Innovative Farming
-A Quarterly International Journal of Agriculture

Review Article

Article: SAAI/IF/436

Plant Disease Responses to Climate Change

Jai P. Rai

Institute of Agricultural Sciences, Banaras Hindu University, RG South Campus, Barkachha, Mirzapur, Uttar Pradesh (231 001), India

*Corresponding email: drjaibhu@gmail.com

KEYWORDS:

Agriculture, Climate change, Crop losses, Pathogens, Plant diseases

ARTICLE INFO

Received on: 03.04.2021
Revised on: 20.08.2021
Published on: 27.08.2021

ABSTRACT

Environmental shift is a growing concern for communities related to agriculture across the world. The present paper looks into the impacts of shifts in climate on plant diseases. The three major constituents of any crop disease are the host (the plant) the pathogen inciting the disease, and the environmental factors. All these three elements are greatly affected by changes in climate that can lead to a surge in the occurrence and intensity of crop diseases. The paper highlights that escalating temperatures, changed patterns of rainfall and intense weather events can all create conditions that favour the growth and spread of phytopathogens. This can lead to substantial yield losses for farmers and put global food security at risk. The paper also discusses the economic consequences of crop diseases, noting that phytopathogens and insect pests are assessed to cause nearly US$ 220 billion in annual losses.

The author argues that a better understanding of how climate shifts affect the connection and correlation between pathogens, crop plants and the environment is necessary to develop strategies for mitigating crop disease risks. He calls for research into the molecular, epidemiological and ecological interactions between these factors. This research can inform the development of climate-durable farming procedures that can assist in ensuring food surety in a fluctuating climate.

How to Cite:

Rai, J.P., 2021. Plant disease responses to climate change. *Innovative Farming* 6(3), 111-122.

INTRODUCTION

Globally, climate shifts are raising alarm for communities in agriculture (Coakley *et al*., 1999). The three primary factors of a disease are the disease-causing agent, the host and the environment of their interaction. The affiliation between these factors determines whether an infection is going to occur or not. Changes in the climatic parameters affect the crop yield and susceptibility of crop plants to diseases in a significant manner. Diseases in crop plants and susceptibility in the host are affected by climate variations, which lead to effect on the overall health of crops. Agricultural methods are altered to address these shifts and avoid productivity losses (Abdou Zayan, 2020).

The occurrence and amount of plant disease outbreaks are rising across the world, raising serious and growing concerns about prime output, international food surety and loss of biological multiplicity (Chakraborty and Newton, 2011; Velasquez *et al.*, 2018; Rohr *et al.*, 2019; Fones *et al.*, 2020; Ristaino *et al.*, 2021; van Dijk *et al.*, 2021). The consequences of these disease epidemics include losses to yield and the environment. For instance, it is estimated that pathogens and pests (microbes that incite ailments and impair the health of the host and its production) by themselves account for nearly 220 billion US dollars of the annual loss of crop yield (Chakraborty and Newton, 2011; Rohr *et al.*, 2019; van Dijk *et al.*, 2021; Ristaino *et al.*, 2021). This has a direct effect on food security, local economies and other related socioeconomic factors. Post-harvest damage brought on by means of pathogenic bacteria including *Xanthomonas euvesicatoria* and *Penicillium* spp. aggravates this even more. Furthermore, the possibility of plant disease amplification brought on by climate change is growing, endangering both the world's natural plant biodiversity and food supply (Velasquez *et al.*, 2018; Burdon and Zhan, 2020; Muluneh, 2021). It is predicted that the enhanced disease pressure brought on by existing and developing pathogens as a result of climate change will negate any possible yield gains over the next fifty years (Chaloner *et al.*, 2021). Similarly, the rise of diseases attributed to changes in the climate represents one of the greatest damages to the fitness of ecosystems globally (Trumbore *et al.*, 2015). Consequently, to ascertain agrarian and natural ecologies that are climate-robust, a better contemplation of the consequences of climate variation on the environmental, epidemiological and molecular relations among diseases, crop plants and the accompanying microbic populations is required (Rohr *et al.*, 2019; Ristaino *et al.*, 2021; van Dijk *et al.*, 2021).

Several phytopathogenic communities, including nematodes, oomycetes, fungi, bacteria and viruses can infect plants. These pathogens vary in their regimes; those biotrophic in nature obtain their food from live cells, whereas those having a necrotrophic nature obtain their nutrition from lifeless organic matter; contamination approaches (outside the cell-extracellular or inside it-intracellular) and aimed tissues of the plant host (such as phloem, xylem, leaves or roots). Comprehending how these numerous phytopathogens interrelate with and respond to diverse disease teamsters (such as additional phytopathogens, host/vectors, commensal microbes and ecosystem) in addition to how they collectively react to climate shifts is a grave challenge in forecasting plant infections spatially or temporally. Academically, there are many ways in which climate shifts could stimulate plant diseases, such as by changing the advancement of phytopathogens, affecting host-pathogen interfaces and transmitter functioning and encouraging the development of new races of pathogens that could destabilize the host-plant resistance (Newbery *et al.*, 2016; Velasquez *et al.*, 2018; Cohen and Leach, 2020). Diseases in crop plants could flourish into new areas because of phytopathogens and plant hosts fluctuating their varieties due to climate shift (Burdon and Zhan, 2020; Delgado-Baquerizo *et al.*, 2020; Chaloner *et al.*, 2021; Dudney *et al.*, 2021). Nevertheless, our consideration of the aspects of climate variation, such as changes in temperature and precipitation, that interrelate with human action to impact phytopathogens in both wild and agricultural bionetworks is still inadequate. For instance, under anticipated climate change scenarios, the copiousness of plant diseases caused by soil-borne fungal species is estimated to rise in the majority of the natural environments, with major but uncertain repercussions for primary productivity globally (Delgado-Baquerizo *et al.*, 2020). Comparably, changes in relative humidity have an impact on pathogen abundance and infectivity.

