Likewise, wheat leaf rust resistance genes *viz.*, Lr2a, Lr210 and Lr217 are also temperature sensitive. Only Lr2a genes show resistance at a temperature beyond 25 ℃ [12]. So, a shift in temperature will surely affect the resistance capacity of these genes. Many mathematical models designed for predicting plant disease epidemics are based on increases in pathogenic growth and infection within specified temperature limits. The effects of increased temperature on plants will tend to vary greatly throughout the year. Warming during colder

Table 1 Influence of elevated temperature on host pathogen interaction.

S. No.	Crop/host	Disease inciting pathogens	Change in severity	References
1	Pineapple	*Fusarium subglutinans*	Decrease	Matos *et al.* [39]
2	Wheat	*Puccinia striformis*	Decrease	Yang *et al.* [40]
3	Wheat	*Tilletia controversa*	Increase	Boland *et al.* [41]
4	Wheat	*Puccinia striformis*	Increase	Milus *et al.* [42]
5	Citrus	*Colletotrichum acutatum*	Increase	Jesus Junior [43]
6	Citrus	*Guignardia citricarpa*	Increase	Jesus Junior [43]
7	Potato	*Phytophthora infestans*	Increase	Hannukkala *et al.* [44]
8	Coffee	*Meloidogyne incognita*	Increase	Ghini *et al.* [45]
9	Chilli	*Ralstonia solanacearum,* *Xanthomonas campestris* pv. *vesicatoria*	Increase	Shin and Yun [46]
10	Tomato	*Ralstonia solanacearum*	Increase	Singh *et al*. [33]
11	Grapevine	*Plasmopara viticola*	Increase	Pugliese *et al.* [47]
12	Wheat	*Blumeria graminis* f. sp. *tritici*	No change	Matic *et al.* [48]
13	Celery	*Fusarium oxysporum* f. sp. *apii*	Increase	Kaur *et al.* [49]

periods of the year may mitigate plant stress, whereas during hotter parts of the year results in strain. A striking example of the potential effect on the yield of crop plants in response to elevated temperature, rice yield in the Philippines was estimated to decline 10% for each 10 ℃ increase in the minimum temperature during the dry season [37]. Neilson and Boag [38] assessed the possible effect of climatic change on the distributions of common virus-transmitting *Xiphinema* and *Longidorus* species of nematode. They reported that an increase of mean temperature 1 ℃ resulted in the northward extension of these nematodes by about 160-200 km.

3.2 Drought

Unpredictable drought is the single most important factor that affects global food security by encouraging the development of epidemics. Usually via unintended outcomes on host physiology, drought is presumed to magnify the frequency of pathogens [50, 51]. For this reason, an increased incidence of drought is expected to enhance the probability that trees will be infected by root pathogens, wound colonizers, and latent colonizers of sapwood [52]. Plants in regions, in which the incidence of drought and other stress conditions increases in frequency, may face root infection by *Armillaria* spp., canker-causing fungi (*Botryosphaeria* & *Diplodia*) and *Phytophthora*, etc. It has also been concluded that drought stress influences the quality and rigidness of viruses, for instance, Maize dwarf mosaic virus (MDMW) and Beet yellows virus (BYV) [53, 54]. *Heterobasidion irregular*, an invasive exotic species in Italy was found to be well accommodated for dispersion in the Mediterranean climate as the indigenous *H. annosum* [55].

3.3 Effect of Elevated CO_2 Levels

Tropospheric CO_2 concentrations are estimated to rise from 355 to 710 ppm, by the year 2050. There are enormous literatures on the beneficial effects of elevated CO_2 concentrations on biomass production, probably due to increased water use efficiency [56]. Higher CO_2 concentrations are expected to increase the photosynthetic rate and crop yield of C3 plants. Depending on the crop studied, there is an increase range of 5% to 40% in yield in free-air CO_2 enrichment (FACE) experiments using the predicted CO_2 concentrations that will be reached by the end of the century [57]. C4 plants (e.g., corn and sugarcane), however, will not benefit from this increase in atmospheric CO_2 due to their already inherent CO_2 concentration mechanisms. Elevated CO_2 concentrations can increase the yields of C3 crop plants. They also increase disease severity in rice and wheat *i.e.* 620 and 780 ppm, respectively;

these are our main staple crops with the highest worldwide production. Much less is known about CO_2 effects on the incidence and severity of biotic diseases of plants. An increase in CO_2 concentrations has a direct effect on both the host plant and the pathogen (Table 2). The well-known effects are an increase in leaf area, leaf thickness, tillering, branching, dry weight, and stem and root length. An increase in CO_2 concentration leads to an increase in canopy size and density resulting in increased high nutritional quality biomass. When this CO_2 concentration is combined with increased canopy humidity, it promotes foliar diseases such as rust, powdery mildew, blight and leaf spot. Under increased temperature and CO_2, new races may intensify as evolutionary forces act on mass pathogenic populations boosted by a combination of increased fecundity and infection cycles under favourable condition within enlarged canopy [58]. For the fungal pathogen *Fusarium graminearum*, elevated CO_2 levels not only increased the susceptibility of wheat varieties (irrespective of the resistant and susceptible genotypes evaluated), but also increased the virulence of the fungal isolate [59], resulting in more severe disease overall. In contrast, in some oomycete plant interactions such as between soybean and *Peronospora manshurica*, CO_2 concentrations of 550 ppm decreased the severity of the disease by more than 50% [60, 61]. Lower plant decomposition rates observed in high CO_2 situations could increase the crop residue on which disease organisms can overwinter, resulting in higher inoculums levels at the beginning of the growing season, and earlier and faster disease epidemics. Higher CO_2 concentration has significant impact on the growth of pathogen which results in greater fungal spore production. However, elevated CO_2 can result in physiological changes to the host plant that can increase host resistance to pathogens [36]. The modified root morphology with branching pattern and exudation of chemical compound in the rhizosphere has been reported due to rise in CO_2 concentration [62]. An increase in CO_2 levels may stimulate the production of plant biomass; although, productivity is regulated by availability of water and nutrients, competition against weeds and loss from pests and diseases. The increase in crop residues results in better survival conditions for necrotrophic pathogen. The reduction in stomatal opening can hinder the stomata-invading pathogens. The shortened growth period and accelerated ripening and senescence can reduce the infection period for biotrophic pathogens and increase the necrotrophic pathogen population. Alternatively, high level of carbohydrates in the host tissue enhances the growth of biotrophic fungi such as rust, powdery mildew [63]. In general, density of normal grown plant will tend to increase leaf surface wetness period and regulate temperature, and hence it makes a chance of infection by foliar pathogens [64].

