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Key Challenges

Phytopathology®
REVIEW

Disaster Plant Pathology: Smart Solutions for Threats to Global Plant Health from Natural and Human-Driven Disasters

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Abstract

Disaster plant pathology addresses how natural and human-driven disasters impact plant diseases and the requirements for smart management solutions. Local to global drivers of plant disease change in response to disasters, often creating environments more conducive to plant disease. Most disasters have indirect effects on plant health through factors such as disrupted supply chains and damaged infrastructure. There is also the potential for direct effects from disasters, such as pathogen or vector dispersal due to floods, hurricanes, and human migration driven by war. Pulse stressors such as hurricanes and war require rapid responses, whereas press stressors such as climate change leave more time for management adaptation but may ultimately cause broader challenges. Smart solutions for the effects of disasters can be deployed through digital agriculture and decision support systems supporting disaster preparedness and optimized humanitarian aid across scales. Here, we use the disaster plant pathology framework to synthesize the effects of disasters in plant pathology and outline solutions to maintain food security and plant health in catastrophic scenarios. We recommend actions for improving food security before and following disasters, including (i) strengthening regional and global cooperation, (ii) capacity building for rapid implementation of new technologies, (iii) effective clean seed systems that can act quickly to replace seed lost in disasters, (iv) resilient biosecurity infrastructure and risk assessment ready for rapid implementation, and (v) decision support systems that can adapt rapidly to unexpected scenarios.

Keywords: disaster microbiology, disease surveillance, food security, global agriculture, humanitarian crises, natural disasters

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Disaster Plant Pathology

Natural and human-driven disasters threaten global food security and livelihoods (Prosekov and Ivanova 2018; Rosegrant and Cline 2003). Large-scale disasters cause widespread and severe damage and directly threaten human health. In the immediate aftermath of disasters such as earthquakes and hurricanes, attention must be focused on human health and safety. In system recovery from disasters, attention to human, animal, and plant health is needed, as disruptions in agrifood systems pose long-term risks to human health (van Bruggen et al. 2019; WHO 2017; Zinsstag et al. 2011). Rapid-onset disasters, such as droughts, floods, wildfires, political turmoil, conflicts, and wars, function as pulse stressors. Long-term disasters, such as climate change, market instability, and food insecurity, function as press stressors. These stressors disrupt food systems, which may have direct or indirect impacts on communities (Fig. 1A), leading to famines and infrastructure destruction (Table 1) (Harris et al. 2018; Savary et al. 2019). The consequences of disasters are most severe for low-income populations, who are already dealing with the impacts of food insecurity and poverty (Carter et al. 2007; Fothergill and Peek 2004).

Mitigating the impacts of disasters on global food systems requires smart tools and predictive systems, the collective actions of agricultural stakeholders, and the development of recovery strategies, particularly for vulnerable populations. The deployment and use of these predictive tools and recovery strategies can help to mitigate the cumulative stress a community or region experiences following a disaster (Fig. 1). The impacts of natural and human-driven disasters on food security are well documented (De Haen and Hemrich 2007; Horsfall and Cowling 1978; Kunreuther et al. 2014; Pelling and Garschagen 2019; Zadoks 2017). A new synthesis of the effects of disasters and compound disasters on plant disease can help to focus plant pathology to effectively provide solutions. Disaster plant pathology supports the interdisciplinary development of smart management solutions to foster disaster preparedness and prevention, reducing the risk for compounding crises.

Recent decades have been defined by rapid ecosystem change, often accompanied by biodiversity loss, shifts in biotic niches, and increased spread of invasive pests and pathogens (Bebber et al. 2014; Mayewski et al. 2004; Turvey 2009). New threats have inspired the development of disaster microbiology, addressing the effects of disasters on microbial populations (Smith and Casadevall 2022), and disaster ecology and disaster psychiatry, addressing anthropological contexts and extreme public health disasters (Shultz et al. 2009). Disaster science has historically addressed responses for public health (Haines et al. 2006; Noji 2000) and is gaining importance across disciplines as human activities become more interconnected, especially under catastrophic scenarios. The increasing occurrence of natural disasters, human travel and migration, and global trade of agricultural goods exacerbates the risk of pest and pathogen movement and establishment (Banholzer et al. 2014; Bebber et al. 2014; Benevolenza and DeRigne 2019; Paini et al. 2016). Recently, there has been a substantial effort to develop smart agricultural tools to help address the uncertainty surrounding plant

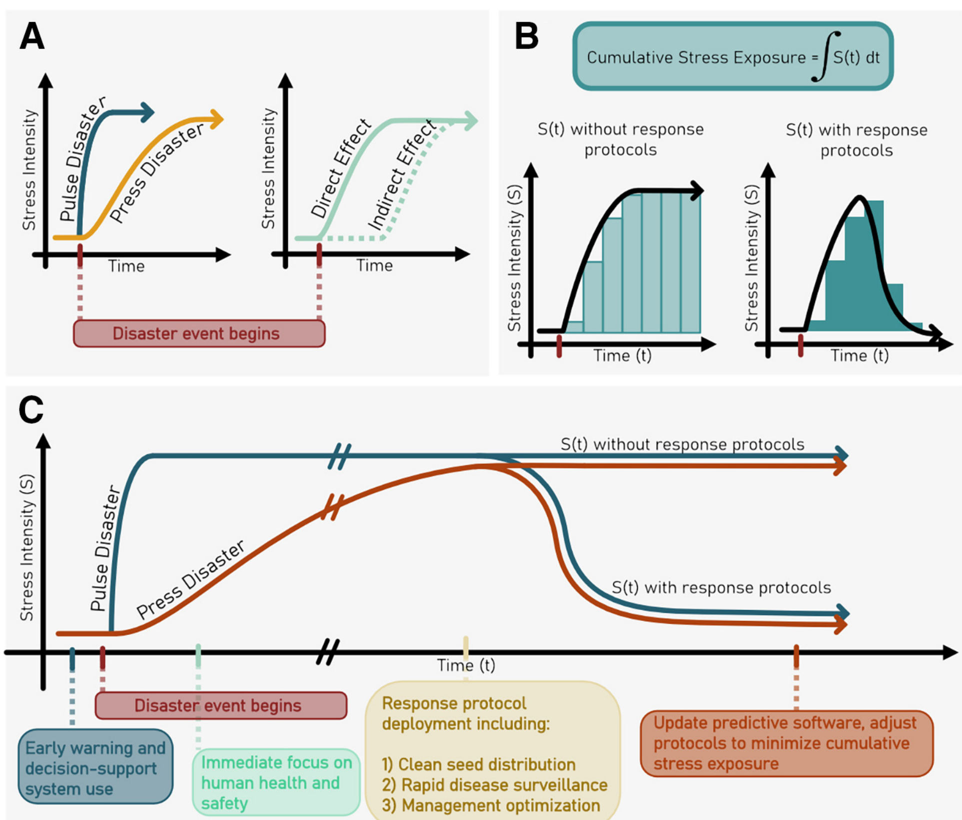


FIGURE 1
Disaster plant pathology addresses how natural and human-driven disasters impact plant disease and the requirements for smart management solutions. The stress intensity over time for plant health is a function of the many impacts of disasters, from pathogen dispersal and plant wounding to reduced capacity for disease management. **A,** Pulse stressors in rapid-onset crises such as hurricanes demand a rapid response, whereas press stressors in slow-onset crises such as climate change provide more time for management adaptation. Most disasters have indirect effects on plant health, such as by destroying infrastructure, and some disasters also have direct effects on plant health, such as introduction of new pathogens in hurricanes. **B,** Rapid and effective response protocols can decrease plant health risk over time. **C,** An example timeline for pulse and press disasters, the timing of preventive and response measures, and their potential impacts on cumulative stress exposure. Timelines vary by disaster type, where deploying response protocols to press stressors may occur before the greatest potential stress intensity is reached.

disease epidemics through computational decision support systems (DSSs) (Zhai et al. 2020). As these tools improve and are more widely available, they can be used in times of crisis for rapid and optimized disaster preparedness and recovery.

Disaster plant pathology provides a framework focusing on the impact of disasters on plant health, plant pathogens, and agricultural systems for tailored solutions and informed decision-making. This framework promotes interdisciplinary collaboration, making it of common interest for communities of plant pathologists, humanitarian groups, economists, computer scientists, meteorologists, and sustainable development strategists. Disaster plant pathology addresses the uncertainty surrounding both human-driven and natural disasters and the resulting challenges in the context of plant health and food security (Fig. 1). The objectives of this paper are to (i) develop the disaster plant pathology framework, focusing on the impact of natural and human-driven disasters on plant disease and food security; (ii) provide an overview of smart agriculture solutions and effective practices for disaster planning and recovery; and (iii) recommend steps for the implementation of disaster plant pathology tools.

Global drivers of pathogen and pest spread

The factors that drive disease, in the presence or absence of disasters, are host susceptibility, environmental conduciveness, and pathogen competence, in the "disease triangle" (Garrett et al. 2022; Scholthof 2007). Combined with climate change, human activities can also contribute to the proliferation of pest and pathogen species to the detriment of agricultural systems (McKinney and Lockwood 1999). If cropping regions expand or host susceptibility increases, new pests and pathogens gain access to vulnerable plant populations (Torchin and Mitchell 2004), which may also facilitate pathogen invasions between wild and cultivated host landscapes (Lacomme et al. 2017). Given rapid growth in international commodity trading, the probability of long-distance pathogen movement drastically increases (Bebber et al. 2014; Clavel et al. 2011; McGeoch et al. 2010). For example, Bebber et al. (2014) reported that more than 10% of crop pests have spread to at least half of the countries growing their host. Climate conduciveness to pests and pathogens is also projected to change, potentially resulting in shifts in the geographic distribution of pathogens, their host ranges, and their vectors (Elad and Pertot 2014; Shaw and Osborne 2011). The ranges of many important plant pests and pathogens have already expanded, although concurrent shifts in moisture and host availability can result in nonlinear impacts on overall disease prevalence (Dudney et al. 2021). Understanding and management of the interactions of host, pathogen, and environment are challenged by increasing exposure to natural and human-driven disasters in ecosystems (Thiery et al. 2021). To optimally manage disease, we must consider not only the disease triangle but also the complexity of natural disasters and humanitarian crises. Ultimately, we need to develop tools for decision makers to address the effects of these pulse and press stressors on plant health.

Natural Disasters

Links between natural disasters and plant health

Wildfires and extreme weather events, such as floods, tropical cyclones, and droughts, severely impact agriculture, food security,

TABLE 1
Disasters can be categorized by the type of crisis: slow-onset (press stressor), rapid-onset (pulse stressor), and complex (adapted from SEADS [2022], an important source of information for disaster recovery)[a]

Crisis	Common crisis traits	Examples
Slow-onset crisis (press stressors)	• Gradual, increasing stress on livelihoods • Specific geographical areas are known to be at risk, low-level predictability • Early response is often nonexistent • Crop area coverage decreases, and crop performance gradually worsens • Reduced crop quality generates lower prices and therefore reduced grower income	• Drought • Plant pests • Plant diseases • Parasitic weeds • Pollution • Salinization • Climate change
Rapid-onset crisis (pulse stressors)	• Occurs with little or no warning, most impact occurs immediately • Specific geographical areas often have known risks • Early response measures exist, though are with short notice • Movement of goods and people needed to manage crops is restricted • Crop loss is excessive • Infrastructure and physical assets are immediately damaged • Markets close due to infrastructure loss, border closures, quarantine, lockdown, or conflict	• Floods • Earthquakes • Typhoons • Volcanic eruption • Tsunami • Pest or disease outbreaks • Cyberattacks
Complex crisis (potentially both press and pulse stressors)	• Associated with protracted political instability and/or internal or external armed conflict • A slow-onset or a rapid-onset crisis can also occur simultaneously, worsening the impacts of the ongoing complex crisis • Crop loss is excessive and low production can become chronic • Infrastructure and services to support production are damaged • Markets are disrupted on a wide scale • Access to productive assets and labor availability is disrupted	• Ongoing conflict with natural disaster impacts • Civil war • Terrorism alongside natural disasters • New types of complex crisis (such as COVID-19)

[a] The type of disaster determines the impact on social and agricultural systems and the response needed.

and natural ecosystems globally (Albrigo et al. 2005; Dale et al. 2001; Irey et al. 2006; Smith et al. 2016). The number of extreme weather events that cause extensive damage has increased in recent decades (Smith et al. 2016), including substantial increases in the United States (Fig. 2). These events strain the tightly woven socioecological systems that maintain modern agriculture and threaten both human and natural environments. Ultimately, extreme weather events can make agriculture less sustainable in some regions, so that farmers lose market share to more competitive and stable regions (Goodwin and Vado 2007; Meissner et al. 2009; Webb et al. 2002), or it can cause complete breakdowns in food systems, resulting in demographic catastrophes such as the "great famine" in 1984–1985 in Ethiopia (Kidane and Hailemariam 1989). Extreme weather events affect how governments can promote and support agriculture by altering resource priorities for a region or driving enactment of new regulations in the face of disaster (Goodwin and Vado 2007). In smallholder systems, particularly, natural disasters cause a shift in coping strategies, limiting agronomic and disease management practices, and even leading to abandonment of farms. Reduced regional management can cause rapid accumulation of pests and pathogens across a landscape and lead to higher transmission rates, resulting in rampant disease spread. Extreme natural disasters can cause temporary or long-term disruptions in critical infrastructure, limiting the ability of stakeholders to monitor and manage pest population outbreaks in the aftermath of a disaster, which puts pressure on decision makers evaluating how best to manage disease (Mitsova et al. 2019). Decisions in response to extreme weather events can have long-reaching effects on agricultural production and food security that are difficult to forecast or mitigate. For instance, following the 2010 earthquakes in Haiti, providing rice as disaster relief resulted in an influx of inexpensive imports, weakening Haiti's domestic rice production (Katz 2010).