Crop plant diseases will presumably rise as a result of climate change. First off, during the past few decades, crop pathogen movement between continents has increased due to globalization and international trade (Brown and Hovmøller, 2002; Sikes *et al.*, 2018), raising the possibility of disease transfer from areas where sickness is common to areas where it is not. In the new geographic area, plant types or cultivars that do not share the history of coevolution with the initiated phytopathogen are likely to promote the prevalence of the phytopathogens and consequent disease outbreaks. In Banana, Panama or wilt disease, is a key image of how commerce and conveyance can add to the development of phytopathogens. *Fusarium oxysporum* f.sp. *cubense*, the incitant of the disease, is a soil-borne fungus, which most probably commenced in Southeast Asia and expanded through the entire world in the 20th century (Fisher *et al.*, 2020). Additionally, contemporary land managing practices that highlight monocultures and high-density farming, accompanied by environmental and climatic changes, perhaps added to the occurrence and flexibility of plant ailments that can increase outside their typical terrestrial boundaries. For example, various insect-pests and diseases relentlessly decrease the returns of soybean and wheat, which are extensively grown in monocultures with high-density. Amongst the most detrimental diseases to these two crops include soybean rust (incited by the fungal pathogen *Phakopsora pachyrhizi*) and blotch of wheat (incited by the fungal phytopathogen, *Zymoseptoria tritici*), which can reduce yield as much as 50% through severe occurrences (Goellner *et al.*, 2010; Fones *et al.*, 2020). Notwithstanding the intricacy of natural ecosystems (such as the interplay of biodiversity), challenges to wild plant communities and productivity are similar owing to climate shift and the associated development and evolution of infections. For instance, the spread of *Phytophthora cinnamomi* due to global warming may have detrimental effects on native plant groups throughout a sizeable portion of the planet (Thompson *et al.*, 2014; Rigg *et al.*, 2018). Climate change-related increases in disease load might have catastrophic effects on societal tensions, production and security of foods, environmental supportability and many plant species.

This analysis examines the potential changes in plant pathogen loads and disease prevalence under future climate scenarios. We investigate the consequences of land usage intensification and climate shift, both present and projected, on the biogeography of the pathogen, communications between phytopathogens and the microbiome of the crop plant, incidence and severity of plant diseases and the overall impact these factors have on primary production and agriculture. We examine potential pathways through which invasion of plant tissues by phytopathogens impacts the microbiome of the crop plant and discuss the possible use of this information to decrease the likelihood of disease occurrences through enhanced disease reconnaissance, prognostic modelling and practical supportable managing approaches (Newbery *et al.*, 2016; Burdon and Zhan, 2020). In conclusion, we suggest various strategies that integrate disease surveillance with policy frameworks to guarantee the enduring viability of worldwide food reassurance and environmental supportability.

PLANT DISEASES AND CLIMATE CHANGE

Given the many variables involving plants, pathogens and the environment, predicting how climate change may affect plant disease is difficult and complex. These variables include the fitness and pathogenicity of the taxa, their dissemination and copiousness (terrestrial range, niche inclination), abiotic interactions, the evolutionary processes of plants and microorganisms, biology of the host with the vector and ecological conditions. For example, when environmental circumstances are favorable for the multiplication of pathogens and susceptible hosts are present; several soil-adaptable phytopathogens can trigger outbreaks of diseases (Cheng *et al.*, 2019; Trivedi *et al.*, 2020). By altering the functional, environmental, biochemical and developmental activities of the pathogen and/or crop host, climate shifts can also impact the communications between hosts and their respective phytopathogens indirectly (Velasquez *et al.*, 2018; Cheng *et al.*, 2019; Desaint *et al.*, 2021). For example, a stretched drought strains the water supply to forest trees, exposing them to infection by phytopathogens that incite the dieback disease (*Phytophthora* spp.). This facilitates the rise of possibly new infections (Desprez-Loustau *et al.*, 2006; Ryu *et al.*, 2018; Hossain *et al.*, 2019). In general, the pathogen, host and biome characteristics are anticipated to influence the direct consequences of climate shifts differently. The data supporting the hypothesis that pathogen virulence and disease development are directly impacted by climate change is weak but growing, as will be covered in the sections that follow.

HIGH TEMPERATURE

Climate warming can appreciably affect features of the populace subtleties of phytopathogens, such as hibernating and endurance, growing extents of populace or the number of generations of species that have several cycles in a year (polycyclic). For instance, a decreased diurnal temperature reduces the inactivity period of *Hemileia vastatrix*, the incitant of coffee leaf rust, stimulating epidemics of this rust in Central America (Toniutti *et al.*, 2017). Higher temperatures cause the incubation time of the pathogen to shorten, increasing the pathogen's prevalence during the growth season. Increased disease relentlessness of *Phytophthora infestans*, the incitant of potato late blight and stem canker of the oilseed rape caused by *Phoma* spp. is linked with increased levels of temperatures and humidity. Ultimately, a study by Barbeito *et al.* (2013) for thirty years established a connection between primary snowmelt and enhanced infection of snow blight (*Phacidium infestans*) in pine trees.