Rise in hostile behavior of *Erysiphe cichoracearum* under elevated CO_2 was observed by Lake and Wade [65], along with changes in attributes of leaf epidermal of the model plant. Similarly Kobayashi *et al.* [66] also reported that both rice blast and sheath blight increased when CO_2 increased from 365 ppm to 550 ppm. However, elevated CO_2 had little or no effect on incidence levels of the panicle blast phase of the disease [67]. At elevated CO_2 levels, red maple leaves exhibit increased resistance for the fungus *Phyllosticta minima*, which was linked with reduced stomatal aperture [26]. Also in the tomato-*Pseudomonas syringae* pv. *tomato* DC3000 interaction, a correlation between increased disease resistance and a reduction of stomatal aperture was discovered under elevated CO_2 conditions [68]. Elevated ozone can have a similar effect such as a 3- to 5-fold increase in rust infection on poplar, however this response is reduced by elevated CO_2 [69]. Nematode genera differ in their reaction to CO_2 enrichment. The ample of *Tylenchus* and *Longidorus* increased after 5 years of CO_2 enrichment, but there was no effect of CO_2 enrichment on the ample of *Paratylenchus*, *Trichodorus* and members of *Hoplolaimidae* in pasture plots [70].

Table 2 Influence of elevated CO_2 concentration on host pathogen interaction.

S. No.	Crop/host	Disease (Pathogens)	Severity level	References
1	Chilli	Phytophthora blight (*Phytophthora capsici*)	Increase	Shin and Yun [46]
		Bacterial wilt (*Ralstonia solanacearum*)	Increase	
		Bacterial spot (*Xanthomonas campestris* pv. *vesicatoria*)	Increase	
		Anthracnose (*Colletotrichum acutatum*)	Decrease	
2	Grapevine	Downy mildew (*Plasmopara viticola*)	Increase	Pugliese *et al.* [47]
3	Wheat	Powdery mildew (*Blumeria graminis* f. sp. *tritici*)	No effect	Matic *et al.* [48]
4	Wheat	Fusarium head blight (*Fusarium graminearum*)	Increase	Vary *et al.* [59]
		Blotch (*Septoria tritici*)		
5	Soybean	Downy mildew (*Peronospora manshurica*)	Decrease	Eastburn *et al.* [60]
		Septoria brown spot (*Septoria glycine*)	Increase	
		Sudden death syndrome (SDS)	No effect	
6	Penciflower (*Stylosanthes*)	Anthracnose (*Colletotrichum gloeosporiodes*)	Decrease	Chakraborty *et al.* [63]
7	Cucurbits	Powdery mildew (*Erysiphe cichoracearum*)	Increase	Lake and Wade [65]
8	Rice	Sheath blight (*Rhizoctonia solani*)	Increase	Kobayashi *et al.* [66]
9	Rice	Blast (*Pyricularia oryzae*)	Increase	Kobayashi *et al.* [66]
10	Tomato	Bacterial speck (*Pseudomonas syringae* pv. *tomato*)	Decrease	Li *et al.* [68]
11	Aspen (Poplar)	Rust (*Melampsora medusae* f. sp *tremuloidae*)	Increase	Karnosky *et al.* [69]
12	Barley	Powdery mildew (*Erysiphe graminis*)	Decrease	Hibberd *et al.* [75]
13	Arabidopsis	*Rhizoctonia solani*	No effect	Zhou *et al.* [76]
		Fusarium oxysporum		
14	Grapevine	Powdery Mildew (*Uncinula necatrix*)	No effect	Pugliese *et al.* [77]
15	Rocket salad	Alternaria leaf spot (*Alternaria japonica*)	Increase	Pugliese *et al.* [78]
		Basil black spot (*Colletotrichum gloeosporiodes*)		
16	Zucchini	Powdery mildew (*Podosphaera xanthii*)	No effect	Pugliese *et al.* [79]
17	Potato	Late blight (*Phytophthora infestans*)	Increase	Hannukkala *et al.* [80]
18	Tomato	Root rot (*Phytophthora parasitica*)	Decrease	Jwa and Walling [81]
19	Wheat	Leaf rust (*Puccinia triticina*)	Increase	Tiedmann and Firstching [82]
20	Basil	Downy mildew (*Peronospora belbahrii*)	Decrease	Gilardi *et al.* [83]
21	Wild rocket and radish	Leaf spot (*Fusarium equiseti*)	Increase	Gullino *et al.* [84]
22	Cucurbits	*Sphaerotheca fuliginea*	Increase	Khan and Rizvi [85]
23	Chickpea	*Fusarium osyxporum* f. sp. *ciceris*	Decrease	Bhatia *et al.* [86]

CO_2 enrichment results increase in population of *Meloidogyne* sp. in grassland turfs [71]. The response of nematode against CO_2 enrichment may be influenced by site or location like the population of *Pratylenchus* sp. has shown positive relation to CO_2 enrichment in gley soil but not in organic soil. Most of nematode families are not influenced by elevated CO_2 excluding two nematode families which were remarkably prejudiced by CO_2 enrichment (*Anguinidae* increased in one case and *Hoplolaimidae* decreased in another) [72]. Generally, the consequences of raised concentration of CO_2 on plant diseases can be positive or negative, however, in most of the cases disease seriousness increased [73, 74].

3.4 Effect of Rainfall and Moisture

Moisture is one of the main factors affecting growth of pathogens. Irregular rainfall pattern for longer period aids in retaining moisture as leaf surface and relative humidity (RH) in atmosphere for longer time and thus provides conducive condition for pathogens and diseases such as late blights and vegetable root diseases including powdery mildews [36]. Several studies demonstrated that changes in the amount of rainfall do not affect the occurrence of the epidemics since they have little effect on the leaf wetting period [45]. However, decreased levels of rainfall may lead to decreased incidence of downy mildew infections in grapes. Under warming situations, the increase in temperature more than compensates for the reduction in duration of leaf wetness, in part because infections that start earlier in the growing season allow more time for epidemics to develop [87]. Similarly, foliar disease of barley caused by *Drechslera teres* is most severe in temperate regions with high rainfall and humidity, and it caused yield losses through the reduction of 1,000-kernel weight [88]. Moreover, high moisture facilitates some soil borne pathogens such *Pythium*, *Phytophthora*, *R. solani* and *Sclerotium rolfsii.* In contrast to these diseases, conidia of powdery mildew pathogen hold their ability to germinate in low moisture; even the conidia of *E. cichoracearun* germinate from 7 to 32 ℃ with an RH of 60%-80%. Some can do so even at 0% RH [89]. Spores of *E. necator* germinate at temperatures from 6 to 23 ℃ with an RH from 33%-90% [90].