Although most immediate attention following these events is reasonably focused on protecting human health and wellbeing, it is important to recognize the interconnectedness of human and plant health. Unintended consequences, such as the impact on domestic rice production following earthquakes in Haiti, highlight the need for a One Health approach to disease management. The One Health framework addresses the interconnections between human, animal, plant, and environmental health (van Bruggen et al. 2019; WHO

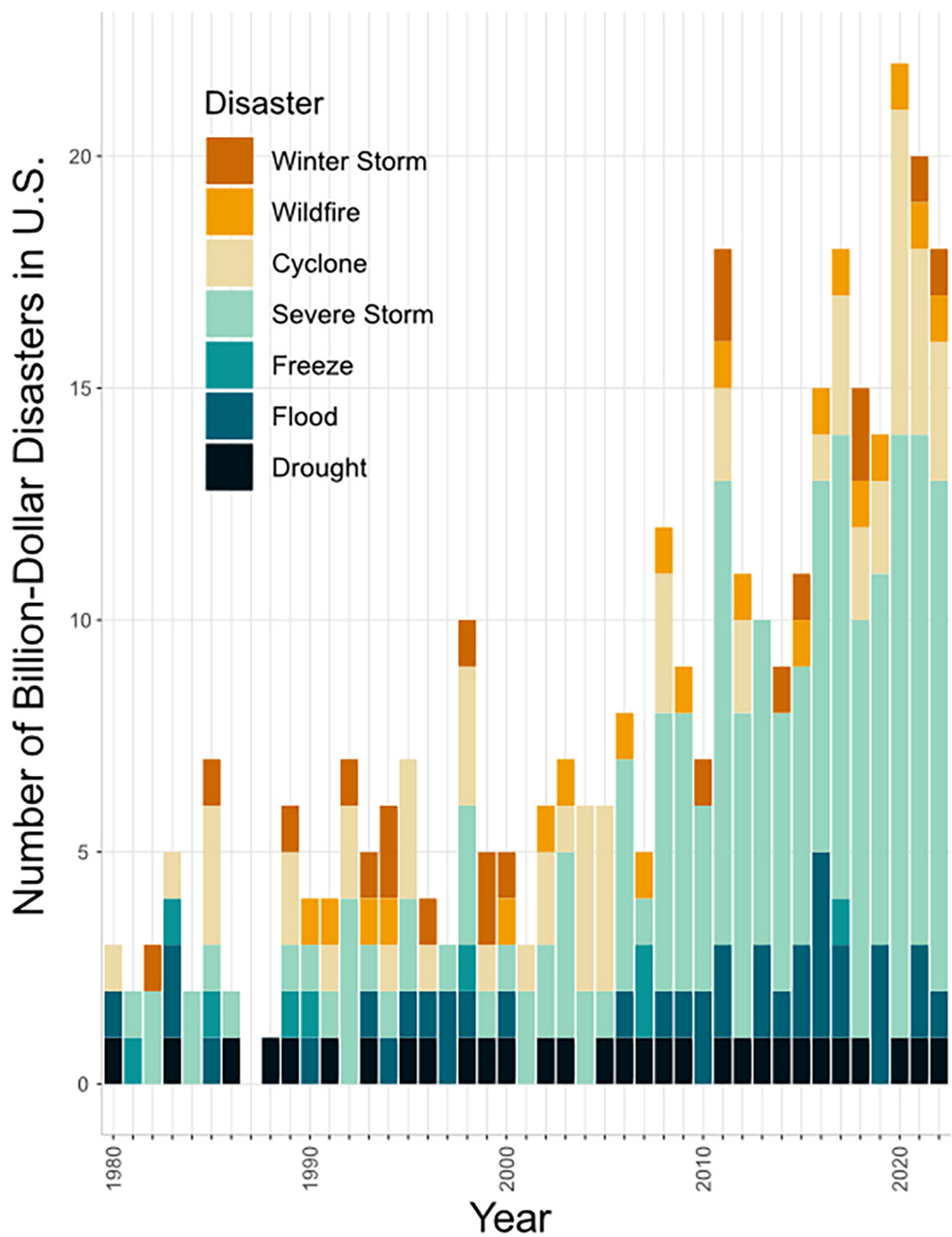


FIGURE 2
The number of billion-dollar disasters in the United States, adjusted for inflation, as reported by the National Centers for Environmental Information (Smith 2021), has been increasing since the 1980s. Cell colors indicate the type of disaster.

2017; Zinsstag et al. 2011). Integrating plant pathology in disaster management strategies can enhance resilient food systems in the aftermath of these catastrophes. Here, we synthesize the literature supporting disaster plant pathology, incorporating the mechanisms that drive disease patterns and the impacts these patterns have on social and ecological systems.

The impacts of major storms and floods

Extreme weather events such as cyclones, hurricanes, and typhoons can directly impact plant health by spreading invasive pathogens and pests into new regions (Brown and Hovmøller 2002; Irey et al. 2006; Lehman 1994; Pan et al. 2006), in addition to the indirect effects of infrastructure damage. Although it is difficult to directly tie a single tropical storm event to a new invasion, there is compelling evidence for several recent outbreaks. For example, the spread of citrus canker in Florida was exacerbated by hurricanes early in the epidemic, with many new outbreaks occurring in the path of the storm (Gottwald et al. 2007; Irey et al. 2006). *Fusarium oxysporum* f. sp. *cubense* Tropical Race 4, a new race of the causal agent of Fusarium wilt of banana, may have been spread in Mozambique by a cyclone, increasing the risk of further spread to adjacent farmlands and neighboring countries in Africa (Dita et al. 2018; Pegg et al. 2019). The soybean rust pathogen *Phakopsora pachyrhizi* was first detected in the United States in Louisiana shortly after Hurricane Ivan in 2004 (Pan et al. 2006). Hurricane Ivan moved north from the lower Caribbean near Colombia and potentially moved spores into the United States. Subsequent tropical storms in 2005 likely exacerbated the epidemic, spreading the pathogen further into the continental United States and making eradication functionally impossible (Kelly et al. 2015). *Puccinia melanocephala*, causing sugarcane rust, is thought to have spread from West Africa to the Caribbean and North America during hurricane force winds in 1978, which carried Saharan dust clouds from Cameroon (Purdy et al. 1985). Beyond spreading invasive pathogens, heavy rainfall and high winds associated with these tropical storm events can destroy crops through lodging and damage tree structures in perennial crops (Gu Her et al. 2020). This damage can make crops more vulnerable to disease and pest infestations by wounding and tearing plants before harvest, causing both immediate and long-term yield loss (Albrigo et al. 2005).

Insect pests can also travel long distances during strong wind events, although hurricane force winds may kill insects before they can establish in new areas. The invasive cactus moth (*Cactoblastis cactorum*) has spread throughout the Caribbean and into Texas, Florida, and Louisiana (Andraca-Gómez et al. 2020). Genetic analyses of populations of *C. cactorum* suggest that the insects have been spread by both long-distance colonization events from hurricanes as well as hitchhiking with commercial marine shipping in the region. Bean golden yellow mosaic virus was likely introduced to Florida by Hurricane Andrew in 1992, which carried viruliferous whiteflies from the Caribbean islands (Thompson 2011). Bean golden yellow mosaic virus caused the reduction or collapse of bean production the following year and became established in Florida (Thompson 2011). Novais et al. (2018) reported that herbivorous insect populations flourished in the months after Hurricane Patricia struck portions of Jalisco state in Mexico in 2015. They hypothesized that new leaves and shoots from recovering trees served as an abundant food source for herbivorous insects and that dead trees and shrubs allowed xylophagous beetle populations to rapidly expand.

Flooding can also rapidly spread many pathogens among adjacent farms and regions. Pathogens with flagella or swimming stages, such as the oomycete pathogens *Pythium*, *Phytophthora*, and *Achlya*, are able to disperse rapidly through flooded regions to new susceptible plants (Browne et al. 2021; de Silva et al. 1999; Nechwatal et al. 2008; Wilcox and Mircetich 1985). Bacterial pathogens with flagella can also spread rapidly in flooded fields and through waterways, leading to severe outbreaks of diseases such as those caused by *Ralstonia solanacearum*. Pathogen propagules with a high lipid content can remain buoyant during floods, allowing the pathogen to float to new hosts, farms, or regions. For example, buoyant microsclerotia produced by *Rhizoctonia solani* can spread rapidly within a rice paddy, potentially causing stem blight on rice (Feng et al. 2017). Similarly, the microsclerotia of *Verticillium dahliae* can spread into new fields through flood irrigation events (Tjamos 1993), and flooding can spread the chlamydospores of *F. oxysporum* f. sp. *cubense* into new regions, a particularly important current threat because of Tropical Race 4 (Dita et al. 2018; Pegg et al. 2019). Soil saturation from flooded conditions can also lead to disease by causing oxygen stress in affected plants and is a serious complication for many plant diseases (Lipps and Bruehl 1978).

The effects of droughts and wildfires

Severe droughts can increase the risk of plant disease by disrupting the usual plant host responses to infection, generating favorable environmental conditions for the survival of some pathogens (Naylor and Coleman-Derr 2018; Swett 2020; Wakelin et al. 2018). For example, prolonged drought increases susceptibility in forest trees to pathogenic *Phytophthora* spp., causing dieback disease and facilitating the establishment of new infections (Desprez-Loustau et al. 2006). Prolonged drought can also upset underground or aboveground ecological interactions that keep pests below economic injury levels, creating favorable conditions for increased pest dispersal in the subsequent growing seasons. For example, droughts have been associated with weakened underground predation, leading to the proliferation of plant-pathogenic nematodes and causing increased plant damage (Franco et al. 2019). Drought stress can have an impact on microbial communities associated with plants, leading to higher levels of mycotoxin production in some cases (Ferrigo et al. 2014). Prolonged drought increases the risk of wildfires across forests and croplands, which may have multifaceted effects on agricultural production and plant health.

Wildfires can damage crops directly by burning plants in the dry harvest season, such as for wheat, maize, or hay, and they can diminish plant nutrient and carbon availability, stressing plant systems (Cobb et al. 2016; Yue and Unger 2018). Fire can damage forest ecosystems, leaving gaps that become habitats open to colonization by invasive pests and pathogens. Fire-damaged trees are often more susceptible to pathogens, depending on the temperature of the burn. If damaged trees are left too long, they can pose a fire risk in later seasons. Wildfires can also affect the quality of nearby crops, such as wine grapes, affecting their flavor (Krstic et al. 2015). Wildfire events have the potential to facilitate the spread of some pathogens through smoke-borne spores (Kobziar et al. 2018). For example, *Rhizina undulata*, a pyrophilic pathogen, requires heat shocks (such as forest fires) for ascospore germination (Jalaluddin 1967). Wildfires may also drive the diversification of soilborne fungi and other microbes (Fox et al. 2022). Post-wildfire restoration planting can introduce pests and pathogens. For example, wildfires in California devastated the coastal mountain range, and plants sourced from native plant nurseries to restore these areas were unknowingly contaminated with *Phytophthora tentaculata*, a quarantined pathogen (Rooney-Latham et al. 2019). This has led to more complications, as forest managers now need to control both introduced diseases and future wildfires.

Climate change and compounding natural disasters

Climate change is a key consideration in disaster plant pathology, likely increasing the frequency of extreme weather events (Stott 2016) and shifting the locations where they occur, the speed at which they occur, their cost, the length of events, and their severity (Coronese et al. 2019; Mendelsohn et al. 2012). Climate change can influence plant-pathogen interactions by modifying the physiological, biochemical, ecological, and evolutionary processes of disease development in the plant host (Cheng et al. 2019; Singh et al. 2023; Trivedi et al. 2022; Velásquez et al. 2018).

Under climate change, habitats with conducive temperatures for plant pathogens can shift to higher altitudes, and latitudes that were previously unsuitable for pathogens may become more conducive to their survival and proliferation (Dudney et al. 2021). This leads to an expansion of pathogen ranges and increased disease pressure at higher elevations (Bebber et al. 2013). Rising temperatures and shifts in precipitation patterns have created more favorable conditions for the population growth and survival of snow fungi (*Gremmeniella abietina* and *Phacidium infestans*), leading to widespread pine mortality at high elevations in the Central Alps (Barbeito et al. 2013). Climate change can also modify food safety risks driven by pathogens; for example, Aflatoxin B_1 was predicted to be a greater problem in European maize under the most probable scenario for climate change (+2°C) (Battilani et al. 2016).