Alterations in temperatures on large-scale can intensely affect the incidence of infections by phytopathogens in agrarian and environmental ecosystems, swelling the threat of disclosure to new insect pests and phytopathogens. Increase in temperatures worldwide is estimated to enhance the copiousness of a number of soil-borne fungal phytopathogens, with considerable impacts on primary productivity (Delgado-Baquerizo *et al.*, 2020). Increases in temperature may lead to the rise and development of newly infectious and better-equipped phytopathogenic strains (Velasquez *et al.*, 2018; Newbery *et al.*, 2016; Cohen and Leach, 2020; Fisher *et al.*, 2020). The transition from the more destructive *Fusarium graminearum*, which favours hot and moist settings, to the gentler *Fusarium culmorum*, which prefers chilly and damp conditions, is expected to increase the severity of wheat head blight of wheat caused by *Fusarium* (Parikka *et al.*, 2012). Similar to this, newer, more forceful and temperate-tolerant forms of *Puccinia striiformis* have come up to supersede the previous strains of the phytopathogen, resulting in significant wheat rust outbreaks across Europe, Australia and the United States (Walter *et al.*, 2016). Many diseases, comprising of stem rot of wheat incited by *Puccinia graminis* f.sp. *tritici*, whose range is now restricted by requirements for overwintering, can expand in response to warming temperatures (Ma *et al.*, 2015). Conversely, during the course of thirty years, a consistent increase in temperatures during summers was noted by Zhan *et al.* (2018), leading to the resident disappearance of *Triphragmium ulmarie*, the phytopathogen causing rust in meadowsweet (*Filipendula ulmaria*). Because of their lower thermal preferences, other diseases like *Phytophthora infestans* can be expected to be less affected with rising temperature (Sparks *et al.*, 2014).

It is unclear what molecular factors make plants more vulnerable to diseases in high temperatures (Cohen and Leach, 2020). Elevated temperatures, however, have the potential to reduce plant immunity, which increases pathogen infection (Goellner *et al.*, 2010). High temperatures in *Arabidopsis* inhibit the synthesis of salicylic acid, a hormone essential for plant defense (Castroverde and Dina, 2021) because master resistant transcript elements like CBP60g are not triggered as well. In plants, the transcription elements of the CBP60g group are highly preserved and the knowledge of their function in the thermosensitive control of plant immunity offers hints for a better comprehension of the effect of an increase in temperature on plant diseases. Increase in temperatures enhances the appearance of receptive genes in rice and production of abscisic acid, that can be associated with an enhanced danger of bacterial blight; astonishingly, regulation of the pathways of abscisic acid was interrelated to endurance at enhanced temperatures (Cohen *et al.*, 2017). Paddy crop which is cultivated in warm temperatures is rather vulnerable to the blast disease incited by *Magnaporthe grsiea's* stimulation of marking genes and production of jasmonic acid.

INCREASED LEVELS OF CARBON DIOXIDE

Assorted occurrences of plant ailments in ecosystems with higher concentrations of carbon dioxide (CO_2) indicate responses of host- and pathogen-dependent carbon dioxide. The severity of powdery mildew on cucurbits induced by *Sphaerotheca fuliginea* was enhanced by elevated CO_2 levels (Khan and Rizvi, 2020), in addition to blotch and head blight in wheat brought on by *Septoria tritici* and *Fusarium* spp., correspondingly (Vary *et al.*, 2015). Conversely, soybean's vulnerability to *Peronospora manshurica*, the downy mildew fungus was diminished (Eastburn *et al.*, 2010). In a similar vein, aspen tree rust disease was exacerbated by alterations in the properties of the leaf surface brought on by increased CO_2 treatment (Karnosky *et al.*, 2002) nonetheless, lessened the severity of the maple tree brown spot disease (Mcelrone *et al.*, 2005). Plant immunological reactions and hormone concentrations which may affect interactions between plants and pathogens are impacted by atmospheric CO_2. For instance, in conditions of elevated CO_2, greater basal expression of genes responding to jasmonic acid strengthened resistance against *Botrytis cinerea*, the leaf pathogen which is necrotrophic in nature but reduced endurance against *Pseudomonas syringae* pv. *tomato*, the leaf pathogen that is hemi-biotrophic (Zhou *et al.*, 2019). Wheat became more vulnerable to the two main pathogens that produce *Z. tritici* splotch and head blight by *Fusarium*, correspondingly, *Z. tritici* and *F. graminearum*, due to a decrease in the efficacy of plant defense pathways under increasing CO_2 (Vary *et al.*, 2015). Increased CO_2 affects the tripartite biotic relationships that exist between *Rhopalosiphum padi*, the aphid vector, the host-wheat and the phytopathogen-barley yellow dwarf virus (BYDV). When compared to non-infected plants, BYDV contamination under elevated CO_2 enhanced the aboveground nitrogen concentration of wheat, which decreased vector performance and phloem consumption (Trębicki *et al.*, 2016). While it is clear that increased carbon dioxide affects the interactions between plants and pathogens, a comprehensive framework to understand and predict these consequences is still lacking.