Low soil moisture affects the incidence and severity of viruses such as BYV and MDMW [53, 54]. As air can hold more water vapor at higher temperatures, the possibility for dew accumulation (and consequently, pathogen infection) increases at higher temperatures. On the other hand, soil moisture is more critical than air humidity for soil-inhabiting pathogens, many of which cause plant wilt diseases. Lower soil moisture decreases the incidence of infection of *R. solanacearum* in tomato plants [91]. In fact, balancing moisture levels that reduces disease incidence but still favors plant growth is an important cultural practice for disease management [92]. Contrary to the effect observed for *Ralstonia* infection of tomato plants, drought conditions caused more aggressive infections by *Magnaporthe oryzae* in rice, resulting in larger pathogen populations and more visible disease symptoms [93]. In the interaction between potato and the bacterial scab pathogen *Streptomyces* spp., lower soil moisture also favors disease development, and as such, increasing soil moisture can be used as a strategy to control this disease [94].

The Phoma stem canker of oilseed rape increased disease severity predicted under regional changes in the UK in both temperature as well as rainfall [95]. Jung [96] reported in central Europe that several *Phytophthora* spp., and these species were responsible for increasing amounts of root rot in forest trees by increasing mean winter temperatures, shift in precipitation from summer to winter, and tendency toward heavier rain. The concentration of mycotoxin produced by Fusarium head blight in grain generally increases with the number of rainy days and days with high RH but decreases with low and high temperatures [96]. Due to the large variation in the response of plant pathogens to climate change, the incidence of pathogens must be characterized as a function of the temperature and humidity. The climate is becoming increasingly extreme and unpredictable, and climate change is affecting plants in natural and agricultural ecosystems [97, 98].

3.5 Combined Effect of Multiple Environmental Factors

It is not straight forward to predict the combined effect of changing environmental conditions for the development of the disease in plans [99, 100]. Prasch and Sonnewald [101] reported that the combined heat, drought and turnip mosaic virus (TuMV) infection in Arabidopsis causes a more severe reduction in plant growth than each individual factor alone. A combination of warm temperature and high RH provides the optimum conditions for the disease development in plant caused by many fungal pathogens [102]. In the interaction between *Botrytis cinerea* and grapes, both air RH near to 100% and temperatures between 20 and 25 ℃ were required for optimal disease [103], and deviations from this optimum conditions resulted in a drastic decrease in disease incidence. In the field, plants and pathogens experience multiple environmental factors. How the combined effects of multiple environmental conditions affect the disease outcome remains one of the most outstanding and challenging questions for the future study of plant pathogen interactions.

4. Management Strategies for Plant Diseases under Climate Change

Adaptation strategies recent predictions and estimations of increased frequency of climate extremes worldwide, as well as changes in eco-zones, might be an indication of global warming-related changes already under way [51, 104, 105]. There is a need to integrate findings and insights from the physical and social sciences with knowledge from local farmers and land managers to provide guidance and suggestions to decision-makers for promotion of robust strategies, including cooperation of both public and private sectors. In addition to changes driven by socio-economic factors, farmers will have to adjust according to the climatic changes in the upcoming years by implementing different types of agronomical techniques which are performing well nowadays such as rearranging the timing of planting and harvesting operations, switching cultivars and doing needful modification or changing thoroughly in their cropping systems and agricultural practices wherever needed [106]. However, adaptation strategies vary with the agricultural systems, location and scenarios of global climate change. At higher levels of adaptation, cropping systems and crop types could be changed altogether in addition to field management adjustments or cultivation areas could shift geographically, following the creation of new agricultural zonations determined by a changing climate [107, 108]. Under warmer climates, crops would tend to mature faster, resulting in less time available for accumulation of carbohydrate and grain production. Therefore, by substituting current cultivars with genotypes requiring longer time to mature, yield potential under climate change may be restored to levels typical of current conditions. In addition to changing planting strategies and cultivar type, land management systems could be adapted to new climate scenarios. Switching from rainfed to irrigate agriculture is the easiest way, even though problems of water availability, cost, and challenges from other sectors need to be examined [51, 106, 109]. It seems unreasonable to expect perfect adaptation in the future to changing climate conditions. Some adaptations will likely be successful (e.g., change in planting dates to avoid heat stress), while other attempted adaptations (e.g., changing varieties and breeds, altered crop rotations, development of new agricultural areas) may not always be effective in avoiding the negative effects of droughts or floods on crops. Importantly, there are additional dimensions to adaptation related to social and cultural aspects that might either favor or hinder adoption of new techniques by farmers, depending on community dynamics [110, 111].

Climate change can affect the efficiency of an agrochemical. Fungicide and bactericide efficacy may change with increased CO_2, moisture, and temperature. The more frequent rainfall events predicted by climate change models result in farmers finding it quite difficult to keep residues of contact fungicides on plants, triggering more frequent applications. The temperature affects the degradation of pesticides, and changes the morphology and physiology of plants affecting their penetration, translocation and mode of action [51]. Changes in duration, onset and intensity of rainfall may alter the efficacy of fungicide. Higher level of precipitations can lead to the wash-off of chemicals. Systemic fungicides could be affected negatively by physiological changes in plants such as smaller stomatal opening or thicker epicuticular waxes in crop plants grown under higher temperatures. Enhanced thickness of epicuticular wax layer on leaves could result in lower uptake of fungicide by the host. According to Ghini *et al.* [45] increased canopy due to elevated CO_2 can affect the penetration, translocation and mode of action of systemic fungicides. Hunsche *et al.* [112] reported the influence of leaf surface characteristics on retention of mancozeb on apple seedlings, bean seedlings and knol-khol plants. Fungicide retention has strong negative correlation with surface roughness and total cuticle wax. It was also found that increased canopy size could have a negative impact on spray coverage and can lead to dilution of active ingredients. Moreover, regulatory means such as exclusion and quarantine processes may become more difficult for authorities as imported crops may frequently harbor the unexpected pathogens.

