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PLANT DISEASE FEATURE

A Global Assessment of the State of Plant Health

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Abstract

The Global Plant Health Assessment (GPHA) is a collective, volunteer-based effort to assemble expert opinions on plant health and disease impacts on ecosystem services based on published scientific evidence. The GPHA considers a range of forest, agricultural, and urban systems worldwide. These are referred to as (Ecoregion × Plant System), i.e., selected case examples involving keystone plants in given parts of the world. The GPHA focuses on infectious plant diseases and plant pathogens, but encompasses the abiotic (e.g., temperature, drought, and floods) and other biotic (e.g., animal pests and humans) factors associated with plant health. Among the 33 (Ecoregion × Plant System) considered, 18 are assessed as in fair or poor health, and 20 as in declining health. Much of the observed state of plant health and its trends are driven by a combination of forces, including climate change, species invasions, and human management. Healthy plants ensure (i) provisioning (food, fiber, and material), (ii) regulation (climate, atmosphere, water, and soils), and (iii) cultural (recreation, inspiration, and spiritual) ecosystem services. All these roles that plants play are threatened by plant diseases. Nearly none of these three ecosystem services are assessed as improving. Results indicate that the poor state of plant health in sub-Saharan Africa gravely contributes to food insecurity and environmental degradation. Results further call for the need to improve crop health to ensure food security in the most populated parts of the world, such as in South Asia, where the poorest of the poor, the landless farmers, are at the greatest risk. The overview of results generated from this work identifies directions for future research to be championed by a new generation of scientists and revived public extension services. Breakthroughs from science are needed to (i) gather more data on plant health and its consequences, (ii) identify collective actions to manage plant systems, (iii) exploit the phytobiome diversity in breeding programs, (iv) breed for plant genotypes with resilience to biotic and abiotic stresses, and (v) design and implement plant systems involving the diversity required to ensure their adaptation to current and growing challenges, including climate change and pathogen invasions.

Keywords: biodiversity, climate change, food security, global population, plant diseases, sustainability

Plants are extraordinarily important for the Earth's climate, its biological diversity, the shape of our landscapes, the quality of the water we drink, the food we eat, and the air quality and temperatures that prevail in our cities. Plants mean life on Earth. Plants generate the oxygen that humans, like all animals, need to live. Plants store carbon dioxide, and in so doing, cool the climate; plants provide food

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and shelter for all forms of life. They filter the air we breathe and the water we drink; and they produce and retain soil. Healthy living plants also are the very essence of recreation, culture, inspiration, and of the natural beauty around us. Healthy living plants are essential to the mind. With the urbanization of the world population, mostly in megacities (Dobbs 2010), human beings are becoming increasingly disconnected from plants in their daily lives. It seems that humans take for granted the food, air, water, beauty, and peace that healthy plants produce and maintain all around us. We believe that reconnecting humans with the reality of plants, with plant life surrounding us, and with nature in general, is a powerful way to improve the well-being of individuals and human societies (Russell et al. 2013).

Three major drivers may be assumed to determine the global dynamics of plant-pathogen relationships: the global population (and the needs of 8 billion humans today, projected to be 9 billion by 2037; United Nations 2019), climate change (Skea et al. 2022), and pathogen invasions (Hyatt-Twynam et al. 2017). A central question is whether, and to what extent, the growing human populations can sustainably coexist with nature in the biosphere. Some aspects of this question may be addressed from a plant health standpoint, because the human appropriation of global resources (Rojstaczer et al. 2001; Vitousek et al. 1986) has a powerful effect on plant health and the state of ecosystems. Human population growth is the overarching force driving the evolution of the biosphere and the health of its plants, whether directly (e.g., agriculture and other land use) or indirectly (e.g., climate change and global exchange).

The state of plant health has a very large influence on the existence, functioning, and performance of plant systems in the biosphere. Plant pathogens play an important role in plant health. Yet there seems to be no scientific reference that considers the current state of plant health globally, or the evolution of plant health in the recent past. The objective of this article is to contribute to filling this gap, based on the results of the Global Plant Health Assessment (GPHA; GPHA 2022). It also aims at addressing through examples the effects of global changes and human activity on plant health, and the feedback of plant health on the performance of plant-based systems. The GPHA is an initiative of the International Society for Plant Pathology (ISPP) motivated by the International Year of Plant Health in 2020. It involves an international, volunteer, peer-reviewed evaluation of the state of plant health across ecoregions of the world, and of the effects of plant disease on ecosystem services (Millennium Ecosystem Assessment; MEA 2005): provisioning (food, fiber, and material), regulating (climate, water, and soils), and cultural (recreation, spiritual renewal, and beauty).