VARIABILITY IN WATER SUPPLY BROUGHT ON BY CLIMATE CHANGE

Climate-prompted vagaries in moisture will perhaps affect plant disease outbreaks in the times to come as changes in comparative air moisture and soil humidity are two of the key components that affect the amount and infectivity of plant ailments (Brown and Hovmøller, 2002). Raised levels of moisture are essential for the propagules of several fungal phytopathogens to sprout and invade the tissues of their respective host plants (Brown and Hovmøller, 2002) to establish the characteristic infection. Elevated levels of moisture generally enhance the virulence of phytopathogens and intensify the contamination rates of lettuce tissues by *Sclerotinia sclerotiorum* (Mamo *et al.*, 2021). When in higher humidity, the stem rot pathogen *Phytophthora sojae* is more prevalent (Tada *et al.*, 2021). Plant immunity responses are modified by bacterial effectors expressed in a humidity-dependent manner, which facilitates *P. syringae*'s establishment in the apoplast (intercellular space aqueous in nature) in the leaves of *Arabidopsis* (Xin *et al.*, 2016). Augmented production of deoxynivalenol (a mycotoxin) by the pathogen *F. graminearum*, which infects a variety of cereals and causes large financial losses as well as a decline in food quality, is also associated with higher humidity (Andersen *et al.*, 2015; Qiu *et al.*, 2016). Conversely, reduced moisture conditions enhance pathogen numbers and disease severity for *Streptomyces* spp., which causes bacterial scab in potatoes and *M. oryzae*, the culprit responsible for rice blast (Johansen *et al.*, 2015; Bidzinski *et al.*, 2016). A general rise in comparative air-moisture may raise the incidence of fungal diseases in general.

Dry periods have changing levels of effects on the rates of infection by phytopathogens and the intensity of the resultant plant ailments (Wakelin *et al.*, 2018). For example, the extent and occurrence of dry periods upsurge the intensity of plant diseases including root rot caused by *Aphanomyces euteiches* in pea, white rot in onion caused by *Sclerotium cepstrum*, take-all incited by *Gaeumannomyces graminis* var. *tritici* in wheat, crown rot caused by *Fusarium* spp. in wheat, blackleg disease in brassica incited by *Leptosphaeria maculans* and black foot caused by *Ilyonectria*/ *Dactylonectria* spp. in grapevine. Contrarywise, radiata pine red needle cast incited by *Phytophthora pluvialis*, or and sclerotinia rot caused by *S. sclerotiorum* in kiwifruit were less intense owing to the reduce moisture levels (Wakelin *et al.*, 2018). Comparable outcomes were documented for the grape bacterial disease *Xylella fastidiosa* (Choi *et al.*, 2013). Since functioning of the phyhtopathogen and nutritional status of the tree are closely correlated, necrotrophic organisms will typically quicken dry periods-prompted tree death by draining tree reserves consequent to the processes of healing and compartmentalization, while diseases incited by biotrophs remain predicted to be of lower intensity during droughts. However, since biotrophs destroy the carbohydrate reserves necessary for a tree's ability to withstand drought, it is anticipated that they will have a more severe drought-dependent impact on trees under stress should they are able to intrude them (Oliva *et al.*, 2014).

Alterations in the vigor and course of communications between plants and their respective phytopathogens along a dryness incline caused by drought can alter the way that disease ranges expand in response to climate shifts (Dudney *et al.*, 2021). For illustration, even as the climate becomes more friendly, the lesser existence of alternate hosts at greater altitudes decreases the possibility of infection, whereas dry periods and an increase in tree death rates in dry areas speed the drop at lower altitudes in the case of blister rust disease of pine. New diseases that are resilient to severe weather and can manipulate shifts in plant functioning as a strain response might potentially develop as a result of dryer periods. For instance, the fungal disease *Macrophomina phaseolina*, which causes dry root rot, prefers to infect chickpea plants during droughts (Rai *et al.*, 2022). Infection of Potato yellow vein virus and symptoms of yellow vein disease in potatoes amplified due to the reduction of plant basal responses of immunity induced by dry periods. The host-virus-vector (greenhouse whitefly) relationships are further altered by these modifications, which improves the virus's horizontal spread.

ADDITIONAL FACTORS AND POTENTIAL OUTCOMES

Some investigations established the collective impacts being more distinct as compared to the separate impacts, despite our incomplete comprehension of the collective impacts of several ecological conditions on the communications between plant hosts and their respective pathogens (Webb *et al.*, 2010; Cohen and Leach, 2019; Teshome *et al.*, 2020) and occasionally combinations of variables are needed for breakouts (Sewelam *et al.*, 2021). For example, the epidemic in Bangladesh of blast disease in wheat, of which *M. oryzae triticum* was the incitant, was attributed to an unusually warm and moist season before harvest that was caused by climate change (Islam *et al.*, 2019). Likewise, elevated temperatures and high humidity facilitated the growth of *B. cinerea* grey mould in grape berries (Ciliberti *et al.*, 2015). Changes in temperature and soil moisture content, for instance, might encourage the invasion and spread of pathogens into previously unexplored geographic and host ranges. In this sense, when yearly temperatures rise, certain fungal diseases are more probable to proliferate in fresh areas of the moderate and boreal biomes (Delgado-Baquerizo *et al.*, 2020), with disproportionately large negative effects on production anticipated in China, certain nations of South America and Europe. Realizing the worldwide dissemination of fungal phytopathogenic infections in plants under potential forthcoming climate situations has been the focus of recent work (Delgado-Baquerizo *et al.*, 2020); however, our realization of the existing distribution of numerous significant pathogens limits our ability to advance (Juroszek and von Tiedemann, 2015; Ristaino *et al.*, 2021). Under predicted global warming, modelling and experimental evidence revealed the incidence of important soil-borne fungal infections from the fungi *Fusarium*, *Phoma*, *Venturia* and *Alternaria*, to possibly rise (Delgado-Baquerizo *et al.*, 2020).