Therefore, some important mitigation strategies for managing plant diseases in respect of climate change include:

- Giving preference to resistant cultivars/varieties at raised temperature.
- New molecules having extreme efficacy at elevated temperature for disease management.
- For prognosis of arrival of diseases, new forecasting model is needed.
- To avoid reasons of epidemics, sowing dates can be shifted.
- Picking of bio-agents having broad range of temperature adoptability.
- Management of disease by integration of all the prevailing technologies.
- Use of effective tillage practices for disease management.

5. Conclusion and Future Research

Globally, plant pathogens reduce 10% to 16% of crop production even with improved pest and disease management measures. Since CO_2, temperature and RH are important factors affecting the plants and their pathogens, global food supply and disease risk are attracting great research interest as the resistance of many popular varieties breaks down. The cultivation practices, use of pesticides, biological strategies, use of resistant variety should be re-evaluated. New tools and technologies should be developed to combat under climate change scenario.

Unstable disease scenarios because of global climatic changes have emphasized the demand of improved agricultural practices and eco-friendly practices in the management of diseases for sustainable crop production. In the changing climate and shift in seasons, choice of crop management practices based on the existing situation is essential. In such situations, weather-based disease monitoring, inoculum monitoring, especially for soil-borne diseases and rapid diagnostics would play an important role. There is a need to adopt new approaches to counter the resurgence of diseases under climate change. Integrated disease management strategies should be developed to decrease dependence on fungicides [113]. 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. 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 farmers and food security at large [114]. Plant-derived soil reforms and botanical pesticides can alleviate the climate change, by lessening the emission of nitrous oxide by nitrification inhibitors namely, nitrapyrin and dicyandiamide [115].

There has been only limited research on the effect 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 develop adaptation and mitigation strategies and options. Firstly, there is need to analyze under climatic change the potential of ongoing physical, chemical and biological control programme, comprising disease-resistant varieties, and secondly to add upcoming climate scenarios in all research pursuing at elaboration new tools and resources. Disease risk analysis based on host-pathogen interactions should be managed 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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Conflicts of Interest

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References

[1] Savary, S., Ficke, A., Aubertot, J. N., and Hollier, C. 2012. "Crop Losses due to Diseases and Their Implications for Global Food Production Losses and Food Security." *Food Security* 4: 519-37.

[2] IPCC. 2007. *Climate Change 2007: Synthesis Report. Contributing of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by R. K. Pachauri, and A. Reisinger. Geneva, Switzerland: IPCC, 104.

[3] Mahato, A. 2014. "Climate Change and Its Impact on Agriculture." *Int. J. Scientific and Res Publica.* 4 (4): 18-26.

[4] Mbow, C., Rosenzweig, C., Barioni, L. G., Benton, T. G., Herrero, M., Krishnapillai, M., Liwenga, E., Pradhan, P., Rivera-Ferre, M. G., Sapkota, T., Tubiello, F. N., and Xu, Y. 2019. "Food Security." In *Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, edited by P. R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi and J. Malley.

[5] Fanzo, J., McLaren, R., Davis, C., and Choufani, J. 2017. "Climate Change and Variability: What Are the Risks for Nutrition, Diets, and Food Systems?" In *IFPRI*, 1-128.

[6] Agrios, G. N. 2005. *Plant Pathology* (5th ed.). San Diego, USA: Elsevier Academic Press, 922.

[7] Chakraborty, S. 2005. "Potential Impact of Climate Change on Plant-Pathogen Interactions." *Australasian Plant Pathology* 34: 443-8.

[8] Anderson, P. K., Cunningham, A. A., Patel, N. G., Morales, F. J., Epstein, P. R., and Daszak, P. 2004. "Emerging Infectious Diseases of Plants: Pathogen, Pollution, Climate Change and Agrotechnology Drivers." *Trends Ecological Evolution* 19: 535-44.

[9] Bergot, M., Cloppet, E., Perarnaud, V., De Que, M., Marcais, B., and Desprez-Loustau, M. L. 2004. "Simulation of Potential Range Expansion of Oak Disease Caused by *Phytophthora cinnamomi* under Climate Change." *Global Change Biology* 10: 1539-52.

[10] Kashyap, P. L., Rai, P., Kumar, S., Chakdar, H., and Srivastava, A. K. 2017. "DNA Barcoding for Diagnosis and Monitoring of Fungal Plant Pathogens." In *Molecular Markers in Mycology, Fungal Biology*, edited by B. P. Singh, and V. K. Gupta. Switzerland: Springer International Publishing, 87-122.

[11] Sharma, S., Rai, P., Rai, S., Srivastava, M., Kashyap, P. L., Sharma, A., and Kumar, S. 2017. "Genomic Revolution in Crop Disease Diagnosis: A Review." In *Plants and Microbes in an Ever Changing Environment*, edited by S. S. Singh. New York: Nova Science Publishers, 257-93.

[12] Das, T., Hajong, M., Majumdar, D., Tombisana Devi, R. K., and Rajesh, T. 2016. "Climate Change Impacts on Plant Diseases." *SAARC J. Agric.* 14 (2): 200-9.

[13] IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by R. Pachauri and L. Meyer. Geneva, Switzerland, 151.

[14] Legreve, A., and Duveiller, E. 2010. "Preventing Potential Diseases and Pest Epidemics under a Changing Climate." In *Climate Change and Crop Production*, edited by M. P. Reynolds. Wallingford: CABI, 50-70.

[15] Yang, L. N., Zhu, W., Wu, E. J., Yang, C., Thrall, P. H., Burdon, J. J., Jin, L. P., Shang, L. P., and Zhan, J. 2016. "Trade-Offs and Evolution of Thermal Adaptation in the

Irish Potato Famine Pathogen." *Molecular Ecol.* 25: 4047-58.

[16] Kocmankova, E., Trnka, M., Juroch, J., Dubrovsky, M., Semeradova, D., Mozny, M., and Zalud, Z. 2009. "Impact of Climate Change on the Occurrence and Activity of Harmful Organisms." *Plant Protec. Sci.* 45: S48-52.

[17] Thompson, M., Gamage, D., Hirotsu, N., Martin, A., and Seneweera, S. 2017. "Effects of Elevated Carbon Dioxide on Photosynthesis and Carbon Partitioning: A Perspective on Root Sugar Sensing and Hormonal Crosstalk." *Frontiers in Physiol.* 8: 578.

[18] Walkelin, S. A., Gallego, M. G., Jones, E., Smaill, S., Lear, G., and Lambie, S. 2018. "Climate Change Induced Drought Impacts on Plant Diseases in New Zealand." *Austra. Plant Pathol.* 47: 101-14.