The El Niño-Southern Oscillation (ENSO) significantly influences agricultural outcomes (Gelcer et al. 2018; Scherm and Yang 1995; Zhao et al. 2021). ENSO is a recurring climate pattern characterized by abnormal sea surface temperatures in the equatorial Pacific Ocean, with warmer temperatures in El Niño years and colder in La Niña years. ENSO effects are linked to flood risk, tornado frequency, and wildfire, with knock-on effects in agriculture. ENSO's impact on plant diseases has been extensively documented, as temperature and rainfall shifts associated with this phenomenon create favorable conditions for the development and spread of many pathogens (Ramírez-Gil et al. 2020; Scherm and Yang 1995). For instance, during El Niño events, Florida is expected to experience increased rainfall and below-average temperatures during winter and spring, with the more humid environment conducive to outbreaks of fungal diseases such as grey mold (*Botrytis* spp.) and anthracnose fruit rots (Pavan et al. 2011). In 2018, El Niño led to a late rainy season in Guatemala that affected 70% of crops in the first harvest and a flood affecting 50% of the second harvest (FAO 2021). In 2023, ENSO was associated with a maximum July ocean temperature of 1.1°C above the twentieth-century average, the hottest ocean temperature on record (NOAA 2023), resulting in a tropical storm reaching Southern California. Intense El Niño events were predicted to double in the twenty-first century due to climate change (Cai et al. 2014; Howden et al. 2007).

Multiple extreme weather events often have compounding effects and can overwhelm mitigation resources at the local, regional, and national levels. As extreme weather events become more frequent, many people experience disaster fatigue (also known as compassion fade), the tendency for decreased compassion and charitable acts as the number of people in need increases (Västfjäll et al. 2014). This reduction in an individual's or a group's willingness to help in the aftermath of subsequent storms can significantly affect the ability of an impacted area to fully recover. This was seen in the aftermath of Hurricane Harvey in Texas, Hurricane Irma in Florida, and Hurricane Maria in Puerto Rico. Despite Hurricane Maria causing more destruction than the former two hurricanes, Puerto Rico received less federal recovery aid and lower public donations (Willison et al. 2019). Hurricane Maria was noted as the worst natural disaster on record in Puerto Rico, and the ability to fully recover given limited federal aid was further hindered by subsequent earthquakes in January 2020 and the COVID-19 global pandemic. These compounding disasters resulted in a major shift in Puerto Rico's wildlife biodiversity, land quality, and water quality (Keenum et al. 2021; Zimmerman et al. 2020). Similarly, shortly following the 2019–2020 bushfires that devastated agriculture-based communities, Australia redirected crisis recovery funding to public health practices in the wake of the COVID-19 pandemic (Usher et al. 2021). This pivot in funding severely impacted agricultural communities, which, at the time, had only partially recovered from the natural disaster. Disaster fatigue is relevant to all extreme events, not just natural disasters, and donations are likely to dwindle during compounding humanitarian crises as well.

Humanitarian Crises

The impacts of conflict and political unrest on plant health

The effects of socioeconomic disasters such as armed conflicts, political unrest, and poverty on plant disease and food security are also important facets of disaster plant pathology. Poverty is central to this discussion due to its impacts on population displacement and quality of life. Many crop pest and disease outbreaks occur in low-income countries due to inadequate crop disease management capacity (Klauser 2018; Ristaino et al. 2021; Savary et al. 2019). In 2021, 59% of people in low-income countries worked in agriculture, compared with 38% in lower-middle-income countries (World Bank 2021a, b), and agricultural workers in low-income countries must deal with the emergence of crop pests and diseases, lack of adequate infrastructure for disease management, and weak relationships among agricultural stakeholders (Etherton et al. 2024; Klauser 2018). Plant disease epidemics, food insecurity, and famines further exacerbate poverty. For example, *Phytophthora infestans*, the causal agent of potato blight, spread through trade to Europe and was the proximate cause of the Irish Potato Famine in the nineteenth century, which led to mass emigration (Andrivon 1996; Fry et al. 1992; Gómez-Alpizar et al. 2007; Ristaino 2002). The severe famine in Ireland was due in part to the near-total dependence on potato among people living in poverty (Large 1940; Vurro et al. 2010). Other examples of plant pathogens exacerbating poverty include brown spot of rice caused by *Cochliobolus miyabeanus* in East Bengal (Padmanabhan 1973), and coffee rust, caused by *Hemileia vastatrix*, in Sri Lanka (Mills 2012).

In the twenty-first century, poverty, political unrest, and inefficient regulation have significantly influenced the development of major plant disease epidemics. For instance, the likelihood of occurrence of cocoa swollen shoot disease, devastating cacao trees in West Africa, correlates with lower household incomes, reduced access to education and healthcare, and reliance on family labor (Adopo et al. 2022). These socioeconomic factors exacerbate poverty cycles, further fueling the disease's spread by limiting farmers' ability to implement effective disease management practices (Adopo et al. 2022). In Venezuela, economic decline and weakened government institutions have led to a notable decline in phytosanitary services (Marys and Rosales 2021), which has likely impaired the effective detection of *F. oxysporum* f. sp. *cubense* Tropical Race 4. *F. oxysporum* f. sp. *cubense* Tropical Race 4 is of particular concern given that it may have been present in Venezuela years before its official detection in 2022 (Sequera 2023). Efforts to control major plant disease epidemics have the potential to be costly to farmers' livelihoods and obstruct humanitarian supply chains. For instance, policies in Malawi have been criticized for restrictions and measures against banana bunchy top disease (which have been reported to be unsuccessful in stopping disease spread yet have negatively impacted livelihoods) (Mikwamba et al. 2020) while simultaneously creating phytosanitary laws preventing maize imports from Tanzania that have been crucial after the food shortages caused by Cyclone Freddy (Masina 2023, 2024). Although the import bans were intended to reduce the risk of introducing maize lethal necrosis disease, they were withdrawn in 2024 after further review (Kwanza 2024). These dynamics illustrate the difficulties of complex crises (Table 1) in which governments and communities must simultaneously address plant epidemics, poverty, political instability, and phytosanitary measures. The interplay of these factors is a critical topic in disaster plant pathology, from both the scientific and regulatory perspectives.

Armed conflict can also create conditions that are favorable to the dissemination and proliferation of plant pathogens, leading to devastating consequences for crop production, food security, and overall stability in affected regions. Conflict may lead to the breakdown of agricultural infrastructure and systems; disrupted supply chains limit farmers' access to critical inputs such as fertilizers, pesticides, and high-quality seed. In a historical example, during World War I, Germany experienced a labor shortage for agriculture and limited draft power, as horses and oxen were requested by the army, and access to copper to make Bordeaux mixture for management of potato late blight was limited because copper was used in bullet shells and electric wire (Zadoks 2008).

Unrest may force farmers to rely on poor-quality seed, leading to low yields. Planting material saved on-farm often leads to accumulation and spread of plant pathogens within farming communities. For instance, the civil war in Burundi disrupted access to agricultural inputs and services, which led to the rapid spread of *Xanthomonas campestris* pv. *musacearum*, causing banana bacterial wilt (Muskekuru 2016; Verwimp and Muñoz-Mora 2018). This conflict also led to a breakdown in disease management efforts, where *X. campestris* spread to new areas through the movement of planting material with fleeing victims (Blomme et al. 2017). The outbreak of banana bunchy top disease in Rwanda and Burundi could be associated with the introduction of cultivars resistant to Fusarium wilt (race 1) from the Democratic Republic of Congo, such as Yangambi KM5. Resistant varieties were introduced to replace the Kayinja cultivars susceptible to Fusarium wilt to help these countries rehabilitate decimated banana plantations (Nakato et al. 2023; Nduwimana et al. 2022). Banana bunchy top disease was already present in the Democratic Republic of Congo in the late 1950s (Kumar et al. 2011), and the subsequent spread of banana bunchy top disease in this region could be linked to this conflict.

Displacement of human populations during war often leads to unintentional movement of pathogen strains to new areas in planting material, further complicating disease management efforts. For example, wheat rust fungi in Syria were reported to be spread with plant material by displaced farmers (Stakman et al. 2015), and cassava mosaic disease spread in Liberia during the civil war from 1989 to 2003, severely impacting agricultural activities (Thresh 2003). In Central America, the Guatemalan civil war (1960 to 1996) had significant effects on agriculture and led to the spread of *H. vastatrix* (Bielecki and Wingenbach 2019). Abandoned and untended farmlands remain a key risk in the spread of banana diseases, such as banana bunchy top disease and Fusarium and bacterial wilts (FAO 2002). For instance, abandoned banana plantations may serve as hubs for the dispersal of *X. campestris* pv. *musacearum* by bees and nectar-feeding insects (Tinzaara et al. 2006).

Wars lead to the collapse of government institutions and the loss of centralized control, significantly hindering disease monitoring and management efforts through disease surveillance, research, and extension services. Farmers' access to information about disease prevention and control is limited due to disruption of extension services, enabling plant pathogens to spread and exacerbating the crisis. This is particularly problematic in low-income countries and for vegetatively propagated crops such as banana, cassava, potato, and sweet potato, where seed degeneration is a major problem for crop production (Thomas-Sharma et al. 2017). During wars, local farmer seed systems can collapse, and external aid is needed; however, external seed aid must be balanced to avoid undermining the formal or informal seed systems that persist. Emergency seed procurement systems need to pay special attention to seed health to prevent unintentional dissemination of planting material infected with seedborne pests and pathogens (Sperling et al. 2004). For example, the eastern Democratic Republic of Congo is home to multiple invasive species (such as banana bunchy top virus and cassava mosaic viruses), as conflict has made it difficult to coordinate programs for disease control, exposing neighboring countries to dispersal of pathogens through infected seed (Uganda in 2020).

The impacts of war on global food security

War, political instability, and poverty contribute to the breakdown of local agricultural infrastructure, which can scale to impact global food insecurity. The current war in Ukraine is an example of how all countries are vulnerable to armed conflict, which not only leads to crop loss and disease spread but also disrupts the global exchange of commodities. The invasion of Ukraine disrupted the global wheat supply and caused a 50% increase in global fertilizer prices due to Russia's significant role as a supplier, accounting for 13% of the world's fertilizer production (Kee et al. 2023). The Syrian civil war, as another example, threatened the seed bank collections at ICARDA (International Center for Agricultural Research in Dry Areas), forcing the ICARDA staff to quickly duplicate select collections before fleeing (Westengen et al. 2020). The ICARDA example emphasizes the importance of the Svalbard Global Seed Vault as a backup for genetic conservation (Asdal and Guarino 2018). The political instability in Venezuela has resulted in a significant decline in domestic agricultural production, in turn affecting the global oilseed market (Lavelle 2016). These regional crises have wide-reaching impacts, such as disrupted global agricultural production, price volatility, and increased global food insecurity. It is important to consider global impacts during local crises and to safeguard agricultural regions to prevent global catastrophes.

Smart Solutions

Using smart agriculture to support disaster recovery

Smart agriculture, or digital agriculture, uses available technology and system-specific data to optimize crop production (Gebbers and Adamchuk 2010; Klerkx et al. 2019; Zhang et al. 2002). Smart systems can provide early warning information systems, risk assessment, crop monitoring, supply chain optimization, decision support, real-time monitoring, and resilience strategies (Garrett et al. 2022; Jaber et al. 2022; Wolfert et al. 2017). Artificial intelligence (AI) performs tasks typically requiring human intelligence, particularly machine learning for improved algorithm performance in image analysis for disease detection and diagnostics, as well as management decision support models. There is the potential for farmers and phytosanitary authorities to use AI to make informed decisions and facilitate recovery efforts, thus minimizing the impact of disasters on agricultural systems (Chandra and Collis 2021; Mehrabi et al. 2021; Talaviya et al. 2020). Through the integration of satellite imagery, weather data, disease incidence reports, early warning systems, and other relevant information, AI models can identify patterns and predict the trajectory of pathogen movement. Farmers and agricultural authorities can use these models to take preventive measures in areas at high risk of infection, effectively managing the spread of disease and accelerating recovery (Talaviya et al. 2020).