Further, a re-investigation of printed survey data (Delgado-Baquerizo *et al.*, 2020) worldwide indicates that changes in temperature and organic matter are closely related to the comparative copiousness of certain significant soil-borne taxa of fungi, including species of *Penicillium*, which harm the quality of fruits and output. Similarly, it is anticipated that climate change would contribute to the range extension of *Neufusicoccum parvum* and *Botryosphaeria dothidea*, which will result in more regular and intense occurrences of diseases. Instead, the comparative occurrences of other diseases that are carried by soil, like the *Pythium* spp. and *Phytophthora* spp. from the taxa of Oomycota (Juroszek and von Tiedeman, 2015), may be extremely sensitive to pH variations in the soil brought on by changes in terrestrial usage and their dispersal is probably going to change responding to both land usage augmentation and climate shifts, which possibly affect the global food security. It is recognized that a variety of environmental conditions interrelate with pathogens that are soil-borne in nature, which explains intricate outlines in the global allocation of such bacteria. The expanding body of information indicating that infections inflict greater harm on lately attacked areas and fresh masses rather they do on innate areas and hosts raises concerns about global alterations in pathogen distribution. For example, dieback disease in ash incited by the fungal phytopathogen, *Hymenoscyphus fraxineus* rarely attacks ash varieties which are natural to Asia, the area of beginning of the disease, but because they spread to Europe some three decades earlier, it has caused immense damage to the European ash trees.

CONCLUSION

Since plant diseases are getting more intense and widespread owing to shifts in climate, there is a grave danger to the food surety of the world population. Interactions between plant hosts and their respective phytopathogens may possibly be affected by climatic factors such as a rise in temperatures, changing patterns of precipitation and an increase in the concentration or levels of carbon dioxide. Phytopathogens have the tendency to move to fresh areas and have the ability to infect fresh hosts and also to those previously considered resistant to these infections. This may lead to severe outbreaks of plant ailments, which may be complemented or contributed by the alterations in environmental parameters brought about by climatic shifts. The consequences of such incidences may include losses to the production and productivity of crops worldwide, financial losses incurred thereby as well as ecological implications arising from this. To reduce these difficulties, strategies with a holistic approach are required. This translates into the development of crop varieties that are climate-resilient, an improved strategy to combat plant diseases that could possibly become more dangerous in changed climatic scenarios. Development and fortification of early warning systems for imminent crop losses from worsening conditions of crops due to diseases may add to the efficiency of the strategy. Along with these, an international collaboration to meet the challenges of plant diseases occurring across boundaries in terms of sharing information and resources is the need of the hour. To maintain the food supply of the world unaffected by these challenging situations, we need to look deeper into the interrelationships among all the three components of the disease triangle-the host, the pathogen and the changing climate or environment.

Conflict of Interest

The authors declare no conflict of interest.

REFERENCES

Abdou Zayan, S., 2020. Impact of climate change on plant diseases and IPM strategies. In: *Plant Diseases - Current Threats and Management Trends*. (Ed.) Topolovec-Pintaric, S. IntechOpen. DOI: https://doi.org/10.5772/intechopen.87055.

Andersen, K.F., Madden, L.V., Paul, P.A., 2015. Fusarium head blight development and deoxynivalenol accumulation in wheat as influenced by post-anthesis moisture patterns. *Phytopathology* 105(2), 210-219. DOI: https://doi.org/10.1094/PHYTO-04-14-0104-R.

Barbeito, I., Brücker, R.L., Rixen, C., Bebi, P., 2013. Snow fungi-induced mortality of *Pinus cembra* at the alpine treeline: Evidence from plantations. *Arctic, Antarctic and Alpine Research* 45(4), 455-470. DOI: https://doi.org/10.1657/1938-4246-45.4.455.

Bidzinski, P., Ballini, E., Ducasse A., Michel C., Zuluaga, P., Genga, A., Chiozzotto, R., Morel, J.B., 2016. Transcriptional basis of drought-induced susceptibility to the rice blast fungus *Magnaporthe oryzae*. *Frontiers in Plant Science* 7, 1-13. DOI: https://doi.org/10.3389/fpls.2016.01558.

Brown, J.K.M., Hovmøller, M.S., 2002. Aerial dispersal of pathogens on the global and continental scales and its impact on plant disease. *Science* 297(5581), 537-541. DOI: https://doi.org/10.1126/science.1072678.

Burdon, J.J., Zhan, J., 2020. Climate change and disease in plant communities. *PLoS Biology* 18(11), e3000949. DOI: https://doi.org/10.1371/journal.pbio.3000949.

Castroverde, C.D.M., Dina, D., 2021. Temperature regulation of plant hormone signaling during stress and development. *Journal of Experimental Botany* 72(21), 7436-7458. DOI: https://doi.org/10.1093/jxb/erab257.

Chakraborty, S., Newton, A.C., 2011. Climate change, plant diseases and food security: An overview. *Plant Pathology* 60(1), 2-14. DOI: https://doi.org/10.1111/j.1365-3059.2010.02411.x.

Chaloner, T.M., Gurr, S.J., Bebber, D.P., 2021. Plant pathogen infection risk tracks global crop yields under climate change. *Nature Climate Change* 11, 710-715. DOI: https://doi.org/10.1038/s41558-021-01104-8.

Cheng, Y.T., Zhang, L., He, S.Y., 2019. Plant-microbe interactions facing environmental challenge. *Cell Host & Microbe* 26(2), 183-192. DOI: https://doi.org/10.1016/j.chom.2019.07.009.