[19] Loustau, M. L. D., Marcais, B., Nageleisen, L. M., Piou, D., and Vannini, A. 2006. "Interactive Effects of Drought and Pathogens in Forest Trees." *Annals of Fruit Sci.* 63 (6): 597-612.

[20] Andre, C., Christin, D., Castroverde, M., and Sheng, Y. H. 2018. "Plant Pathogen Walfare under Changing Climate Conditions." *Curr. Biol.* 28 (10): 619-34.

[21] Chakraborty, S., and Datta, S. 2003. "How Will Plant Pathogens Adapt to Host Plant Resistance at Elevated CO_2 under a Changing Climate?" *New Phytol.* 159: 733-42.

[22] Ladányi, M., and Horvath, L. 2010. "A Review of the Potential Climate Change Impact on Insect Populations—General and Agricultural Aspects." *Appl. Ecological Enviro. Res.* 8 (2): 143-52.

[23] Li, J., Lin, X., Chen, A., Peterson, T., Ma, K., Bertzky, M., Clais, P., Kapos, V., Peng, C., and Polter, D. 2013. "Global Priority Conservation Areas in the Face of 21st Century Climate Change." *Plos ONE* 8 (1): e54389.

[24] Suzuki, N., Rivero, R. M., Shulaev, V., Blumwald, E., and Mittler, R. 2014. "Abiotic and Biotic Stress Combination." *New Phytol.* 203 (1): 32-43.

[25] Ashoub, A., Baeumlisberger, M., Neupaerti, M., Karas, M., and Bruggeman, W. 2015. "Characterization of Common and Distinctive Adjustments of Wild Barley Leaf Proteome under Drought Acclimation Heat Stress and Their Combination." *Plant Molecular Biology* 87 (45): 459-71.

[26] McElrone, A. J., Reid, C. D., Hoye, K. A., Hart, E., Jackson, R. B. 2005. "Elevated CO_2 Reduces Disease Incidence and Severity of a Red Maple Fungal Pathogen via Changes in Host Physiology and Leaf Chemistry." *Global Change Biol* 11: 1828-36.

[27] Prank, M., Kenaley, S. C., Bergstrom, G. C., Acevedo, M., and Mahowald, N. M. 2019. "Climate Change Impacts the Spread Potential of Wheat Stem Rust: A Significant Crop Disease." *Environ. Res Lett* 14 (12): 124053. doi: 10.1088/1748-9326/ab57de.

[28] Oerke, E. C. 2006. "Crop Losses to Pests." *J Agric. Sci* 144: 31-43.

[29] Dixon, G. R. 2012. "Climate Change—Impact on Crop Growth and Food Production, and Plant Pathogens." *Can. J. Plant Pathol.* 34: 362-79.

[30] Madden, L. V., Hughes, G., and Bosch, F. V. 2007. *The Study of Plant Disease Epidemics.* St Paul, MN: The American Phytopathological Society Press.

[31] Siebold, M., and von Tiedemann, A. 2012. "Potential Effects of Global Warming on Oilseed Rape Pathogens in Northern Germany." *Fungal Ecol.* 5: 62-72.

[32] Schaad, N. W. 2008. "Emerging Plant Pathogenic Bacteria and Global Warming." In *Pseudomonas syringae Pathovars and Related Pathogens—Identification Epidemiology and Genomics*, edited by M. B. Fatmi, A. Collmer, N. S. Iacobellis, J. W. Masfield, J. Murillo, N. W. Schaad, and M. Ulrich. Dordrecht: Springer, 369-70.

[33] Singh, D., Yadav, D. K., Sinha, S., and Choudhary, G. 2013. "Effect of Temperature, Cultivars, Injury of Root and Inoculums Load of *Ralstonia solanacearum* to Cause Bacterial Wilt of Tomato." *Archives of Phytopathology and Plant Protection* 47 (13): 1574-83. http://dx.doi.org/10.1080/03235408.2013.851332.

[34] Mina, U., and Sinha, P. 2008. "Effects of Climate Change on Plant Pathogens." *Environmental News* 14 (4): 6-10.

[35] Pareek, A., Meena, B. M., Sharma, S., Tetarwal, M. L., Kalyan, R. K., and Meena, B. L. 2017. "Impact of Climate Change on Insect Pests and Their Management Strategies." In *Climate Change and Sustainable Agriculture.* Pitam Pura, New Delhi: New India Publishing Agency, 253-86.

[36] Coakley, S. M., Scherm, H., and Chakraborty, S. 1999. "Climate Change and Plant Disease." *Annu. Rev. Phytopathol.* 37: 399-426.

[37] Peng, S. B., Huang, J. L., Sheehy, J. E., Laza, R. C., Visperas, R. M., Zhong, X. H., Centeno, G. S., Khush, G. S., and Cassman, K. G. 2004. "Rice Yields Decline with Higher Night Temperature from Global Warming." *Proceeding in National Academic Sciences, U.S.A.* 101: 9971-5.

[38] Neilson, R., and Boag, B. 1996. "The Predicted Impact of Possible Climatic Change on Virus-Vector Nematodes in Great Britain." *Eur. J. Plant Pathol.* 102: 193-9.

[39] Matos, A. P., Cabral, J. R. S., Sanches, N. F., and Caldas, R. C. 2000. "Effect of Temperature and Rainfall on the Incidence of *Fusarium subglutinans* on Pineapple Fruits." *Acta Horticulturae* 529: 265-72.

[40] Yang, X. B., Sun, P., and Hu, B. H. 1998. "Decadal Change of Plant Diseases as Affected by Climate in Chinese Agro Ecosystems." In *Proceedings of the 7th*

International Congress of Plant Pathology, Edinburgh, Scotland, UK.

[41] Boland, G. J., Melzer, M. S., Hopkin, A., Higgins, V., and Nassuth, A. 2004. "Climate Change and Plant Diseases in Ontario." *Can. J. Plant Pathol.* 26 (3): 335-50.

[42] Milus, E. A., Seyran, E., and McNew, R. 2006. "Aggressiveness of *Puccinia striiformis* f. sp. *tritici* Isolates in the South-Central United States." *Plant Dis.* 90 (7): 847-52.