AI tools have great potential for designing and building smart agricultural systems specifically tailored for disease management. AI tools are already being developed for early disease detection; disease diagnostics (Mohanty et al. 2016; Selvaraj et al. 2020); risk assessments (Chavez et al. 2015; Ghahari et al. 2019); optimizing the dosage, timing, and application of agricultural inputs (Abioye et al. 2022; Talaviya et al. 2020); and continuously monitoring plant health, environmental conditions, and disease prevalence (Bolten et al. 2010; Giraldo et al. 2019), with the potential to use remotely sensed data from unmanned aerial vehicles or satellites (Clohessy et al. 2021; Mohanty et al. 2016; Selvaraj et al. 2020; Zhang et al. 2019). As an example of rapid risk assessment (https://www.garrettlab.com/r2m/), Mouafo-Tchinda et al. (2024) developed risk maps in Cameroon and Ethiopia for key potato and sweet potato pests and diseases as input for focused agricultural investments and humanitarian aid during disasters (Etherton et al. 2024). Such risk maps can be integrated into AI-driven DSSs, which can analyze large amounts of data, including historical disease records, crop health data, and expert knowledge (Bregaglio et al. 2022; Jaber et al. 2022; Shtienberg 2013). Where these tools are available, they can be used, particularly during crises, to construct strategies for disaster relief and aid for agricultural systems, in combination with rapid assessment of crop pests and diseases, and capacity-building programs for stakeholders: for example, rapid multiplication technologies for seed production, diagnostics for seedborne diseases, seed regulation, and information about improved varieties (Andrade-Piedra et al. 2023). DSSs to anticipate slow-onset crises can support disease resistance breeding in preparation for future disease priorities.

AI for natural disasters

Acknowledging the challenges posed by climate variability and extreme weather events, governments are increasingly motivated to support research and improved climate and weather information and services to help growers enhance their disaster preparedness and resilience (Vedeld et al. 2020). However, accurate weather and climate predictions are only valuable if accompanied by well-defined actions that can be taken to mitigate potential losses (Jones et al. 2000). DSSs can serve as valuable tools to assist stakeholders in making informed decisions regarding agricultural practices, resource allocation, and risk management (McBratney et al. 2005; Zhai et al. 2020). These systems can use machine learning to analyze forecast data with historical weather patterns, satellite imagery, and crop models, providing farmers, policymakers, and researchers with actionable insights (Breuer et al. 2008; Garrett et al. 2022).

Numerous DSSs have been implemented worldwide to address challenges in the agricultural sector, with some developed to monitor and alert stakeholders about risks of disease occurrence. Applications include monitoring for apple scab (Fernandes et al. 2011), apple fire blight and downy mildew in grapevines (Firanj Sremac et al. 2018), Fusarium head blight in wheat (Landschoot et al. 2013), and potato late blight (Small et al. 2015; Wharton et al. 2008). AgroClimate is another example of a DSS designed to tackle weather- and climate-based risks in agriculture (Fraisse et al. 2016). AgroClimate provides several tools to assist growers with plant disease management. The strawberry (Pavan et al. 2011), blueberry (Gama et al. 2021), and citrus advisory systems (Perondi et al. 2020) couple current and forecast weather data with disease models to predict risks and recommend fungicide applications when conditions are favorable for disease development. The Citrus Copper Application Scheduler employs models to predict fruit growth at early developmental stages and the rate of copper residue decay, determining when the copper residue on fruit is no longer sufficient for disease management (Zortea et al. 2013). These tools have proven valuable to farmers in Florida, a region frequently affected by weather variability driven by ENSO and extreme weather events such as hurricanes (Gama et al. 2022; Perondi et al. 2020).

Predicting the occurrence of natural disasters, themselves, becomes more practical with advances in AI and machine learning. Long- and short-term forecasting of earthquakes is now available, using machine learning to predict the magnitude of these disasters (Bhatia et al. 2023). As another example, Avand et al. (2021) investigated the factors that impact flood damage and forecasted future flooding in the Tajan watershed in Iran. Historical trends can also be used for training models for disaster prediction; for example, the historical global distribution of wildfires, floods, and earthquakes shows the current vulnerabilities of regions to reoccurring disasters (Fig. 3) (Brakenridge 2024; NASA Earthdata 2023; Zomer et al. 2022). By continuously integrating new technologies and high-quality weather and climate data, DSS capabilities can be expanded to help stakeholders address the challenges posed by climate variability and extreme weather events in agriculture and many other sectors.

AI for humanitarian crises

Addressing the challenges posed by armed conflicts and political instability requires not only immediate responses to manage disease outbreaks but also long-term efforts to rebuild and strengthen agricultural systems and institutions in post-conflict scenarios, enhancing resilience to future plant pathogen challenges. It is essential to incorporate plant health considerations into relief operations, in balance with other humanitarian needs. This will often include implementing protocols to assess the phytosanitary status of seed

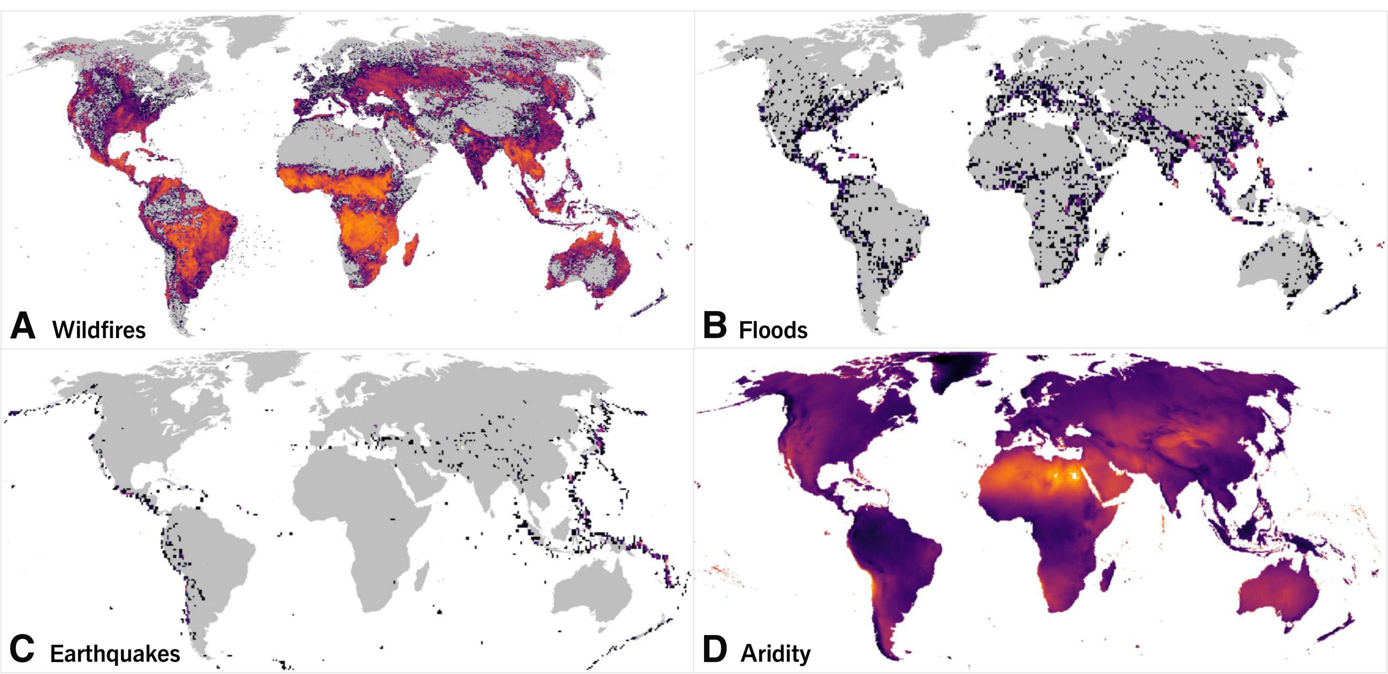


FIGURE 3
Global vulnerability of plant landscapes to extreme events based on historical event records for **A,** wildfires from 2000 to 2020 (Brakenridge 2024; NASA Earthdata 2023); **B,** floods from 1985 to 2021 (Brakenridge 2024); **C,** earthquakes of magnitude 7 or greater from 1900 to 2022 (USGS 2023); and **D,** aridity index (Zomer et al. 2022). Maps indicate higher frequencies of extreme event reports with lighter shading, while grey backgrounds indicate absence of reports.

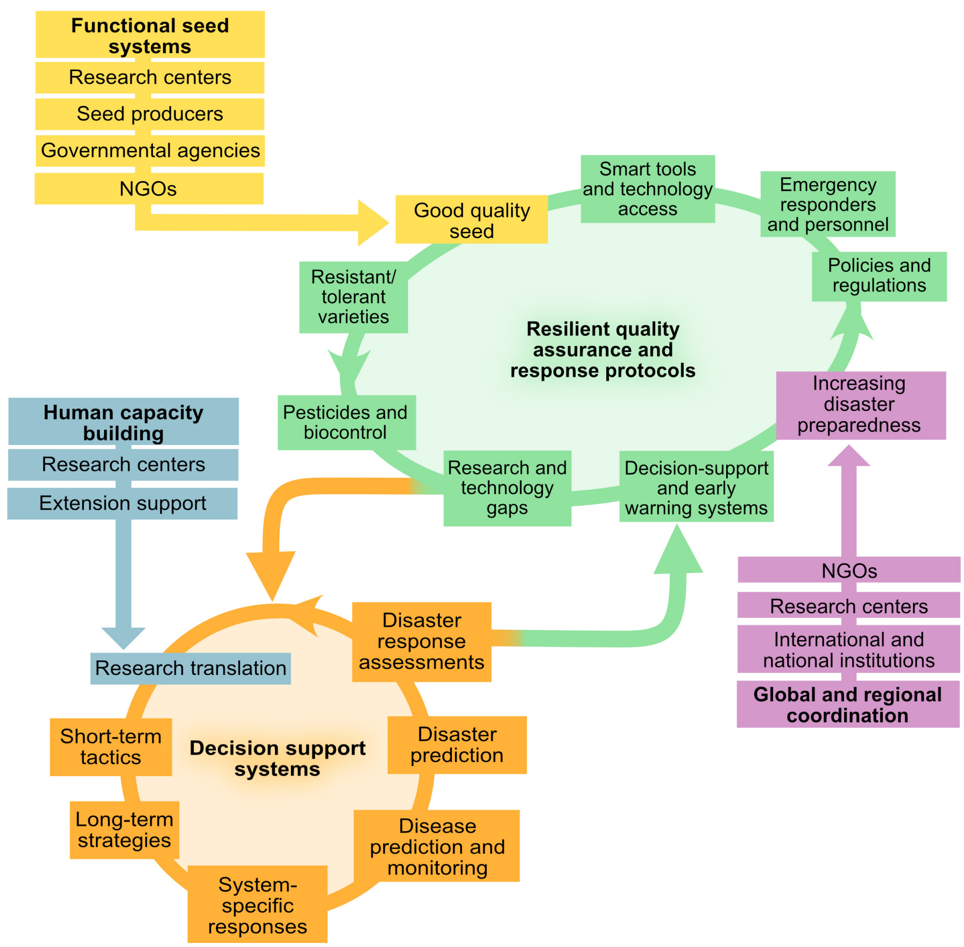
(and potential quarantine measures), providing agricultural extension services to promote disease awareness and control measures, and ensuring proper disease surveillance and monitoring. By safeguarding plant health, disaster relief efforts can be more effective and sustainable in the long term.

Early warning systems have been developed to help humanitarian groups proactively prepare for disasters and can play a crucial role in proactive preparedness. For instance, the African Standby Force, a "Continental Early Warning System," was designed to rapidly aid in political decision-making to prevent or mediate disputes (Cilliers 2008; IPI 2010). The Integrated Early Warning System collects data regarding significant political events in a signal database and can perform conflict modeling to forecast armed conflicts or political unrest (Lockheed Martin 2014). Similarly, the Political Instability Task Force, a domestic United States government database, can assess the value of potential predictor variables for estimating the likelihood that conflicts arise (Goldstone et al. 2010). Although these systems were not initially designed for agricultural stakeholders, integrating systems such as these could significantly enhance preparedness and rapid response efforts for growers. FEWS NET, or the Famine Early Warning Systems Network, analyzes crop production, market prices, weather data, and other factors to predict the likelihood of food insecurity (USAID 2023). FEWS NET can also predict natural disasters such as droughts and floods, which may lead to food shortages.

Disasters may disrupt or weaken seed systems across geographical scales, and humanitarian seed aid often combines immediate relief to vulnerable households affected by crises with activities that protect or rebuild crop-related livelihoods (SEADS 2022). It is important for humanitarian aid to provide clean or disease-free seeds to seed producers following disasters, when agricultural infrastructure may be damaged. This type of aid can mitigate the long-distance spread of seedborne diseases, provide food security for these growers, and help with crop and community resilience. National Plant Protection Organizations are often left to deal with unmanaged pest risk during an emergency due to phytosanitary breakdown, and seed aid may directly introduce plant pests and pathogens (Secretariat of the International Plant Protection Convention 2021) or indirectly alter plant health by, for example, introducing long-maturing varieties to beneficiaries when fast-maturing varieties are better suited and farmer preferred, introducing serious weeds, and distributing material that is not adapted to the crisis area or otherwise unacceptable to farmers (Sperling and McGuire 2010). There have been significant developments in low-cost and practical field-based quality assurance protocols (Sulle et al. 2022), an increasing recognition that the overwhelming majority of seed planted by smallholder farmers is sourced from local markets and farmers' own fields (Sperling and McGuire 2010) and thus largely beyond the scope of seed regulatory efforts. To that end, the Commission on Phytosanitary Measures has adopted International Standards for Phytosanitary Measures and introduced guidance on risk management associated with commonly provided seed, food, and other humanitarian aid (Secretariat of the International Plant Protection Convention 2021).