Choi, H.K., Iandolino, A., da Silva, F.G., Cook, D.R., 2013. Water deficit modulates the response of *Vitis vinifera* to the Pierce's disease pathogen *Xylella fastidiosa*. *Molecular Plant-Microbe Interactions* 26(6), 643-657. DOI: https://doi.org/10.1094/MPMI-09-12-0217-R.

Ciliberti, N., Fermaud, M., Roudet, J., Rossi, V., 2015. Environmental conditions affect *Botrytis cinerea* infection of mature grape berries more than the strain or transposon genotype. *Phytopathology* 105(8), 1090-1096. DOI: https://doi.org/10.1094/PHYTO-10-14-0264-R.

Coakley, S.M., Scherm, H., Chakraborty, S., 1999. Climate change and plant disease management. *Annual Review of Phytopathology* 37(1), 399-426. DOI: https://doi.org/10.1146/annurev.phyto.37.1.399.

Cohen, S.P., Liu, H., Argueso, C.T., Pereira, A., Vera Cruz, C., Verdier, V., Leach, J.E., 2017 RNA-seq analysis reveals insight into enhanced rice *Xa7*-mediated bacterial blight resistance at high temperature. *PLoS ONE* 12(11), e0187625. DOI: https://doi.org/10.1371/journal.pone.0187625.

Cohen, S.P., Leach, J.E., 2019. Abiotic and biotic stresses induce a core transcriptome response in rice. *Scientific Reports* 9, 6273. DOI: https://doi.org/10.1038/s41598-019-42731-8.

Cohen, S.P., Leach, J.E., 2020. High temperature-induced plant disease susceptibility: more than the sum of its parts. *Current Opinion in Plant Biology* 56, 235-241. DOI: https://doi.org/10.1016/j.pbi.2020.02.008.

Delgado-Baquerizo, M., Guerra, C.A., Cano-Díaz, C., Egidi, E., Wang, J., Eisenhauer, N., Singh, B.K., Maestre, F.T., 2020. The proportion of soil-borne pathogens increases with warming at the global scale. *Nature Climate Change* 10, 550-554. URL: https://doi.org/10.1038/s41558-020-0759-3.

Desaint, H., Aoun, N., Deslandes, L., Vailleau, F., Roux, F., Berthomé, R., 2021. Fight hard or die trying: When plants face pathogens under heat stress. *New Phytologist* 229(2), 712-734. DOI: https://doi.org/10.1111/nph.16965.

Desprez-Loustau, M.L., Marçais, B., Nageleisen, L.M., Piou, D., Vannini, A., 2006. Interactive effects of drought and pathogens in forest trees. *Annals of Forest Science* 63(6), 597-612. DOI: https://doi.org/10.1051/forest:2006040.

Dudney, J., Willing, C.E., Das, A.J., Latimer, A.M., Nesmith, J.C.B., Battles, J.J., 2021. Nonlinear shifts in infectious rust disease due to climate change. *Nature Communications* 12, 5102. DOI: https://doi.org/10.1038/s41467-021-25182-6.

Eastburn, D.M., Degennaro, M.M., Delucia, E.H., Dermody, O., Mcelrone, A.J., 2010. Elevated atmospheric carbon dioxide and ozone alter soybean diseases at SoyFACE. *Global Change Biology* 16(1), 320-330. DOI: https://doi.org/10.1111/j.1365-2486.2009.01978.x.

Fisher, M.C., Gurr, S.J., Cuomo, C.A., Blehert, D.S., Jin, H., Stukenbrock, E.H., Stajich, J.E., Kahmann, R., Boone, C., Denning, D.W., Gow, N.A.R., Klein, B.S., Kronstad, J.W., Sheppard, D.C., Taylor, J.W., Wright, G.D., Heitman, J., Casadevall, A., Cowen, L.E., 2020. Threats posed by the fungal kingdom to humans, wildlife and agriculture. *mBio* 11(3), e00449-20. DOI: https://doi.org/10.1128/mbio.00449-20.

Fones, H.N., Bebber, D.P., Chaloner, T.M., Kay, W.T., Steinberg, G., Gurr, S.J., 2020. Threats to global food security from emerging fungal and oomycete crop pathogens. *Nature Food* 1, 332-342. DOI: https://doi.org/10.1038/s43016-020-0075-0.

Goellner, K., Loehrer, M., Langenbach, C., Conrath, U., Koch, E., Schaffrath, U., 2010. *Phakopsora pachyrhizi*, the causal agent of Asian soybean rust. *Molecular Plant Pathology* 11(2), 169-177. DOI: https://doi.org/10.1111/j.1364-3703.2009.00589.x.

Hossain, M., Veneklaas, E.J., Hardy, G.E., Poot, P., 2019. Tree host-pathogen interactions as influenced by drought timing: Linking physiological performance, biochemical defence and disease severity. *Tree Physiology* 39(1), 6-18. DOI: https://doi.org/10.1093/treephys/tpy113.

Islam, M.T., Kim, K.H., Choi, J., 2019. Wheat blast in Bangladesh: The current situation and future impacts. *The Plant Pathology Journal* 35(1), 1-10. DOI: https://doi.org/10.5423/PPJ.RW.08.2018.0168.

Johansen, T.J., Dees, M.W., Hermansen, A., 2015. High soil moisture reduces common scab caused by *Streptomyces turgidiscabies* and *Streptomyces europaei scabiei* in potato. *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science* 65(3), 193-198. DOI: https://doi.org/10.1080/09064710.2014.988641.