[43] Jesus Júnior, W. C., Cecilio, R. A., Valadares Júnior, R., Cosmi, F. C., and Moraes, W. B. 2007. "Aquecimento Global E O Potencial Impacto Na Cultura E Doenças Do Mamoeiro." In *Papaya Brazil-manejo, qualidade e mercado do mamão*, edited by D. Martins, A. N. Costa, and A. F. S. Costa. Vitória: Incaper, 83-100. (in Portuguese)

[44] Hannukkala, A. O., Kaukoranta, T., Lehtinen, A., and Rahkonen, A. 2007. "Late-Blight Epidemics on Potato in Finland, 1933-2002; Increased and Earlier Occurrence of Epidemics Associated with Climate Change and Lack of Rotation." *Plant Pathol.* 56 (1): 167-76.

[45] Ghini, R., Hamada, E., and Bettiol, W. 2008. "Climate Change and Plant Diseases." *Scientia Agricola* 65: 98-107.

[46] Shin, J. W., and Yun, S. C. 2010. "Elevated CO_2 and Temperature Effects on the Incidence of Four Major Chili Pepper Diseases." *Plant Pathol. J.* 26 (2): 178-84.

[47] Pugliese, M., Gullino, M. L., and Garibaldi, A. 2011. "Effect of Climate Change on Infection of Grapevine by Downy and Powdery Mildew under Controlled Environment." *Commun. Agric. and Appl Biol. Sci.* 76: 2.

[48] Matic, S., Cucu, M. A., Garibaldi, A., and Gullino, M. L. 2018. "Combined Effect of CO_2 and Temperature on Wheat Powdery Mildew Development." *Plant Pathol. J.* 34 (4): 136-326.

[49] Kaur, S., Barakat, R., Kaur, J., and Epstein, L. 2021. "The Effect of Temperature on Disease Severity and Growth of *Fusarium oxysporum* f. sp. *apii* Races 2 and 4 in Celery." *Phytopathology* 112 (2): 364-72. https://doi.org/10.1094/PHYTO-11-20-0519-R.

[50] Desprez-Loustau, M. L., Marçais, B., Nageleisen, L.-M., Piou, D., and Vannini, A. 2006. "Interactive Effects of Drought and Pathogens in Forest Trees." *Ann Forest Sci.* 63: 597-612.

[51] Elad, Y., and Pertot, I. 2014. "Climate Change Impacts on Plant Pathogens and Plant Diseases." *J. Crop Improvement* 28: 99-139.

[52] Sturrock, R. N., Frankel, S. J., Brown, A., Hennon, P. E., Kliejunas, J. T., Lewis, K. J., Worrall, J. J., and Woods, A. J. 2011. "Climate Change and Forest Diseases." *Plant Pathol.* 60: 133-49.

[53] Olsen, A. J., Pataky, J. K., Darcy, C. J., and Ford, R. E. 1990. "Effects of Drought Stress and Infection by Maize Dwarf Mosaic Virus (MDMV) in Sweet Corn." *Plant Dis.* 74: 147-51.

[54] Clover, G. R. G., Smith, H. G., Azam-Ali, S. N., and Jaggard, K. W. 1999. "The Effects of Drought on Sugar Beet Growth in Isolation and in Combination with Beet Yellows Virus (BYV) Infection." *J. Agri. Sci.* 133: 251-61.

[55] Garbelotto, M., Linzer, L., Nicolotti, G., and Gonthier, P. 2010. "Comparing the Influences of Ecological and Evolutionary Factors on the Successful Invasion of a Fungal Forest Pathogen." *Biol. Invasions* 12: 943-57.

[56] Dong, J. L., Gruda, N., Lam, S. K., Li, X., and Duan, Z. Q. 2018. "Effects of Elevated CO_2 on Nutritional Quality of Vegetables: A Review." *Front Plant Sci*. 9: 924. doi: 10.3389/Fpls.2018.00924.

[57] Ainsworth, E. A., and Long, S. P. 2005. "What Have We Learned from 15 Years of Free-Air CO_2 Enrichment (FACE)? A Meta-Analytic Review of the Responses of Photosynthesis, Canopy Properties and Plant Production to Rising CO_2." *New Phytol.* 165: 351-72.

[58] Chakraborty, S. 2013. "Migrate or Evolve: Options for Plant Pathogens under Climate Change." *Global Change Biology* 19: 1985-2000.

[59] Vary, Z., Mullins, E., Mcelwain, J. C., and Doohan, F. M. 2015. "The Severity of Wheat Diseases Increases when Plants and Pathogen Are Acclimatized to Elevated Carbon Dioxide." *Global Change Biology* 21: 2661-9.

[60] Eastburn, D. M., Degennaro, M. M., Delucia, E. H., Dermody, O., and Mcelrone, A. J. 2010. "Elevated Atmospheric Carbon Dioxide and Ozone Alter Soybean Disease at Soy FACE." *Global Change Biol.* 16: 320-30.

[61] Debela, C., and Tola, M. 2018. "Effect of Elevated CO_2 and Temperature on Crop-Disease Interactions under Rapid Climate Change." *Int. J. Envir. Sci. and Natural Res.* 13 (1): 1-7. doi: 10.19080/IJESNR.2018.13.551358.

[62] Pickles, B. J., Genney, D. R., Anderson, I. C., and Alexander, I. J. 2012. "Spatial Analysis of Ectomyccorhizal Fungi Reveals That Root Tip Communities Are Structured by Competitive Interaction." *Molecular Ecol.* 21 (20): 5110-23.

[63] Chakraborty, S., Murray, G., and White, N. 2002. *Impact of Climate Change on Important Plant Diseases in Australia*. A Report for the Rural Industries Research and Development Corporation, RIRDC Publication No. W02/010, RIRDC Project No CST-4A.

[64] Dalla Pria, M., Christiano, R. C. S., Furtado, E. L., Amorim, L., and Bergamin, F. A. 2006. "Effect of Temperature and Leaf Wetness Duration on Infection of Sweet Oranges by Asiatic Citrus Canker." *Plant Pathol.* 55: 657-63.

[65] Lake, J. A., and Wade, R. N. 2009. "Plant-Pathogen Interactions and Elevated CO_2: Morphological Changes in Favour of Pathogens." *J. Experimental Bot.* 60: 3123-31.

[66] Kobayashi, T., Ishiguro, K., Nakajima, T., Kim, H. Y., Okada, M., and Kobayashi, K. 2006. "Effects of Elevated Atmospheric CO_2 Concentration on the Infection of Rice Blast and Sheath Blight." *Ecol. and Epidemiol.* 96 (4): 425-31.