Informal seed systems of roots, tubers, and bananas (RTB), based on vegetative planting material, are an increasingly important focus in disaster response and recovery. Quality assurances in such systems are challenging even when there are in situ diagnostics and strong regulations. The bulkiness and perishability of RTB planting material often compels farmers to save their own RTB planting material year after year, although seed quality assurance innovations in RTB seed systems are noteworthy (Sulle et al. 2022). Quality assurances in informal commercial seed systems are often based on

FIGURE 4
Key recommendations in disaster plant pathology for designing pathogen and pest management systems before crises and iteratively improving them during and after crises. (i) Regional and global coordination and (ii) human capacity building are key for successful implementation. (iii) Effective clean seed systems and (iv) resilient biosecurity infrastructure and risk assessment help systems prepare for and recover from disasters. (v) Decision support systems should leverage data from disaster response systems, with periodic reassessments following current or ongoing crises to ensure effectiveness.



reputation and trust within longstanding social networks (Sperling and Almekinders 2023). Quality assurance schemes for seed outgrowers and early-generation seed are only partial considerations, however, as repeated use of seed saved on-farm in subsequent seasons must be complemented by broader public awareness campaigns aimed at helping farmers to identify and take action against pests and pathogens.

Current status and next steps

DSSs and some types of AI tools for improving disaster relief and management allocation are not new ideas. These types of frameworks have been around since the late 1900s (Keen 1980; Sprague 1980), although they do not seem to be widely used, particularly during rapid-onset disasters. There are several reasons for this, including limited accessibility to technological infrastructure, data constraints and quality, maintenance, and a general resistance against these systems. Collective action of informed decision makers, along with effective policies supporting disease management, is often necessary for successful regional implementation (Etherton et al. 2023; Garcia Figuera et al. 2022). A key part of disaster plant pathology is advocacy for these systems to be established, in conjunction with data collection from a range of key sources, facilitating decision-making.

One of the most significant obstacles to global implementation of these tools is their restricted availability. A lack of internet accessibility, data storage, and power supply may stop the use of DSSs that rely on Bluetooth or internet connectivity to process data or stop the use of early warning systems that are hosted online. As of 2022, only 68% of the world's population had internet access, with regional internet access rates reported as 55% in Asia, 65% in Central America, and 41% in Africa (Argaez 2022). Internet accessibility is often significantly lower in farming communities (Mehrabi et al. 2021). Internet access and decision support for disaster relief represent a complicated effort. The infrastructure required includes physical hardware (such as fiber optic cables and cellular towers), internet service providers, satellite communication, routers, data centers, and, most importantly, the end user's adoption of both the internet and a smartphone device. Many of these tools rely on the availability and adoption of goods. Access to the internet has several practical benefits. For example, rural farmers in India have used improved internet access for marketplace research, resulting in visible increases in profit margins, through internet campaigns such as Digital India (Jamaluddin 2013; Kaka et al. 2019). Internet access can aid in disaster preparedness through access to early warning systems and precise weather updates (Ray et al. 2017), as well as in disaster relief through funding programs facilitated through social media (Ogie et al. 2022). It is imperative that both local governments and humanitarian groups rally for comprehensive internet access programs for all communities, ensuring crises preparedness and relief.

We highlight five key recommendations for designing plant health management solutions in a conceptual framework for disaster plant pathology (Fig. 4). (i) Regional and global cooperation across international and national institutions is important for system success. For example, the proposed global surveillance system for crop disease (Carvajal-Yepes et al. 2019) would help National Plant Protection Organizations prepare for potential pathogen invasions and evaluate the risk of importing seed from specific countries. Cooperation that is established and reinforced before disasters increases preparedness so response times can be shortened. (ii) Human capacity building is key across use and development of DSSs, disease diagnostics, field sampling, and implementation of management on individual farms and across regions. Typical capacity building for plant pathology supports the development of integrated pest management, such as resistant varieties, pesticides, biocontrol, and DSSs. In the context of disasters, the same resources are needed, along with the agility to implement management in response to rapid-onset crises and to account for the many factors influencing the options for management in complex crises. (iii) Effective clean seed systems can replace seed stores lost in disasters without adding the risk of introducing pathogens. When pathogens or pests are already endemic, seed with pathogen levels below appropriate phytosanitary thresholds (Choudhury et al. 2017) can help avoid regional disease buildup while maintaining more affordable seed prices. (iv) It is important to implement a resilient biosecurity infrastructure and disease risk assessments before disasters so that labs are prepared for rapid diagnostic procedures when quickly moving food and seed in response to disasters. Ongoing assessment of gaps in rapid pest diagnostics, management, technologies, and management access is needed to improve response systems. (v) DSSs should be integrated across available data and models to support implementation of long-term strategies such as the development of resistant varieties and short-term tactics such as decisions about on-farm pesticide use. In the context of disasters, DSSs must be ready to adapt rapidly to unexpected scenarios so that they can support regional prioritization of limited resources for disease management in response to crises and should be reassessed regularly to ensure effectiveness. Effective altruism discussions make the case for including consideration of low-probability existential threats, which in disaster plant pathology include compounded disasters in the context of complex crises (Garrett et al. 2020). Ongoing assessment and improvement of DSSs should target both better disease prediction and better recommendations for implementing disaster responses, through lessons learned in a community of practice.

Conclusions

The interactions between natural and human-driven disasters, plant disease, and global food security are critical concerns that demand expertise and knowledge from scientists working in disaster plant pathology. This paper provides a framework for addressing how the multifaceted relationships among these elements threaten plant health, local and global economies, and food security. Disasters often occur simultaneously, such as when natural disasters strike during an ongoing political crisis. Disasters may have a direct impact on regional plant health, such as through the spread of pathogens and plant wounding, causing immediate declines in crop health, and indirect effects through delayed stressors, such as loss of infrastructure, further complicating the timeline for appropriate disaster response. Interdisciplinary attention is needed to understand these complex interactions in disaster plant pathology.

To address these challenges, we need to actively integrate AI and DSSs to continually improve disaster management, which is a promising area of research in disaster plant pathology with direct tangible outcomes. Through predictive analyses, early warning systems, and real-time crop monitoring, humanitarian aid and governmental interventions can help to ensure the quality and safety of agricultural production for growers. These intricate relationships require global cooperation, and in the face of climate change and geopolitical complexities, a collective and proactive response is needed to protect plant health.

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Literature Cited

Abioye, E. A., Hensel, O., Esau, T. J., Elijah, O., Abidin, M. S. Z., Ayobami, A. S., Yerima, O., and Nasirahmadi, A. 2022. Precision irrigation management using machine learning and digital farming solutions. AgriEngineering 4: 70-103.

Adopo, W. A., Adolphe, M. G., Tiehi, N., Koffi, C., Kouakou, K., and Ballo, Z. 2022. Impact of swollen shoot disease on the livelihoods of smallholder cocoa farmers in Côte d'Ivoire. ESI Preprints 11:258.

Albrigo, L. G., Buker, R. S., Burns, J. K., Castle, W. S., Futch, S., McCoy, C. W., Muraro, R. P., Rogers, M. E., Syvertsen, J. P., and Timmer, L. W. 2005. The impact of four hurricanes in 2004 on the Florida citrus industry: Experiences and lessons learned. Proc. Fla. State Hortic. Soc. 118:66-74.

Andraca-Gómez, G., Lombaert, E., Ordano, M., Pérez-Ishiwara, R., Boege, K., Domínguez, C. A., and Fornoni, J. 2020. Local dispersal pathways during the invasion of the cactus moth, *Cactoblastis cactorum*, within North America and the Caribbean. Sci. Rep. 10:11012.

Andrade-Piedra, J., Dontsop, P., Dunia, D., Kulakow, P., Harahagazwe, D., Mouafo-Tchinda, R., Omondi, A., Ogero, K., Rajendran, S., and McEwan, M. 2023. Tools4SeedSystems: Working towards resilience through root, tuber and banana crops in humanitarian settings. Capacity needs assessment for root, tuber and banana seed interventions in humanitarian settings: Cameroon and DRC. Technical Report, International Potato Center.

Andrivon, D. 1996. The origin of *Phytophthora infestans* populations present in Europe in the 1840s: A critical review of historical and scientific evidence. Plant Pathol. 45:1027-1035.

Argaez, E. 2022. Internet World Stats: Usage and Population Statistics. Miniwatts Marketing Group. https://www.internetworldstats.com

Asdal, Å., and Guarino, L. 2018. The Svalbard global seed vault: 10 years—1 million samples. Biopreserv. Biobank. 16:391-392.

Avand, M., Moradi, H., and Ramazanzadeh lasboyee, M. 2021. Using machine learning models, remote sensing, and GIS to investigate the effects of changing climates and land uses on flood probability. J. Hydrol. 595:125663.

Banholzer, S., Kossin, J., and Donner, S. 2014. The impact of climate change on natural disasters. Pages 21-49 in: Reducing Disaster: Early Warning Systems for Climate Change. A. Singh and Z. Zommers, eds. Springer Dordrecht, the Netherlands.

Barbeito, I., Brücker, R. L., Rixen, C., and Bebi, P. 2013. Snow fungi—induced mortality of *Pinus cembra* at the alpine treeline: Evidence from plantations. Arctic Antarctic Alpine Res. 45:455-470.

Battilani, P., Toscano, P., Van der Fels-Klerx, H. J., Moretti, A., Camardo Leggieri, M., Brera, C., Rortais, A., Goumperis, T., and Robinson, T. 2016. Aflatoxin B_1 contamination in maize in Europe increases due to climate change. Sci. Rep. 6:24328.

Bebber, D. P., Holmes, T., and Gurr, S. J. 2014. The global spread of crop pests and pathogens. Glob. Ecol. Biogeogr. 23:1398-1407.

Bebber, D. P., Ramotowski, M. A. T., and Gurr, S. J. 2013. Crop pests and pathogens move polewards in a warming world. Nat. Clim. Change 3:985-988.

Benevolenza, M. A., and DeRigne, L. 2019. The impact of climate change and natural disasters on vulnerable populations: A systematic review of literature. J. Hum. Behav. Soc. Environ. 29:266-281.

Bhatia, M., Ahanger, T. A., and Manocha, A. 2023. Artificial intelligence based real-time earthquake prediction. Eng. Appl. Artif. Intell. 120:105856.

Bielecki, C. D., and Wingenbach, G. 2019. Using a livelihoods framework to analyze farmer identity and decision making during the Central American coffee leaf rust outbreak: Implications for addressing climate change and crop diversification. Agroecol. Sustain. Food Syst. 43:457-480.

Blomme, G., Dita, M., Jacobsen, K. S., Pérez Vicente, L., Molina, A., Ocimati, W., Poussier, S., and Prior, P. 2017. Bacterial diseases of bananas and enset: Current state of knowledge and integrated approaches toward sustainable management. Front. Plant Sci. 8:1290.

Bolten, J. D., Crow, W. T., Zhan, X., Jackson, T. J., and Reynolds, C. A. 2010. Evaluating the utility of remotely sensed soil moisture retrievals for operational agricultural drought monitoring. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 3:57-66.

Brakenridge, R. 2024. Global Active Archive of Large Flood Events. Dartmouth Flood Observatory, University of Colorado. http://floodobservatory.colorado.edu (accessed April 1, 2024).

Bregaglio, S., Savian, F., Raparelli, E., Morelli, D., Epifani, R., Pietrangeli, F., Nigro, C., Bugiani, R., Pini, S., Culatti, P., Tognetti, D., Spanna, F., Gerardi, M., Delillo, I., Bajocco, S., Fanchini, D., Fila, G., Ginaldi, F., and Manici, L. M. 2022. A public decision support system for the assessment of plant disease infection risk shared by Italian regions. J. Environ. Manage. 317:115365.

Breuer, N. E., Cabrera, V. E., Ingram, K. T., Broad, K., and Hildebrand, P. E. 2008. AgClimate: A case study in participatory decision support system development. Clim. Change 87:385-403.

Brown, J. K. M., and Hovmøller, M. S. 2002. Aerial dispersal of pathogens on the global and continental scales and its impact on plant disease. Science 297:537-541.

Browne, G. T., Hasey, J. K., Ott, N. J., Forbes, H., Arnold, K., and Milliron, L. 2021. Flooding by California rivers results in walnut scion infections by species of *Phytophthora*. Plant Health Prog. 22:368-373.

Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M. J., Wu, L., England, M. H., Wang, G., Eric, G., and Jin, F.-F. 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. Nat. Clim. Change 4:111-116.

Carter, M. R., Little, P. D., Mogues, T., and Negatu, W. 2007. Poverty traps and natural disasters in Ethiopia and Honduras. World Dev. 35:835-856.

Carvajal-Yepes, M., Cardwell, K., Nelson, A., Garrett, K. A., Giovani, B., Saunders, D. G. O., Kamoun, S., Legg, J. P., Verdier, V., Lessel, J., Neher, R. A., Day, R., Pardey, P., Gullino, M. L., Records, A. R., Bextine, B., Leach, J. E., Staiger, S., and Tohme, J. 2019. A global surveillance system for crop diseases. Science 364:1237-1239.