Juroszek, P., von Tiedemann, A., 2015. Linking plant disease models to climate change scenarios to project future risks of crop diseases: A review. *Journal of Plant Diseases and Protection* 122, 3-15. DOI: https://doi.org/10.1007/BF03356525.

Khan, M.R., Rizvi, T.F., 2020. Effect of elevated levels of CO_2 on powdery mildew development in five cucurbit species. *Scientific Reports* 10, 4986. DOI: https://doi.org/10.1038/s41598-020-61790-w.

Karnosky, D.F., Percy, K.E., Xiang, B., Callan, B., Noormets, A., Mankovska, B., Hopkin, A., Sober, J., Jones, W., Dickson, R.E., 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(4), 329-338. DOI: https://doi.org/10.1046/j.1354-1013.2002.00479.x.

Ma, L., Qiao, J., Kong, X., Zou, Y., Xu, X., Chen, X., Hu, X., 2015. Effect of low temperature and wheat winter-hardiness on survival of *Puccinia striiformis* f. sp. *tritici* under controlled conditions. *PLoS ONE* 10(6), e0130691. DOI: https://doi.org/10.1371/journal.pone.0130691.

Mamo, B.E., Eriksen, R.L., Adhikari, N.D., Hayes, R.J., Mou, B., Simko, I., 2021. Epidemiological characterization of lettuce drop (*Sclerotinia* spp.) and biophysical features of the host identify soft stem as a susceptibility factor. *PhytoFrontiers* 1(3), 182-204. DOI: https://doi.org/10.1094/PHYTOFR-12-20-0040-R.

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 Biology* 11(10), 1828-1836. DOI: https://doi.org/10.1111/j.1365-2486.2005.001015.x.

Muluneh, M.G., 2021. Impact of climate change on biodiversity and food security: a global perspective - a review article. *Agriculture and Food Security* 10, 36. DOI: https://doi.org/10.1186/s40066-021-00318-5.

Newbery, F., Qi, A., Fitt, B.D.L., 2016. Modelling impacts of climate change on arable crop diseases: Progress, challenges and applications. *Current Opinion in Plant Biology* 32, 101-109. DOI: https://doi.org/10.1016/j.pbi.2016.07.002.

Oliva, J., Stenlid, J., Martinez-Vilalta, J., 2014. The effect of fungal pathogens on the water and carbon economy of trees: Implications for drought-induced mortality. *New Phytologist* 203(4), 1028-1035. DOI: https://doi.org/10.1111/nph.12857.

Parikka, P., Hakala, K., Tiilikkala, K., 2012. Expected shifts in *Fusarium* species' composition on cereal grain in Northern Europe due to climatic change. *Food Additives & Contaminants: Part A* 29(10), 1543-1555. DOI: https://doi.org/10.1080/19440049.2012.680613.

Qiu, J., Dong, F., Yu, M., Xu, J., Shi, J., 2016. Effect of preceding crop on *Fusarium* species and mycotoxin contamination of wheat grains. *Journal of the Science of Food and Agriculture* 96(13), 4536-4541. DOI: https://doi.org/10.1002/jsfa.7670.

Rai, A., Irulappan, V., Senthil-Kumar, M., 2022. Dry root rot of chickpea: A disease favored by drought. *Plant Disease* 106(2), 346-356. DOI: https://doi.org/10.1094/PDIS-07-21-1410-FE.

Rigg, J.L., McDougall, K.L., Liew, E.C.Y., 2018. Susceptibility of nine alpine species to the root rot pathogens *Phytophthora cinnamomi* and *P. cambivora*. *Australasian Plant Pathology* 47, 351-356. DOI: https://doi.org/10.1007/s13313-018-0564-x.

Ristaino, J.B., Anderson, P.K., Bebber, D.P., Brauman, K.A., Cunniffe, N.J., Fedoroff, N.V., Finegold, C., Garrett, K.A., Gilligan, C.A., Jones, C.M., Martin, M.D., MacDonald, G.K., Neenan, P., Records, A., Schmale, D.G., Tateosian, L., Wei, Q., 2021. The persistent threat of emerging plant disease pandemics to global food security. *PNAS* 118(23), e2022239118. DOI: https://doi.org/10.1073/pnas.2022239118.

Rohr, J.R., Barrett, C.B., Civitello, D.J., Craft, M.E., Delius, B., DeLeo, G.A., Hudson, P.J., Jouanard, N., Nguyen, K.H., Ostfeld, R.S., Remais, J.V., Riveau, G., Sokolow, S.H., Tilman, D., 2019. Emerging human infectious diseases and the links to global food production. *Nature Sustainability* 2, 445-456. DOI: https://doi.org/10.1038/s41893-019-0293-3.

Ryu, M., Mishra, R.C., Jeon, J., Lee, S.K., Bae, H., 2018. Drought-induced susceptibility for *Cenangium ferruginosum* leads to progression of *Cenangium*-dieback disease in *Pinus koraiensis*. *Scientific Reports* 8, 16368. DOI: https://doi.org/10.1038/s41598-018-34318-6.

Sewelam, N., El-Shetehy, M., Mauch, F., Maurino, V.G., 2021. Combined abiotic stresses repress defense and cell wall metabolic genes and render plants more susceptible to pathogen infection. *Plants* 10(9), 1946. DOI: https://doi.org/10.3390/plants10091946.

Sikes, B.A., Bufford, J.L., Hulme, P.E., Cooper, J.A., Johnston, P.R., Duncan, R.P., 2018. Import volumes and biosecurity interventions shape the arrival rate of fungal pathogens. *PLoS Biology*

16(5), e2006025. DOI: https://doi.org/10.1371/journal.pbio.2006025.

