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Review article

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Climate change impacts on plant pathogens, food security and paths forward

Supplementary Table 1 Examples of major plant pathogens, their damages and how they are likely to respond to climate change. For each pathogen, we provide the diseases caused, plant hosts and geographical distribution (global or restricted to particular regions). Here, we focused on bacterial, fungal and oomycetous pathogens.

Domain	**Pathogen**	**Host**	**Disease**	**Symptoms**	**Distribution**	**Responses to the climate change**
Bacteria	*Agrobacterium tumefaciens*	Grapevines, stone and pome fruit trees, nut trees, and a few ornamentals	Crown gall tumour; spread via aerial dispersal of spores	Induces neoplastic growths at wound sites on host plants and severely limits crop yield and growth vigour.	Global	The effect of climate change is largely unknown.
Bacteria	*Xanthomonas oryzae* pv. *oryzae*	Rice	Bacterial blight; spread through irrigation water, wind, rain splash.	Water-soaked lesions that expand into yellowish-brown lesions with uneven edges. Thrives in xylem vessels.	Rice growing areas of Asia and Africa.	Disease more severe at high temperatures, particularly in humid conditions. Most single resistance genes lose efficacy at high temperatures. Ref: [1, 2]
Bacteria	*Xylella fastidiosa*	A wide range of host plant species, including almond, citrus and olive.	Pierce's disease, leaf scorch, wilt and die-back. Vector-transmitted (transmission by xylem-sap feeding insects)	Interacts primarily with nonliving tissues in both its insect and plant hosts. Causes significant economic losses due to limited control options.	Endemic to Americas, and recently introduced in a restricted range in Mediterranean regions	The effect of climate change is largely unknown on a global scale. However, Europe-based models suggest that, as the minimum winter temperatures might increase, the bacterium could spread to other suitable regions. Ref: [3]

Fungi	*Magnaporthe oryzae*	Rice, 50 species of grasses and sedges	rice blast disease; spread via aerial dispersal of spores, or via water splash.	Spores infect plants, particularly when humidity is high, often killing young plants. In older plants, the fungus can spread and prevent seed formation.	Global	In the areas where climatic conditions are already suitable for rice blast disease, climate change can reduce the disease risk due to increased air temperatures above the optimal ranges for pathogen infectivity (17-28 °C). However, the disease impact can increase in areas with more favourable thermal regimes, leading to earlier host infection and colonization. Precipitation increase positively correlates with leaf blast severity and incidence, with values over 200 mm corresponding to high disease impact. Refs: [4]
Fungi	*Alternaria solani*	Solanaceae, including potato, tomato, eggplant	Early blight; spread via aerial dispersal of spores	Overwinters on infected crop debris or weedy hots and needs warm and moist environment to germinate. Infects mature plants through wounds in the roots, and spread to the entire plant causing defoliation	Global	Warm, humid (24-29°C) environmental conditions are conducive to infection. Range is likely to increase at the global scale with warmer temperatures. Refs: [5]
Fungi	*Botrytis cinerea*	Over 200 crop hosts worldwide. Vegetables (i.e. cabbage, lettuce, broccoli, beans)	Botrytis bunch rot; spread via aerial dispersal of spores	Most destructive on mature or senescent host tissues, but can infect at all growth stages. Infection of plant tissue typically requires	Global	Changes in seasonal weather patterns causing prolonged wet and warm (18-30C) growing seasons are likely to increase disease risk and severity. Models available mostly for grapes. Refs:[6]

		and small fruit crops (grape, strawberry, raspberry, blackberry) are most severely affected.		moisture and wet growing seasons.		
Fungi	*Fusarium graminearum* species complex	Wheat, barely, oat	Fusarium head blight; spread via aerial dispersal of spores	Infects plants at the flowering stage. Overwinters on infested crop residues and needs warm and moist environment to germinate. Produces mycotoxins that make grain unsuitable for use as food or feed	Global	Increases in relative humidity favour both inoculum production and infection. Range is likely to increase with warming, with European, Middle Eastern and North African countries at higher risk of outbreaks. Quantitative information on the differential responses among FGSC members is lacking. Refs: [5, 7]
Fungi	*Penicillium digitatum*	Many species of Citrus	Green mold disease	Infects fruit through wounds. It is one of the most severe postharvest pathogens, especially in arid zones and tropical subclimates	Global	Can grow in relatively wide temperature range (6–37°C) and is drought resistant. Fruit pH and metabolic composition are the main drivers of colonisation and infection; Likely to change with changes in temperature and rainfall patterns. Refs: [8]
Fungi	*Puccinia graminis f. sp. tritici*	Cereals (including wheat, rye and barley)	Stem (black) rust; spread via aerial dispersal of spores	Most destructive *Puccinia* sp. for wheat. It can attack all above-ground parts of the plant, including the stem, leaves and inflorescence. Can result in 100% yield	Global	A warmer and drier climate is predicted to benefit the spore production and spread, and more severe diseases can be expected in cold regions, where the fungus will have better chances of overwintering due to expected subfreezing temperature. However, projected drier conditions will