[67] Gória, M. M., Ghini R., and Bettiol, W. 2013. "Elevated Atmospheric CO_2 Concentration Increases Rice Blast Severity." *Tropical Plant Pathol.* 38 (3): 253-7.

[68] Li, X., Sun, Z., Shao, S., Zhang, S., Ahammed, G. J., Zhang, G., Jiyang, Y., Zhou, J., Xia, X., Zhou, Y., Yu, J., and Shi, K. 2015. "Tomato-*Pseudomonas syringae* Interactions under Elevated CO_2 Concentration: The Role of Stomata." *J. Experimental Bot.* 66: 307-16.

[69] Karnosky, D. F., Percy, K. E., and Xiang, B. X. 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 Biol.* 8: 329-38.

[70] Yeates, G. W., Newton, P. C. D., and Ross, D. J. 2003. "Significant Changes in Soil Microfauna in Grazed Pasture under Elevated Carbon Dioxide." *Biology and Fertility of Soils* 38 (5): 319-26.

[71] Yeates, G. W., Tate, K. R., and Newton, P. C. D. 1997. "Response of the Fauna of a Grassland Soil to Doubling of Atmospheric Carbon Dioxide Concentration." *Biology and Fertility of Soils* 25 (3): 307-15.

[72] Ayers, E., Wall, D. H., Simmons, B. L., Field, C. B., Milchunas, D. G., Morgan, J. A., and Roy, J. 2008. "Belowground Nematode Herbivores Are Resistant to Elevated Atmospheric CO_2 Concentrations in Grassland Eco-Systems." *Soil Biol. and Biochem.* 40: 978-85.

[73] 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 (UVB) Radiation on Plant Diseases." *Environ Pollution,* 88: 219-45.

[74] Zhou, Y., Vroegop-Vos, I., Schuurink, R. C., Pieterse, C. M. J., and Wees, S. C. M. V. 2017. "Atmospheric CO_2 Alters Resistance of Arabidopsis to *Pseudomonas syringae* by Affecting Abscisic Acid Accumulation and Stomatal Responsiveness to Coronatine." *Front. Plant Sci.* 8: Article 700. doi: 10.3389/fpls.016.01680.

[75] Hibberd, J. M., Whitbread, R., and Farrar, J. F. 1996. "Effect of 700 μmol mol^{-1} CO_2 and Infection with Powdery Mildew on the Growth and Carbon Partitioning of Barley." *New Phytol.* 134 (2): 309-15.

[76] Zhou, Y., Leeuwen, S. K. V., Pieterse, C. M. J., Bakker, P. A. H. M., and Wees, S. C. M. V. 2019. "Effects of Atmospheric CO_2 on Defense against Leaf and Root Pathogen of Arabidopsis." *Eur. J. Pl. Pathol.* 154: 31-42.

[77] Pugliese, M., Gullino, M. L., and Garibaldi, A. 2010. "Effects of Elevated CO_2 and Temperature on Interactions of Grapevine and Powdery Mildew: First Result under Phytotron Condition." *J. Plant Dis. Protec.* 117 (1): 9-14.

[78] Pugliese, M., Cogliati, E., Gullino, M. L., and Garibaldi, A. 2012. "Effect of Climate Change on Alternaria Leaf Spot of Rock Salad and Black Spot of Basil under Controlled Environment." *Commun Agric. and Appl. Biol. Sci.* 77 (3): 241-4.

[79] Pugliese, M., Liu, J., Titone, P., Garibaldi, A., and Gullino, M. L. 2012. "Effects of Elevated CO_2 and Temperature on Interactions of Zucchini and Powdery Mildew." *Phytopathol. Medit.* 51 (3): 480-7.

[80] Hannukkala, A. O., Kaukoranta, T., Lehtinen, A., and Rahkonen, A. 2007. "Late Blight Epidemics on Potato Ion Finland, 1933-2002; Increased and Earlier Occurrence of Epidemics Associated with Climate Change and Lack of Rotation." *Pl. Pathol.* 56 (1): 167-76.

[81] Jwa, N. S., and Walling, L. L. 2001. "Influence of Elevated CO_2 Concentration on Disease Development in Tomato." *New Phytol.* 149: 509-18.

[82] Tiedemann, A. V., and Firsching, K. H. 2000. "Interactive Effects of Elevated Ozone and Carbon Dioxide on Growth and Yield of Leaf Rust-Infected Versus Non-infected Wheat." *Environ. Pollution* 108 (3): 357-63.

[83] Gilardi, G., Pugliese, M., Chitarra, W., Ramon, I., Gullino, M. L., and Garibaldi, A. 2016. "Effect of Elevated Atmospheric CO_2 and Temperature Increases on the Severity of Basil Downy Mildew Caused by *Peronospora belbahrii* under Phytotron Conditions." *J. Phytopathol.* 164: 114-21.

[84] Gullino, M. L., Gilardi, G., and Garibaldi, A. 2017. "Effect of a Climate Change Scenario on *Fusarium equiseti* Leaf Spot on Wild Rocket and Radish under Phytotron Simulation." *Phytoparasitica* 46: 124-9.

[85] Khan, M. R., and Rizvi, T. F. 2020. "Effect of Elevated Levels of CO_2 on Powdery Mildew Development in Five Cucurbit Species." *Scientific Reports* 10: 4986.

[86] Bhatia, A., Mina, U., Kumar, V., Tomer, R., Kumar, A., Chakrabarti, B., Singh, R. N., and Singh, B. 2021. "Effect of Elevated Ozone and Carbon Dioxide Interaction on Growth, Yield, Nutrient Content and Wilt Disease Severity in Chickpea Grown in Northern India." *Heliyon* 7: e06049.

[87] Salinari, F., Giosue, S., Tubiello, F. N., Rettori, A., Rossi, V., Spanna, F., Rosenzweig, C., and Gullino, M. L. 2006. "Downy Mildew (*Plasmopara viticola*) Epidemics on

Grapevine under Climate Change." *Global Change Biol.* 12: 1299-307.

[88] Deimel, H., and Hoffmann, G. M. 1991. "Detrimental Effects of Net Blotch Disease of Barley Plants Caused by *Drechslera teres* (Sacc.) Shoemaker." *J. Plant Dis. Protec.* 98: 137-61.

[89] Khan, A. U., and Khan, I. S. 1992. "Incidence and Severity of Cucurbit Powdery Mildew in Uttar Pradesh." *Indian Phytopath.* 45 (2): 190-3.