Chandra, R., and Collis, S. 2021. Digital agriculture for small-scale producers: Challenges and opportunities. Commun. ACM 64:75-84.

Chavez, E., Conway, G., Ghil, M., and Sadler, M. 2015. An end-to-end assessment of extreme weather impacts on food security. Nat. Clim. Change 5:997-1001.

Cheng, Y. T., Zhang, L., and He, S. Y. 2019. Plant-microbe interactions facing environmental challenge. Cell Host Microbe 26:183-192.

Choudhury, R. A., Garrett, K. A., Klosterman, S. J., Subbarao, K. V., and McRoberts, N. 2017. A framework for optimizing phytosanitary thresholds in seed systems. Phytopathology 107:1219-1228.

Cilliers, J. 2008. The African Standby Force: An update on progress. Institute for Security Studies (ISS), Paper 160.

Clavel, J., Julliard, R., and Devictor, V. 2011. Worldwide decline of specialist species: Toward a global functional homogenization? Front. Ecol. Environ. 9:222-228.

Clohessy, J. W., Sanjel, S., O'Brien, G. K., Barocco, R., Kumar, S., Adkins, S., Tillman, B., Wright, D. L., and Small, I. M. 2021. Development of a high-throughput plant disease symptom severity assessment tool using machine learning image analysis and integrated geolocation. Comput. Electron. Agric. 184:106089.

Cobb, R. C., Meentemeyer, R. K., and Rizzo, D. M. 2016. Wildfire and forest disease interaction lead to greater loss of soil nutrients and carbon. Oecologia 182:265-276.

Coronese, M., Lamperti, F., Keller, K., Chiaromonte, F., and Roventini, A. 2019. Evidence for sharp increase in the economic damages of extreme natural disasters. Proc. Natl. Acad. Sci. U.S.A. 116:21450-21455.

Dale, V. H., Joyce, L. A., McNulty, S., Neilson, R. P., Ayres, M. P., Flannigan, M. D., Hanson, P. J., Irland, L. C., Lugo, A. E., Peterson, C. J., Simberloff, D., Swanson, F. J., Stocks, B. J., and Wotton, B. M. 2001. Climate change and forest disturbances: Climate change can affect forests by altering the frequency, intensity, duration, and timing of fire, drought, introduced species, insect and pathogen outbreaks, hurricanes, windstorms, ice storms, or landslides. BioScience 51:723-734.

De Haen, H., and Hemrich, G. 2007. The economics of natural disasters: Implications and challenges for food security. Agric. Econ. 37:31-45.

de Silva, A., Patterson, K., Rothrock, C., and McNew, R. 1999. Phytophthora root rot of blueberry increases with frequency of flooding. HortScience 34: 693-695.

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. For. Sci. 63:597-612.

Dita, M., Barquero, M., Heck, D., Mizubuti, E. S. G., and Staver, C. P. 2018. Fusarium wilt of banana: Current knowledge on epidemiology and research needs toward sustainable disease management. Front. Plant Sci. 9:1468.

Dudney, J., Willing, C. E., Das, A. J., Latimer, A. M., Nesmith, J. C. B., and Battles, J. J. 2021. Nonlinear shifts in infectious rust disease due to climate change. Nat. Commun. 12:5102.

Elad, Y., and Pertot, I. 2014. Climate change impacts on plant pathogens and plant diseases. J. Crop Improv. 28:99-139.

Etherton, B. A., Plex Sulá, A. I., Mouafo-Tchinda, R. A., Kakuhenzire, R., Kassaye, H. A., Asfaw, F., Kosmakos, V. S., McCoy, R. W., Xing, Y., Yao, J., Sharma, K., and Garrett, K. A. 2024. Translating Ethiopian potato seed networks: Identifying strategic intervention points for managing bacterial wilt and other diseases. bioRxiv 579952.

Etherton, B. A., Choudhury, R. A., Alcalá-Briseño, R. I., Xing, Y., Sulá, A. I. P., Carrillo, D., Wasielewski, J., Stelinski, L. L., Grogan, K. A., Ballen, F., Blare, T., Crane, J., and Garrett, K. A. 2023. Are avocados toast? A framework to analyze decision-making for emerging epidemics, applied to laurel wilt. Agric. Syst. 206:103615.

FAO. 2002. Bananas. Food and Agriculture Organization of the United Nations.

FAO. 2021. Dry Corridor Central America. Food and Agricultural Organization of the United Nations.

Feng, S., Shu, C., Wang, C., Jiang, S., and Zhou, E. 2017. Survival of *Rhizoctonia solani* AG-1 IA, the causal agent of rice sheath blight, under different environmental conditions. J. Phytopathol. 165:44-52.

Fernandes, J. M. C., Pavan, W., and Sanhueza, R. M. 2011. SISALERT - A generic web-based plant disease forecasting system. Pages 225-233 in: Proceedings of the International Conference of Information and Communication Technologies for Sustainable Agri-production and Environment (HAICTA 2011), Skiathos, 8-11 September, 2011. M. Salampasis and A. Matopoulos, eds.

Ferrigo, D., Raiola, A., and Causin, R. 2014. Plant stress and mycotoxin accumulation in maize. Agrochimica 58:116-127.

Firanj Sremac, A., Lalić, B., Marčić, M., and Dekić, L. 2018. Toward a weather-based forecasting system for fire blight and downy mildew. Atmosphere 9:484.

Fothergill, A., and Peek, L. A. 2004. Poverty and disasters in the United States: A review of recent sociological findings. Nat. Hazards 32:89-110.

Fox, S., Sikes, B. A., Brown, S. P., Cripps, C. L., Glassman, S. I., Hughes, K., Semenova-Nelsen, T., and Jumpponen, A. 2022. Fire as a driver of fungal diversity—A synthesis of current knowledge. Mycologia 114:215-241.

Fraisse, C., Andreis, J. H., Borba, T., Cerbaro, V., Gelcer, E., Pavan, W., Pequeno, D., Perondi, D., Shen, X., Staub, C., Uryasev, O., and Wagner, A. P. 2016. AgroClimate-Tools for managing climate risk in agriculture. Agrometeoros 24:121-129.

Franco, A. L. C., Gherardi, L. A., de Tomasel, C. M., Andriuzzi, W. S., Ankrom, K. E., Shaw, E. A., Bach, E. M., Sala, O. E., and Wall, D. H. 2019. Drought suppresses soil predators and promotes root herbivores in mesic, but not in xeric grasslands. Proc. Natl. Acad. Sci. U.S.A. 116:12883-12888.

Fry, W. E., Goodwin, S. B., Matuszak, J. M., Spielman, L. J., Milgroom, M. G., and Drenth, A. 1992. Population genetics and intercontinental migrations of *Phytophthora infestans*. Annu. Rev. Phytopathol. 30:107-130.

Gama, A. B., Cordova, L. G., Rebello, C. S., and Peres, N. A. 2021. Validation of a decision support system for blueberry anthracnose and fungicide sensitivity of *Colletotrichum gloeosporioides* isolates. Plant Dis. 105:1806-1813.

Gama, A. B., Perondi, D., Dewdney, M. M., Fraisse, C. W., Small, I. M., and Peres, N. A. 2022. Evaluation of a multi-model approach to estimate leaf wetness duration: An essential input for disease alert systems. Theor. Appl. Climatol. 149:83-99.

Garcia Figuera, S., Babcock, B., Lubell, M., and McRoberts, N. 2022. Collective action in the area-wide management of an invasive plant disease. Ecol. Soc. 27:12.

Garrett, K. A., Bebber, D. P., Etherton, B. A., Gold, K. M., Sulá, A. I. P., and Selvaraj, M. G. 2022. Climate change effects on pathogen emergence: Artificial intelligence to translate big data for mitigation. Annu. Rev. Phytopathol. 60:357-378.

Garrett, K. A., Alcalá-Briseño, R. I., Andersen, K. F., Brawner, J., Choudhury, R. A., Delaquis, E., Fayette, J., Poudel, R., Purves, D., Rothschild, J., Small, I. M., Thomas-Sharma, S., and Xing, Y. 2020. Effective altruism as an ethical lens on research priorities. Phytopathology 110:708-722.

Gebbers, R., and Adamchuk, V. I. 2010. Precision agriculture and food security. Science 327:828-831.

Gelcer, E., Fraisse, C. W., Zotarelli, L., Stevens, F. R., Perondi, D., Barreto, D. D., Malia, H. A., Ecole, C. C., Montone, V., and Southworth, J. 2018. Influence of El Niño-Southern oscillation (ENSO) on agroclimatic zoning for tomato in Mozambique. Agric. For. Meteorol. 248:316-328.

Ghahari, A., Newlands, N. K., Lyubchich, V., and Gel, Y. R. 2019. Deep learning at the interface of agricultural insurance risk and spatio-temporal uncertainty in weather extremes. N. Am. Actuar. J. 23:535-550.

Giraldo, J. P., Wu, H., Newkirk, G. M., and Kruss, S. 2019. Nanobiotechnology approaches for engineering smart plant sensors. Nat. Nanotechnol. 14: 541-553.

Goldstone, J. A., Bates, R. H., Epstein, D. L., Gurr, T. R., Lustik, M. B., Marshall, M. G., Ulfelder, J., and Woodward, M. 2010. A global model for forecasting political instability. Am. J. Political Sci. 54:190-208.

Gómez-Alpizar, L., Carbone, I., and Ristaino, J. B. 2007. An Andean origin of *Phytophthora infestans* inferred from mitochondrial and nuclear gene genealogies. Proc. Natl. Acad. Sci. U.S.A. 104:3306-3311.

Goodwin, B. K., and Vado, L. A. 2007. Public responses to agricultural disasters: Rethinking the role of government. Can. J. Agric. Econ. 55:399-417.

Gottwald, T. R., da Graça, J. V., and Bassanezi, R. B. 2007. Citrus huanglongbing: The pathogen and its impact. Plant Health Prog. 8. https://doi.org/10.1094/PHP-2007-0906-01-RV

Gu Her, Y., Smyth, A., Fletcher, P., Bassil, E., Stingl, U., Brym, Z., and Qiu, J. 2020. Hurricane impacts on Florida's agriculture and natural resources. UF/IFAS, Gainesville, FL.

Haines, A., Kovats, R. S., Campbell-Lendrum, D., and Corvalan, C. 2006. Climate change and human health: Impacts, vulnerability, and mitigation. Lancet 367:2101-2109.

Harris, R. M. B., Beaumont, L. J., Vance, T. R., Tozer, C. R., Remenyi, T. A., Perkins-Kirkpatrick, S. E., Mitchell, P. J., Nicotra, A. B., McGregor, S., Andrew, N. R., Letnic, M., Kearney, M. R., Wernberg, T., Hutley, L. B., Chambers, L. E., Fletcher, M.-S., Keatley, M. R., Woodward, C. A., Williamson, G., Duke, N. C., and Bowman, D. M. J. S. 2018. Biological responses to the press and pulse of climate trends and extreme events. Nat. Clim. Change 8:579-587.

Horsfall, J. G., and Cowling, E. B. 1978. Pathometry: The Measurement of Plant Disease. Academic Press, New York.

Howden, S. M., Soussana, J.-F., Tubiello, F. N., Chhetri, N., Dunlop, M., and Meinke, H. 2007. Adapting agriculture to climate change. Proc. Natl. Acad. Sci. U.S.A. 104:19691-19696.

IPI. 2010. Operationalizing the African Standby Force. International Peace Institute.

Irey, M., Gottwald, T. R., Graham, J. H., Riley, T. D., and Carlton, G. 2006. Post-hurricane analysis of citrus canker spread and progress towards the development of a predictive model to estimate disease spread due to catastrophic weather events. Plant Health Prog. 7. https://apsjournals.apsnet.org/doi/10.1094/PHP-2006-0822-01-RS

Jaber, M. M., Ali, M. H., Abd, S. K., Jassim, M. M., Alkhayyat, A., Aziz, H. W., and Alkhuwaylidee, A. R. 2022. Predicting climate factors based on big data analytics based agricultural disaster management. Phys. Chem. Earth Parts A/B/C 128:103243.

Jalaluddin, M. 1967. Studies on *Rhizina undulata*: I. Mycelial growth and ascospore germination. Trans. Brit. Mycol. Soc. 50:449-459.

Jamaluddin, N. 2013. Adoption of E-commerce practices among the Indian farmers, a survey of Trichy District in the state of Tamil Nadu, India. Procedia Econ. Financ. 7:140-149.

Jones, J. W., Hansen, J. W., Royce, F. S., and Messina, C. D. 2000. Potential benefits of climate forecasting to agriculture. Agric. Ecosyst. Environ. 82:169-184.

Kaka, N., Madgavkar, A., Kshirsagar, A., Gupta, R., Manyika, J., Bahl, K., and Gupta, S. 2019. Digital India: Technology to transform a connected nation. McKinsey Global Institute.