				losses on susceptible wheat cultivars and reduced grain quality.		reduce substantially the probability of an infection starting from deposited spores, except in irrigated fields. Refs: [9,10]
Fungi	*Puccinia psidii*	Myrtaceae	Guava rust, eucalyptus rust or myrtle rust; spread via aerial dispersal of spores	Infects, impacts, and often kills newly expanding leaves and stems as well as fruit and flowers, resulting in shoot dieback, reduced recruitment, and adult plant mortality. Major threat to native plant communities and plantations	Tropical fungus, endemic to South and Central America, recently introduced in Australia, New Zealand, USA and South Africa	Disease severity is likely to increase with annual precipitation >1500 mm and high foliage projective cover, and decrease with increasing temperature (>32C). Wet tropics are identified as highly susceptible regions under future climate scenarios. Ref. [11-13]
Fungi	*Ralstonia solanacearum*	Major diseases of tomato and other vegetables	Bacterial wilt disease; spread via aerial dispersal of spores	Infects via wounds, root tips or cracks at the sites of lateral root emergence. Thrives in the water-transporting xylem vessels of its host plants. Causes important losses in many developing countries.	Wet tropics, subtropics and some temperate regions of the world	The effect of climate change is not quantified and few models exist. However, the pathogen is favoured by high temperatures, and global warming is likely to increase disease risk. Ref: [14, 15]
Fungi	*Verticillium dahliae*	>150 crop hosts, including cotton, grapes, almonds, strawberries,	Verticillium wilt; spread via aerial dispersal of spores	Infects the roots of plants, directly or through wounds; Causes premature foliar chlorosis and necrosis and vascular discoloration in stems	Global	Favoured by moist soils and a temperature range of 21-27° C. Climate change is expected to stimulate fungal growth by increasing soil temperatures towards the biological optimum in colder soils or by

		lettuce, tomatoes		and roots. Major economic losses in crops are in temperate regions of the world		extending the infection period. Global models are not available . Refs: [16]
Fungi	*Zymoseptoria tritici*	wheat	Septoria tritci blotch; spread via aerial dispersal of spores, or via water splash.	Infects host is via leaf stomatal openings, causing necrosis and reduction in photosynthetic capacity, which affects grain yield.	Temperate regions	Thrives in climates with rain during the development of wheat (e.g., European temperate regions). Increases in humidity favour an increase in infection rate and pathogen growth. Changes in seasonal rainfall patterns are likely to affect distribution and infectivity. However climatic models are not available. Refs: [17, 18]
Oomycetes	*Phytophthora infestans*	potato	Potato late blight; spread via aerial dispersal of spores, or via water splash.	Infects all parts of the potato plant and, under moderate temperature (16–22°C) and high humidity (over 97%), can destroy entire crops within a few days of infection	Global	*P. infestans* has a low optimal growth temperature (13-22C) and global warming will have small effect on infection risk in most of the growing regions of the Northern Hemisphere, except for the very coolest potato-growing areas. Ref:[19]
Oomycetes	*Phytophtora ramorum*	Many oak species and woody ornamentals	Sudden oak death and ramorum blight; spread via aerial dispersal of spores, or via water splash.	Highly persistent in soil, infects root tips via wounds causing stem cankers, tip and shoot dieback and leaf blight. Recently emerged, it is responsible for extensive mortality of trees and shrubs in both natural	Europe and North America	Adapted to cool temperatures with optimal growth at 20 °C. Requires seasonally high moisture to germinate. Likely to be affected by changes in seasonal rainfall patterns, but climatic models are not available. Refs: [20]

				communities and plantations		
Oomycetes	*Pythium spp.*	Multiple crop species (e.g., tabaco, tomatoes and other vegetables)	Pythium-induced root rot is a common disease in crops. Infested soil or plant material can spread disease.	Highly persistent in soil, infects root tips. Can survive long periods of time in soil decomposing organic matter.	Global	Cause disease mostly in range of 20-30oC, particularly sever infection under wet and high soil moisture conditions. Likely to be affected by change in temperature and annual rainfall patterns.

Supplementary Methods for Figure 2:

Global maps of the likely distributions of the current and future of the relative abundance of soil-borne plant pathogens were implemented[21], we performed ordinary least squares models to project each map of the current and future states of the proportion of Phytophthora spp. and Pythium spp. and Penicillium sp. from soil worldwide. Implementation of these models was preceded by exploratory correlation analyses to identify the most important factors associated with the distributions of potential plant pathogens. These included climate; mean annual temperature and mean annual precipitation; vegetation type, forest and grassland; elevation; and soil variables, soil texture, soil carbon and soil pH. To assess the accuracy of the predictions calculated from the model, we calculated how much the parameter space of the predictors differed from the original dataset.

To locate the areas of the projection far from the sampling points, the masking criterion p-value < 0.01 was used to show the areas generated by the model in the projection that are closer to the sampling points. We used the Mahalanobis distance of any multidimensional point of the eight dimensions given by the exogenous variables to the centre of the known distribution that we have previously calculated and the distance of any multidimensional point to the convex hull formed by the all data locations that were used in the model[22]. Subsequently, we used outlier identification to mask our results and provide more reliable predictions at the 0.99 quantiles of the chi-square distribution with eight degrees of freedom to which each location belongs[23].The variables that were constant in the future projections were elevation and soil variables. Implementation of these models was preceded by exploratory correlation analyses to identify the most important factors associated with potential plant pathogen distributions from available data (Supplementary Table 1).

To map future (2050) projections of the relative abundance of soil-borne plant pathogens, we used climate and land-use datasets[24-25]. We used the historical and future ISMIP2a dataset of Representative Concentration Pathway (RCP)2.6, RCP6.0 and RCP8.5 for 2050 in combination with Shared Socioeconomic Pathways (SSP). We used two different general circulation models (gfdl-esm2m and noresm1-m)[26]. Each SSP corresponds to a specific RCP; here we select the combinations SSP1-RCP2.6, SSP4-RCP6.0 and SSP5-RCP8.5. For the land-use projections, we relied on the dataset provided by the Land-use Harmonized v2.0 project (http://luh.umd.edu/)[27].

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