This article first outlines the objective of the GPHA, then the approaches and methods it implemented. Reports generated by GPHA project teams involved in the assessment (GPHA 2022), arranged according to 16 plant systems, are then summarized. Key elements derived from the GPHA are addressed in a final section.

Objectives of the GPHA

The GPHA is based on an array of (Plant System × Ecoregion) case studies (Table 1) to generate insight into plant diseases in human-made and natural ecosystems. In these ecosystems, plant diseases are considered through three lenses: ecological, agricultural, and evolutionary.

The goal of the GPHA is not to produce a comprehensive description of the state of health of every plant system in each part of Earth. Instead, the goal is to assess the importance and consequences of plant health in systems that (i) are iconic in their contribution to human cultures and societies (cultural role); (ii) that play critical roles in the mainstay of humanity, including but not limited to food security (provisioning role); and (iii) that are vital in the sustainability of the biosphere (regulating role). These characteristics are captured in the line drawings of Table 1. Plant systems in various ecoregions (i.e., distinct world regions defined on the basis of their ecological and socio-economic characteristics; Bailey 1996; MEA 2005) were selected for their specific roles toward these three services (MEA 2005). Table 1 summarizes the choices of plant systems and ecoregions that were made to provide an overall view of the importance and consequences of plant health. The collection of (Plant System × Ecoregion) case studies is also expected to enable comparisons among them and shed renewed light on questions such as the importance of plant diversity in disease management, the level of disease control that is acceptable in the management of disease in ecosystems, and the consequences of pathogen invasions under climate change.

This global assessment thus addresses widely different plant systems (Table 1; Fig. 1) from very simplified to extremely complex, with two dimensions: the diversity of plant species, and time. While human-made plant systems such as agrosystems have time constants (i.e., broadly, the delay for a given factor to cause measurable effect in a system; Leffelaar 1993) in the range of 10^0 to 10^3 years in their evolution, the time constants of ecosystems where human interventions are limited are much longer (10^2 to 10^4 years). Primeval forests have evolutionary time constants in the range of 10^4 to 10^6 years. Evolutionary time constants are important to understand processes, evolution, management, and vulnerability of plant systems to disease (Stukenbrock and McDonald 2008).

The GPHA considers several forest systems, both temperate and subtropical (Table 1). It also addresses urban forests (in one example only), which have become increasingly important in the last century. The GPHA also considers a range of agricultural systems. There, farmers do battle against plant diseases using three main instruments: host plant resistance, chemicals, and crop management. The battle is unending. In some cases, humans seem to have the upper hand and diseases are controlled durably; in other cases, it seems that the battle cannot ever be won, and that relentless control efforts have ever-increasing economic and environmental costs. When a balance seems achieved between management efforts and returns to humans, considering benefits other than just crop yield brings new insights; sometimes, apparent success may come with overlooked and unexpected costs.

Approaches and Methods

We developed an approach aimed at producing material grounded on scientific evidence that will help in developing policies to ensure sustainability of plant health globally and locally. A detailed description of the aim, overall principles and organization, and steps taken in the GPHA is provided in Supplementary File A. The key features of approaches and methods implemented are presented here. The assessment considers human-made ecosystems, including agrosystems, peri-urban horticulture, household (kitchen) gardens, and urban vegetation, and a range of forest systems around the world. Plant health is seen through the lens of infectious plant diseases. The GPHA therefore concentrated on viruses, bacteria, phytoplasmas, fungi, oomycetes, nematodes, and other organisms behaving as plant pathogens through dispersal, survival, specialization, and adaptation (e.g., parasitic plants). Pathogen vectors were also considered. Because plant health is not restricted to infectious diseases, attention was paid when relevant to the full range of factors which may influence the course of the healthy life of plants, whether biological (e.g., insects), physical (e.g., droughts, fires, and floods), or chemical (e.g., pesticides and ozone).

GPHA participants contributed in three different ways: to the overall coordination of the GPHA, as lead experts of a given team, or as experts involved in one of the GPHA teams. Teams were established for each (Plant System × Ecoregion) combination, with a lead expert mobilizing two or three experts.