Katz, J. M. 2010. With cheap food imports, Haiti can't feed itself. The Washington Post 20. https://www.citizenstrade.org/ctc/wp-content/uploads/2011/05/20100320_haitcannotfeeditself_ap.pdf

Kee, J., Cardell, L., and Zereyesus, Y. A. 2023. Global Fertilizer Market Challenged by Russia's Invasion of Ukraine. USDA, Economic Research Service. https://www.ers.usda.gov/amber-waves/2023/september/global-fertilizer-market-challenged-by-russia-s-invasion-of-ukraine/

Keen, P. G. W. 1980. Decision support systems: A research perspective. Pages 23-44 in: Decision Support Systems: Issues and Challenges. Proceedings of an International Task Force Meeting.

Keenum, I., Medina, M. C., Garner, E., Pieper, K. J., Blair, M. F., Milligan, E., Pruden, A., Ramirez-Toro, G., and Rhoads, W. J. 2021. Source-to-tap assessment of microbiological water quality in small rural drinking water systems in Puerto Rico six months after Hurricane Maria. Environ. Sci. Technol. 55:3775-3785.

Kelly, H. Y., Dufault, N. S., Walker, D. R., Isard, S. A., Schneider, R. W., Giesler, L. J., Wright, D. L., Marois, J. J., and Hartman, G. L. 2015. From select agent to an established pathogen: The response to *Phakopsora pachyrhizi* (soybean rust) in North America. Phytopathology 105:905-916.

Kidane, A., and Hailemariam, A. 1989. Mortality, fertility and population projection of famine affected regions of Ethiopia. Pages 177-193 in: Proceedings of the Workshop on Famine Experience and Resettlement in Ethiopia, Addis Abeba (Ethiopia), 29-30 Dec 1988. IDR.

Klauser, D. 2018. Challenges in monitoring and managing plant diseases in developing countries. J. Plant Dis. Prot. 125:235-237.

Klerkx, L., Jakku, E., and Labarthe, P. 2019. A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. NJAS Wageningen J. Life Sci. 90-91:100315.

Kobziar, L. N., Pingree, M. R. A., Larson, H., Dreaden, T. J., Green, S., and Smith, J. A. 2018. Pyroaerobiology: The aerosolization and transport of viable microbial life by wildland fire. Ecosphere 9:e02507.

Krstic, M. P., Johnson, D. L., and Herderich, M. J. 2015. Review of smoke taint in wine: Smoke-derived volatile phenols and their glycosidic metabolites in grapes and vines as biomarkers for smoke exposure and their role in the sensory perception of smoke taint. Aust. J. Grape Wine Res. 21: 537-553.

Kumar, P. L., Hanna, R., Alabi, O. J., Soko, M. M., Oben, T. T., Vangu, G. H. P., and Naidu, R. A. 2011. *Banana bunchy top virus* in sub-Saharan Africa: Investigations on virus distribution and diversity. Virus Res. 159:171-182.

Kunreuther, H., Gupta, S., Bosetti, V., Cooke, R., Dutt, V., Ha-Duong, M., Held, H., Llanes-Regueiro, J., Patt, A., Shittu, E., and Weber, E. 2014. Integrated risk and uncertainty assessment of climate change response policies. Pages 151-206 in: Climate Change 2014: Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, U.K.

Kwanza, K. 2024. Malawi Lifts Ban on Maize Importation from Tanzania Amidst Controlled Maize Lethal Necrosis Disease. Kilimo Kwanza, Nakuru, Kenya. https://kilimokwanza.org/malawi-lifts-ban-on-maize-importation-from-tanzania-amidst-controlled-maize-lethal-necrosis-disease/

Lacomme, C., Glais, L., Bellsted, D. U., Dupuis, B., Karasev, A. V., and Jacquot, E. 2017. Potato Virus Y: Biodiversity, Pathogenicity, Epidemiology and Management. Springer, New York, NY.

Landschoot, S., Waegeman, W., Audenaert, K., Van Damme, P., Vandepitte, J., De Baets, B., and Haesaert, G. 2013. A field-specific web tool for the prediction of Fusarium head blight and deoxynivalenol content in Belgium. Comput. Electron. Agric. 93:140-148.

Large, E. C. 1940. The Advance of the Fungi. American Phytopathological Society, St. Paul, MN.

Lavelle, D. B. 2016. Petro-Socialism and Agrarianism: Agrarian Reform, Food, and Oil in Chavista Venezuela. University of California, Berkeley, CA.

Lehman, P. S. 1994. Dissemination of phytoparasitic nematodes. Nematology Circular 208.

Lipps, P. E., and Bruehl, G. W. 1978. Snow rot of winter wheat in Washington. Phytopathology 68:1120-1127.

Lockheed Martin. 2014. World-Wide Integrated Crisis Early Warning System.

Marys, E., and Rosales, L. C. 2021. Plant disease diagnostic capabilities in Venezuela: Implications for food security. Front. Sustain. Food Syst. 5:715463.

Masina, L. 2023. Malawi Bans Maize Imports From Kenya, Tanzania Over Disease. VOAnews. https://www.voanews.com/a/malawi-bans-maize-imports-from-kenya-tanzania-over-disease/7407664.html

Masina, L. 2024. Malawi's Maize Import Ban Forces WFP to Mill Grain From Tanzania. VOAnews. https://www.voanews.com/a/malawi-s-maize-import-ban-forces-wfp-to-mill-grain-from-tanzania/7434617.html

Mayewski, P. A., Rohling, E. E., Stager, J. C., Karlén, W., Maasch, K. A., Meeker, L. D., Meyerson, E. A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R. R., and Steig, E. J. 2004. Holocene climate variability. Quat. Res. 62:243-255.

McBratney, A., Whelan, B., Ancev, T., and Bouma, J. 2005. Future directions of precision agriculture. Precis. Agric. 6:7-23.

McGeoch, M. A., Butchart, S. H. M., Spear, D., Marais, E., Kleynhans, E. J., Symes, A., Chanson, J., and Hoffmann, M. 2010. Global indicators of biological invasion: Species numbers, biodiversity impact and policy responses. Divers. Distrib. 16:95-108.

McKinney, M. L., and Lockwood, J. L. 1999. Biotic homogenization: A few winners replacing many losers in the next mass extinction. Trends Ecol. Evol. 14:450-453.

Mehrabi, Z., McDowell, M. J., Ricciardi, V., Levers, C., Martinez, J. D., Mehrabi, N., Wittman, H., Ramankutty, N., and Jarvis, A. 2021. The global divide in data-driven farming. Nat. Sustain. 4:154-160.

Meissner, H., Lemay, A., Bertone, C., Schwartzburg, K., Ferguson, L., and Newton, L. 2009. Evaluation of Pathways for Exotic Plant Pest Movement Into and Within the Greater Caribbean Region. U.S. Department of Agriculture. https://www.semanticscholar.org/paper/EVALUATION-OF-PATHWAYS-FOR-EXOTIC-PLANT-PEST-INTO-Meissner-Bertone/c8e3422d38d214a388eba0a7c049fbb00495b225

Mendelsohn, R., Emanuel, K., Chonabayashi, S., and Bakkensen, L. 2012. The impact of climate change on global tropical cyclone damage. Nat. Clim. Change 2:205-209.

Mikwamba, K., Dessein, J., and Kambewa, D. 2020. Fighting banana bunchy top disease in Southern Malawi: The interface of knowledge systems and dynamics in a development arena. J. Agric. Educ. Ext. 26:163-182.

Mills, L. A. 2012. Ceylon Under British Rule, 1795-1932. Routledge, New York.

Mitsova, D., Escaleras, M., Sapat, A., Esnard, A.-M., and Lamadrid, A. J. 2019. The effects of infrastructure service disruptions and socio-economic vulnerability on hurricane recovery. Sustainability 11:516.

Mohanty, S. P., Hughes, D. P., and Salathé, M. 2016. Using deep learning for image-based plant disease detection. Front. Plant Sci. 7:1419.

Mouafo-Tchinda, R. A., Etherton, B. A., Plex Sulá, A. I., Andrade-Piedra, J., Ogero, K., Omondi, B. A., McEwan, M. A., Tene Tayo, P. M. T., Harahagazwe, D., Cherinet, M., Gebeyehu, S., Sperling, L., and Garrett, K. A. 2024. Pathogen and pest risks to vegetatively propagated crops in humanitarian contexts: Geographic priorities for Cameroon and Ethiopia. bioRxiv 580019.

Muskekuru, E.-M. 2016. Burundi: Acute Food Insecurity Situation May-June 2016. Integrated Food Security Phase Classification.

Nakato, G. V., Okonya, J. S., Kantungeko, D., Ocimati, W., Mahuku, G., Legg, J. P., and Blomme, G. 2023. Influence of altitude as a proxy for temperature on key *Musa* pests and diseases in watershed areas of Burundi and Rwanda. Heliyon 9:e13854.

NASA Earthdata. 2023. Wildfires. NASA Earthdata. https://www.earthdata.nasa.gov/topics/human-dimensions/natural-hazards/wildfires (accessed April 1, 2024).

Naylor, D., and Coleman-Derr, D. 2018. Drought stress and root-associated bacterial communities. Front. Plant Sci. 8:2223.

Nduwimana, I., Sylla, S., Xing, Y., Simbare, A., Niyongere, C., Garrett, K. A., and Bonaventure Omondi, A. 2022. Banana seed exchange networks in Burundi–Linking formal and informal systems. Outlook Agric. 51:334-348.

Nechwatal, J., Wielgoss, A., and Mendgen, K. 2008. Flooding events and rising water temperatures increase the significance of the reed pathogen *Pythium phragmitis* das a contributing factor in the decline of *Phragmites australis*. Pages 109-115 in: Ecological Effects of Water-Level Fluctuations in Lakes. Developments in Hydrobiology, vol 204. K. M. Wantzen, K.-O. Rothhaupt, M. Mörtl, M. Cantonati, L. G. Tóth, and P. Fischer, eds. Springer, Dordrecht, the Netherlands.

NOAA. 2023. Monthly Global Climate Report for July 2023. National Centers for Environmental Information. https://www.ncei.noaa.gov/access/monitoring/monthly-report/global

Noji, E. K. 2000. The public health consequences of disasters. Prehospital Disaster Med. 15:21-31.

Novais, S., Macedo-Reis, L. E., Cristobal-Peréz, E. J., Sánchez-Montoya, G., Janda, M., Neves, F., and Quesada, M. 2018. Positive effects of the catastrophic Hurricane Patricia on insect communities. Sci. Rep. 8: 15042.

Ogie, R. I., James, S., Moore, A., Dilworth, T., Amirghasemi, M., and Whittaker, J. 2022. Social media use in disaster recovery: A systematic literature review. Int. J. Disaster Risk Red. 70:102783.

Padmanabhan, S. Y. 1973. The great Bengal famine. Annu. Rev. Phytopathol. 11:11-24.

Paini, D. R., Sheppard, A. W., Cook, D. C., De Barro, P. J., Worner, S. P., and Thomas, M. B. 2016. Global threat to agriculture from invasive species. Proc. Natl. Acad. Sci. U.S.A. 113:7575-7579.

Pan, Z., Yang, X. B., Pivonia, S., Xue, L., Pasken, R., and Roads, J. 2006. Long-term prediction of soybean rust entry into the continental United States. Plant Dis. 90:840-846.

Pavan, W., Fraisse, C. W., and Peres, N. A. 2011. Development of a web-based disease forecasting system for strawberries. Comput. Electron. Agric. 75:169-175.

Pegg, K. G., Coates, L. M., O'Neill, W. T., and Turner, D. W. 2019. The epidemiology of Fusarium wilt of banana. Front. Plant Sci. 10:1395.

Pelling, M., and Garschagen, M. 2019. Put equity first in climate adaptation. Nature 569:327-329.

Perondi, D., Fraisse, C. W., Dewdney, M. M., Cerbaro, V. A., Andreis, J. H. D., Gama, A. B., Junior, G. J. S., Amorim, L., Pavan, W., and Peres, N. A. 2020. Citrus advisory system: A web-based postbloom fruit drop disease alert system. Comput. Electron. Agric. 178:105781.

Prosekov, A. Y., and Ivanova, S. A. 2018. Food security: The challenge of the present. Geoforum 91:73-77.

Purdy, L. H., Krupa, S. V., and Dean, J. L. 1985. Introduction of sugarcane rust into the Americas and its spread to Florida. Plant Dis. 69:689-693.

Ramírez-Gil, J. G., Henao-Rojas, J. C., and Morales-Osorio, J. G. 2020. Mitigation of the adverse effects of the El Niño (El Niño, La Niña) southern oscillation (ENSO) phenomenon and the most important diseases in avocado cv. Hass crops. Plants 9:790.

Ray, P. P., Mukherjee, M., and Shu, L. 2017. Internet of things for disaster management: State-of-the-art and prospects. IEEE Access 5:18818-18835.

Ristaino, J. B. 2002. Tracking historic migrations of the Irish potato famine pathogen, *Phytophthora infestans*. Microbes Infect. 4: 1369-1377.