Sparks, A.H., Forbes, G.A., Hijmans, R.J., Garrett, K.A., 2014. Climate change may have limited effect on global risk of potato late blight. *Global Change Biology* 20(12), 3621-3631. DOI: https://doi.org/10.1111/gcb.12587.

Tada, T., Tanaka, C., Katsube-Tanaka, T., Shiraiwa, T., 2021. Effects of wounding and relative humidity on the incidence of Phytophthora root and stem rot in soybean seedlings. *Physiological and Molecular Plant Pathology* 116, 101737. DOI: https://doi.org/10.1016/j.pmpp.2021.101737.

Teshome, D.T., Zharare, G.E., Naidoo, S., 2020. The threat of the combined effect of biotic and abiotic stress factors in forestry under a changing climate. *Frontiers in Plant Science* 11, 601009. DOI: https://doi.org/10.3389/fpls.2020.601009.

Thompson, S.E., Levin, S., Rodriguez-Iturbe, I., 2014. Rainfall and temperatures changes have confounding impacts on *Phytophthora cinnamomi* occurrence risk in the southwestern USA under climate change scenarios. *Global Change Biology* 20(4), 1299-1312. DOI: https://doi.org/10.1111/gcb.12463.

Toniutti, L., Breitler, J.C., Etienne, H., Campa, C., Doulbeau, S., Urban, L., Lambot, C., Pinilla, J.H., Bertrand, B., 2017. Influence of environmental conditions and genetic background of *Arabica* coffee (*C. arabica* L.) on leaf rust (*Hemileia vastatrix*) pathogenesis. *Frontiers in Plant Science* 8, 2025. DOI: https://doi.org/10.3389/fpls.2017.02025.

Trębicki, P., Vandegeer, R.K., Bosque-Pérez, N.A., Powell, K.S., Dader, B., Freeman, A.J., Yen, A.L., Fitzgerald, G.J., Luck, J.E., 2016. Virus infection mediates the effects of elevated CO_2 on plants and vectors. *Scientific Reports* 6, 22785. DOI: https://doi.org/10.1038/srep22785.

Trivedi, P., Leach, J.E., Tringe, S.G., Sa, T., Singh, B.K., 2020. Plant-microbiome interactions: From community assembly to plant health. *Nature Reviews Microbiology* 18(11), 607-621. DOI: https://doi.org/10.1038/s41579-020-0412-1.

Trumbore, S., Brando, P., Hartmann, H., 2015. Forest health and global change. *Science* 349(6250), 814-818. DOI: https://doi.org/10.1126/science.aac6759.

van Dijk, M., Morley, T., Rau, M.L., Saghai, Y., 2021. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010-2050. *Nature Food* 2, 494-501. DOI: https://doi.org/10.1038/s43016-021-00322-9.

Vary, Z., Mullins, E., McElwain, J.C., Doohan, F.M., 2015. The severity of wheat diseases increases when plants and pathogens are acclimatized to elevated carbon dioxide. *Global Change Biology* 21(7), 2661-2669. DOI: https://doi.org/10.1111/gcb.12899.

Velasquez, A.C., Castroverde, C.D.M., He, S.Y., 2018. Plant-pathogen warfare under changing climate conditions. *Current Biology* 28(10), R619-R634. DOI: https://doi.org/10.1016/j.cub.2018.03.054.

Wakelin, S., Gómez-Gallego, M., Jones, E., Smaill, S., Lear, G., Lambie, S., 2018. Climate change induced drought impacts on plant diseases in New Zealand. *Australasian Plant Pathology* 47, 101-114. DOI: https://doi.org/10.1007/s13313-018-0541-4.

Walter, S., Ali, S., Kemen, E., Nazari, K., Bahri, B.A., Enjalbert, J., Hansen, J.G., Brown, J.K., Sicheritz-Pontén, T., Jones, J., de Vallavieille-Pope, C., Hovmøller, M.S., Justesen, A.F., 2016. Molecular markers for tracking the origin and worldwide distribution of invasive strains of *Puccinia striiformis*. *Ecology and Evolution* 6(9), 2790-2804. DOI: https://doi.org/10.1002/ece3.2069.

Webb, K.M., Oña, I., Bai, J., Garrett, K.A., Mew, T., Vera Cruz, C.M., Leach, J.E., 2010. A benefit of high temperature: Increased effectiveness of a rice bacterial blight disease resistance gene. *The*

New Phytologist 185(2), 568-576. DOI: https://doi.org/10.1111/j.1469-8137.2009.03076.x.

Xin, X.F., Nomura, K., Aung, K., Velásquez, A.C., Yao, J., Boutrot, F., Chang, J.H., Zipfel, C., He, S.Y., 2016. Bacteria establish an aqueous living space in plants crucial for virulence. *Nature* 539(7630), 524-529. DOI: https://doi.org/10.1038/nature20166.

Zhan, J., Ericson, L., Burdon, J.J., 2018. Climate change accelerates local disease extinction rates in a long-term wild host-pathogen association. *Global Change Biology* 24(8), 3526-3536. DOI: https://doi.org/10.1111/gcb.14111.

Zhou, Y., Van Leeuwen, S.K., Pieterse, C.M.J., Bakker, P.A.H.M., Van Wees, S.C.M., 2019. Effect of atmospheric CO_2 on plant defense against leaf and root pathogens of *Arabidopsis*. *European Journal of Plant Pathology* 154, 31-42. DOI: https://doi.org/10.1007/s10658-019-01706-1.

***