[90] Bendek, C. E., Campbell, P. A., Torres, R., Donoso, A., and Latorre, B. A. 2007. "The Risk Assessment Index in Grape Powdery Mildew Control Decisions and the Effect of Temperature and Humidity on Conidial Germination of *Erysiphe necator*." *Spanish J. Agric. Res.* 5 (4): 522-32.

[91] Islam, T. M. D., and Toyota, K. 2004. "Effect of Moisture Conditions and Pre-incubation at Low Temperature on Bacterial Wilt of Tomato Caused by *Ralstonia solanacearum*." *Microbes Environ.* 19: 244-7.

[92] Juroszek, P., and Tiedemann, A. V. 2011. "Potential Strategies and Future Requirements for Plant Disease Management under a Changing Climate." *Plant Pathol.* 60: 100-12.

[93] Bidzinski, P., Ballini, E., Ducasse, A., Michel, C., Zuluaga, P., Genga, A., Chiozzotto, R., and Morel, J. B. 2016. "Transcriptional Basis of Drought Induced Susceptibility to the Rice Blast Fungus *Magnaporthe oryzae*." *Front. Plant Sci.* 7: 1558.

[94] Johansen, T. J., Dees, M. W., and Hermansen, A. 2015. "High Soil Moisture Reduces Common Scab Caused by *Streptomyces turgidiscabies* and *Streptomyces europaeiscabiei* in Potato." *Acta Agric. Scand. B* 65: 193-8.

[95] Evans, N., Baierl, A., Semenov, M. A., Gladders, P., and Fitt, B. D. L. 2008. "Range and Severity of a Plant Disease Increased by Global Warming." *J. Royal Soc. Interface* 5: 525-31.

[96] Jung, T. 2009. "Beech Decline in Central Europe Driven by the Interaction between *Phytophthora* Infections and Climatic Extremes." *Forest Pathol.* 39: 73-94.

[97] Chakraborty, S., and Newton, A.C. 2011. "Climate Change, Plant Diseases and Food Security: An Overview." *Plant Pathol.* 60: 2-14.

[98] Stern, N. 2007. *The Economics of Climate Change: The Stern Review*. Cambridge, UK: Cambridge University Press, 712.

[99] Atkinson, N. J., and Urwin, P. E. 2012. "The Interaction of Plant Biotic and Abiotic Stresses from Genes to the Field." *J. Exp. Bot*. 63: 3523-43.

[100] Rejeb, I. B., Pastor, V., and Mauch-Mani, B. 2014. "Plant Responses to Simultaneous Biotic and Abiotic Stress: Molecular Mechanisms." *Plants* 3: 458-75.

[101] Prasch, C. M., and Sonnewald, U. 2013. "Simultaneous Application of Heat, Drought, and Virus to *Arabidopsis* Plants Reveals Significant Shifts in Signaling Networks." *J. Plant Physiol*. 162 (4):1849-66.

[102] Clarkson, J. P., Fawcett, L., Anthony, S. G., and Young, C. 2014. "A Model for *Sclerotinia sclerotiorum* Infection and Disease Development in Lettuce, Based on the Effects of Temperature, Relative Humidity and Ascospore Density." *PLoS One* 9 (4): e94049.

[103] Ciliberti, N., Fermaud, M., Roudet, J., and Rossi, V. 2015. "Environmental Conditions Affect *Botrytis cinerea* Infection of Mature Grape Berries More Than the Strain or Transposon Genotype." *J. Phytopathol.* 105 (8): 1090-6.

[104] Milly, P. C. D., Wetherald, R. T., Dunne, K. A., and Delworth, T. L. 2002. "Increasing Risk of Great Floods in a Changing Climate." *Nature* 415: 514-7.

[105] Root, T. L., Price, J. T., Hall, K. R., Schneider, S. H., Rosenzweig, C., and Pounds, J. A. 2003. "Fingerprints of Global Warming on Wild Animals and Plants." *Nature* 421: 57-60.

[106] Rosenzweig, C., Strzepek, K. M., Major, D. C., Iglesias, A., Yates, D. N., McCluskey, A., and Hillel, D. 2004. "Water Resources for Agriculture in a Changing Climate: International Case Studies." *Global Environ. Change* 14: 345-60.

[107] Reilly, J., Tubiello, F., McCarl, B., Abler, D., Darwin, R., Fuglie, K., Hollinger, S., Izaurralde, C., Jagtap, S., Jones, J., Mearns, L., Ojima, D., Paul, E., Paustian, K., Riha, S., Rosenberg, N., and Rosenzweig, C. 2003. "US Agriculture and Climate Change: New Results." *Climatic Change* 57: 43-69.

[108] Fischer, G., Shah, M., Velthuizen, H., and Nachtergael, F. O. 2001. *Global Agro-Ecological Assessment for Agriculture in the 21st Century.* Vienna, Austria: International Institute for Applies Systems Analysis, IIASA Publications.

[109] Tubiello, F. N., Jagtap, S., Rosenzweig, C., Goldberg, R., and Jones, J. W. 2002. "Effects of Climate Change on US Crop Production from the National Assessment. Simulation Results Using Two Different GCM Scenarios. Part I: Wheat, Potato, Corn, and Citrus." *Climate Res.* 20 (3): 259-70.

[110] Smith, J. B., Klein, R. J. T., and Huq, S. 2003. *Climate Change, Adaptive Capacity, and Development.* London: Imperial College Press, 347.

[111] Smit, B., and Skinner, M. W. 2002. "Adaptation Options in Agriculture to Climate Change: A Typology." *Mitigation and Adaptation Strategies for Global Change* 7: 85-114.

[112] Hunsche, M., Bringe, K., Schmitz-Eiberger, M., and

Noga, G. 2006. “Leaf Surface Characteristics of Apple Seedlings, Bean Seedlings and Kohlrabi Plants and Their Impact on the Retention and Rainfastness of Mancozeb.” *Pest Manag. Sci.* 62: 839-47.

[113] Gautam, H. R., Bhardwaj, M. L., and Kumar, R. 2013. “Climate Change and Its Impact on Plant Diseases.” *Curr. Sci.* 105 (12): 1685-91.

[114] Boonekamp, P. M. 2012. “Are Plant Diseases Too Much Ignored in the Climate Change Debate?” *Eur. J. Plant Pathol.* 133: 291-4.

[115] Pathak, H. 2010. “Mitigating Greenhouse Gas and Nitrogen Loss with Improved Fertilizer Management in Rice: Quantification and Economic Assessment.” *Nutr Cycling Agroecosyst.* 87: 443-54.