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., and Wei, Q. 2021. The persistent threat of emerging plant disease pandemics to global food security. Proc. Natl. Acad. Sci. U.S.A. 118:e2022239118.

Rooney-Latham, S., Blomquist, C. L., Kosta, K. L., Gou, Y. Y., and Woods, P. W. 2019. *Phytophthora* species are common on nursery stock grown for restoration and revegetation purposes in California. Plant Dis. 103:448-455.

Rosegrant, M. W., and Cline, S. A. 2003. Global food security: Challenges and policies. Science 302:1917-1919.

Sprague, R. H., Jr. 1980. A framework for the development of decision support systems. MIS Q. 4:1-26.

Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., and Nelson, A. 2019. The global burden of pathogens and pests on major food crops. Nat. Ecol. Evol. 3:430-439.

Scherm, H., and Yang, X. 1995. Interannual variations in wheat rust development in China and the United States in relation to the El Niño/Southern Oscillation. Phytopathology 85:970-976.

Scholthof, K.-B. G. 2007. The disease triangle: Pathogens, the environment and society. Nat. Rev. Microbiol. 5:152-156.

SEADS. 2022. Standards for Supporting Crop-Related Livelihoods in Emergencies. Practical Action Publishing, Rugby, U.K.

Secretariat of the International Plant Protection Convention. 2021. Safe provision of food and other humanitarian aid to prevent the introduction of plant pests during an emergency situation. In: Commission on Phytosanitary Measures Recommendation No. 9. AO on behalf of the Secretariat of the International Plant Protection Convention, Rome, Italy.

Selvaraj, M. G., Vergara, A., Montenegro, F., Ruiz, H. A., Safari, N., Raymaekers, D., Ocimati, W., Ntamwira, J., Tits, L., Omondi, A. B., and Blomme, G. 2020. Detection of banana plants and their major diseases through aerial images and machine learning methods: A case study in DR Congo and Republic of Benin. ISPRS J. Photogramm. Remote Sens. 169:110-124.

Sequera, V. 2023. Banana fungus may worsen hunger crisis in Venezuela. Reuters. https://www.reuters.com/world/americas/banana-fungus-may-worsen-hunger-crisis-venezuela-2023-05-10/

Shaw, M. W., and Osborne, T. M. 2011. Geographic distribution of plant pathogens in response to climate change. Plant Pathol. 60:31-43.

Shtienberg, D. 2013. Will decision-support systems be widely used for the management of plant diseases? Annu. Rev. Phytopathol. 51:1-16.

Shultz, J. M., Espinel, Z., Galea, S., and Reissman, D. 2009. Disaster ecology: Implications for disaster psychiatry. Pages 69-96 in: Textbook of Disaster Psychiatry. Cambridge University Press, Cambridge, U.K.

Singh, B. K., Delgado-Baquerizo, M., Egidi, E., Guirado, E., Leach, J. E., Liu, H., and Trivedi, P. 2023. Climate change impacts on plant pathogens, food security and paths forward. Nat. Rev. Microbiol. 21:640-656.

Small, I. M., Joseph, L., and Fry, W. E. 2015. Development and implementation of the BlightPro decision support system for potato and tomato late blight management. Comput. Electron. Agric. 115:57-65.

Smith, A. B. 2021. 2021 U.S. billion-dollar weather and climate disasters in historical context. NOAA National Centers for Environmental Information.

Smith, A., Lott, N., Houston, T., Shein, K., Crouch, J., and Enloe, J. 2016. U.S. Billion-Dollar Weather & Climate Disasters: 1980-2017. NOAA National Centers for Environmental Information.

Smith, D. F. Q., and Casadevall, A. 2022. Disaster microbiology—a new field of study. mBio 13:e01680-22.

Sperling, L., and Almekinders, C. J. M. 2023. Informal *commercial* seed systems: Leave, suppress or support them? Sustainability 15:14008.

Sperling, L., and McGuire, S. J. 2010. Persistent myths about emergency seed aid. Food Policy 35:195-201.

Sperling, L., Remington, T., Haugen, J. M., and Nagoda, S. 2004. Addressing Seed Security in Disaster Response: Linking Relief with Development, Overview. International Center for Tropical Agriculture, Cali, Colombia.

Stakman, W., Hodson, D., Cotty, P., Johansson, E., Gilbertson, L., and Stack, J. 2015. The war and wheat rust situation in Syria. Cereal Rusts Powdery Mildews Bull. 43.

Stott, P. 2016. How climate change affects extreme weather events. Science 352:1517-1518.

Sulle, E., Pointer, R., Kumar, P. L., and McEwan, M. 2022. Inventory of novel approaches to seed quality assurance mechanisms for vegetatively propagated crops (VPCs) in seven African countries. International Institute of Tropical Agriculture (IITA). International Potato Center (CIP).

Swett, C. L. 2020. Managing crop diseases under water scarcity. Annu. Rev. Phytopathol. 58:387-406.

Talaviya, T., Shah, D., Patel, N., Yagnik, H., and Shah, M. 2020. Implementation of artificial intelligence in agriculture for optimisation of irrigation and application of pesticides and herbicides. Artif. Intell. Agric. 4:58-73.

Thiery, W., Lange, S., Rogelj, J., Schleussner, C.-F., Gudmundsson, L., Seneviratne, S. I., Andrijevic, M., Frieler, K., Emanuel, K., Geiger, T., Bresch, D. N., Zhao, F., Willner, S. N., Büchner, M., Volkholz, J., Bauer, N., Chang, J., Ciais, P., Dury, M., François, L., Grillakis, M., Gosling, S. N., Hanasaki, N., Hickler, T., Huber, V., Ito, A., Jägermeyr, J., Khabarov, N., Koutroulis, A., Liu, W., Lutz, W., Mengel, M., Müller, C., Ostberg, S., Reyer, C. P. O., Stacke, T., and Wada, Y. 2021. Intergenerational inequities in exposure to climate extremes. Science 374:158-160.

Thomas-Sharma, S., Andrade-Piedra, J., Carvajal Yepes, M., Hernandez Nopsa, J. F., Jeger, M. J., Jones, R. A. C., Kromann, P., Legg, J. P., Yuen, J., Forbes, G. A., and Garrett, K. A. 2017. A risk assessment framework for seed degeneration: Informing an integrated seed health strategy for vegetatively propagated crops. Phytopathology 107:1123-1135.

Thompson, W. M. O. 2011. The Whitefly, *Bemisia tabaci* (Homoptera: Aleyrodidae) Interaction with Geminivirus-Infected Host Plants: *Bemisia tabaci*, Host Plants and Geminiviruses. Springer, Dordrecht, the Netherlands.

Thresh, J. M. 2003. The cassava mosaic virus pandemic in Africa. Plant Mol. Biol. 53:793-804.

Tinzaara, W., Gold, C. S., Ssekiwoko, F., Bandyopadhyay, R., Abera, A., and Eden-Green, S. 2006. Role of insects in the transmission of banana bacterial wilt. Afr. Crop Sci. J. 14:105-110.

Tjamos, E. C. 1993. Prospects and strategies in controlling verticillium wilt of olive 1. EPPO Bull. 23:505-512.

Torchin, M. E., and Mitchell, C. E. 2004. Parasites, pathogens, and invasions by plants and animals. Front. Ecol. Environ. 2:183-190.

Trivedi, P., Batista, B. D., Bazany, K. E., and Singh, B. K. 2022. Plant–microbiome interactions under a changing world: Responses, consequences and perspectives. New Phytol. 234:1951-1959.

Turvey, S. T. 2009. Holocene Extinctions. OUP, Oxford, U.K.

USAID. 2023. Famine Early Warning System Network (FEWS NET).

Usher, K., Ranmuthugala, G., Maple, M., Durkin, J., Douglas, L., Coffey, Y., and Bhullar, N. 2021. The 2019–2020 bushfires and COVID-19: The ongoing impact on the mental health of people living in rural and farming communities. Int. J. Ment. Health Nurs. 30:3-5.

van Bruggen, A. H. C., Goss, E. M., Havelaar, A., van Diepeningen, A. D., Finckh, M. R., and Morris, J. G., Jr. 2019. One Health-Cycling of diverse microbial communities as a connecting force for soil, plant, animal, human and ecosystem health. Sci. Total Environ. 664:927-937.

Västfjäll, D., Slovic, P., Mayorga, M., and Peters, E. 2014. Compassion fade: Affect and charity are greatest for a single child in need. PLOS One 9:e100115.

Vedeld, T., Hofstad, H., Mathur, M., Büker, P., and Stordal, F. 2020. Reaching out? Governing weather and climate services (WCS) for farmers. Environ. Sci. Policy 104:208-216.

Velásquez, A. C., Castroverde, C. D. M., and He, S. Y. 2018. Plant–pathogen warfare under changing climate conditions. Curr. Biol. 28:R619-R634.

Verwimp, P., and Muñoz-Mora, J. C. 2018. Returning home after civil war: Food security and nutrition among Burundian households. J. Dev. Stud. 54: 1019-1040.

Vurro, M., Bonciani, B., and Vannacci, G. 2010. Emerging infectious diseases of crop plants in developing countries: Impact on agriculture and socio-economic consequences. Food Security 2:113-132.

Wakelin, S. A., Gomez-Gallego, M., Jones, E., Smaill, S., Lear, G., and Lambie, S. 2018. Climate change induces drought impacts on plant diseases in New Zealand. Australas. Plant Pathol. 47:101-114.

Webb, G. R., Tierney, K. J., and Dahlhamer, J. M. 2002. Predicting long-term business recovery from disaster: A comparison of the Loma Prieta earthquake and Hurricane Andrew. Glob. Environ. Change B Environ. Hazards 4:45-58.

Westengen, O. T., Lusty, C., Yazbek, M., Amri, A., and Asdal, Å. 2020. Safeguarding a global seed heritage from Syria to Svalbard. Nat. Plants 6:1311-1317.

Wharton, P. S., Kirk, W. W., Baker, K. M., and Duynslager, L. 2008. A web-based interactive system for risk management of potato late blight in Michigan. Comput. Electron. Agric. 61:136-148.

WHO. 2017. One Health. World Health Organization 736.

Wilcox, W. F., and Mircetich, S. M. 1985. Effects of flooding duration on the development of Phytophthora root and crown rots of cherry. Phytopathology 75:1451-1455.

Willison, C. E., Singer, P. M., Creary, M. S., and Greer, S. L. 2019. Quantifying inequities in US federal response to hurricane disaster in Texas and Florida compared with Puerto Rico. BMJ Glob. Health 4:e001191.

Wolfert, S., Ge, L., Verdouw, C., and Bogaardt, M.-J. 2017. Big data in smart farming–a review. Agric. Syst. 153:69-80.

World Bank. 2021a. Employment in agriculture (% of total employment) (modeled ILO estimate) - Lower middle income. https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS?locations=XN

World Bank. 2021b. Employment in agriculture (% of total employment) (modeled ILO estimate) - Low income. https://data.worldbank.org/indicator/SL.AGR.EMPL.ZS?locations=XM

Yue, X., and Unger, N. 2018. Fire air pollution reduces global terrestrial productivity. Nat. Commun. 9:5413.

Zadoks, J. C. 2017. On social and political effects of plant pest and disease epidemics. Phytopathology 107:1144-1148.

Zadoks, J. C. 2008. On the Political Economy of Plant Disease Epidemics: Capita Selecta in Historical Epidemiology. Wageningen Academic Publishers, Wageningen, the Netherlands.

Zhai, Z., Martínez, J. F., Beltran, V., and Martínez, N. L. 2020. Decision support systems for agriculture 4.0: Survey and challenges. Comput. Electron. Agric. 170:105256.

Zhang, J., Huang, Y., Pu, R., Gonzalez-Moreno, P., Yuan, L., Wu, K., and Huang, W. 2019. Monitoring plant diseases and pests through remote sensing technology: A review. Comput. Electron. Agric. 165:104943.

Zhang, N., Wang, M., and Wang, N. 2002. Precision agriculture—a worldwide overview. Comput. Electron. Agric. 36:113-132.

Zhao, Q., Liu, K., Li, Z., Liu, Y., and Yao, Y. 2021. A novel ENSO monitoring index and its potential for drought application. J. Atmos. Sol. Terr. Phys. 225:105762.

Zimmerman, J. K., Willig, M. R., and Hernández-Delgado, E. A. 2020. Resistance, resilience, and vulnerability of social-ecological systems to hurricanes in Puerto Rico. Ecosphere 11:e03159.

Zinsstag, J., Schelling, E., Waltner-Toews, D., and Tanner, M. 2011. From "one medicine" to "one health" and systemic approaches to health and well-being. Prev. Vet. Med. 101:148.

Zomer, R. J., Xu, J., and Trabucco, A. 2022. Version 3 of the Global Aridity Index and Potential Evapotranspiration Database. Sci. Data. 9:409.

Zortea, T., Dewdney, M. M., and Fraisse, C. W. 2013. Development of a web-based system to optimize copper fungicide application in citrus groves. Appl. Eng. Agric. 29:893-903.