The assessment is templated on the Millennium Ecosystem Assessment (MEA 2005). A series of ecoregions (Bailey 1996) of the world were selected (Fig. 1; Table 1); in each of these, key plant systems were identified. Each team produced a report that was standardized in format and size (Supplementary File A) through a specified set of questions. Each report is grounded in scientific, published, and citable evidence. Critically, the assessment considers plant health as a whole, and not specific plant diseases. Neither does a given report cover the entire set of plants or vegetation in a given plant system: keystone plant species that play a critical role in ecosystems (Bond 1994) were identified by each team, as indicated in Supplementary File C.

A standardized procedure was developed and shared with each team of experts in order to generate harmonized information on each chosen (Plant System × Ecoregion). Teams of experts followed an identical approach, from identification of a plant system in a given world ecoregion to answering and elaborating on a formatted set of questions as outlined in Fig. 2 (see details in Supplementary File A).

Table 1. Selected plant systems and ecoregions and their importance and challenges[a]

Plant systems and their meaning (society, cultural)	Importance of ecosystem services	Known challenges of plant systems, including plant diseases	Ecoregions selected
 **Wheat** *Demeter, goddess of harvest and agriculture, on a silver coin, 4th century BCE, Middle East.*	Wheat is the most widely cultivated world food crop. WE, NAm, SAm, the plains of EA, and the Indo-Gangetic plains of SA are major world granaries, the first three as trade sources; the last two providing food to regional population hubs, each exceeding 1.3 billion humans.	Wheat yields have reached a plateau in most of the world's granaries. Many plant diseases affect wheat. Several invasions and pandemics occurred in the past 30 years. Some diseases are enhanced by climate change and may contribute to yield ceilings.	WE, NAm, SAm, EA, SA
 **Rice** *Ifugao Sculpture, Philippines. The Louvre.*	Rice is the icon of the world's food crops. All of it is intended for human food, not for animal feed, biofuel, or industrial purposes. Most of the world's rice is produced and consumed in Asia, home to four billion humans and 26 of the world's 42 megacities.	Rice yields have reached ceilings in several of the key Asian "rice bowls" despite shortened crop rotations and strongly increased chemical inputs. Major rice diseases remain challenging and new ones are emerging.	SEA, EA, SA
 **Maize** *Maya maize god. He is also the patron of scribal arts, which he invented. Classic Period (200–900 CE).*	Almost all maize plant parts can be used for food, animal feed, or industrial raw materials. Maize is at the center of strong value chains in NAm, mainly for purposes other than food. Maize is a major food crop in SSA.	Maize production systems in NAm and SSA are extremely different, with purposes in different technological and value-chain contexts. Many diseases exist, especially in SSA where several pandemics have occurred and disease emergences are threatening.	NAm, SSA
 **Potato** *Axomamma, goddess of potato. Inca mythology.*	Potato, domesticated in SAm, is the fourth most important world food crop by weight with half the world's production in China. Long value chains produce food to starch for various industries.	Production is threatened by climate change and diseases. Potato late blight remains a challenging problem globally with massive fungicide costs in the Global North.	SAm, EA, WE
 **Cassava** *Head from Ife (Nigeria): 14th–15th century CE, bronze.*	*Manihot esculenta*, a 16th century introduction of slave traders from the Amazon to Africa, is critical to food security in SSA.	Cassava has chronically poor productivity everywhere in SSA. Plant diseases are known as major bottlenecks to productivity. Several pandemics have occurred in the past 30 years.	SSA

(*Continued on next page*)

[a] WE = Western Europe; NAm = North America; SAm = South America; EA = East Asia; SA = South Asia; SEA = Southeast Asia; SSA = sub-Saharan Africa; CA = Central America; MED = Mediterranean; AUS = Australasia. Line drawings prepared from public domain sources (Wikipedia) and reprinted with permission from the GPHA, 2022.

Questions pertaining to system states were to be answered on a five-point scale: “Excellent,” “Good,” “Fair,” “Poor,” or “Bad.” These classes correspond to a series of colors from dark green to red (Supplementary File A). Questions pertaining to trends in states were to be answered on a three-point scale: “declining,” “improving,” or “stable.” These classes correspond to arrows pointing down, up, or level. Questions on system states may concern each of the different types of ecosystem services: provisioning, regulating, or cultural. Responses to questions on trends in plant health and in the affected delivery of ecosystem services are represented by colored boxes (states) with arrows (trends) as shown in Supplementary File A.

As in the Millennium Ecosystem Assessment (MEA 2005), the information gathered was verified internally as outlined in Fig. 3. Each member of the coordination group acted as an editor for a given report, and had the report reviewed by a reviewer. Lead experts

Table 1. (*Continued from previous page*)

Plant systems and their meaning (society, cultural)	Importance of ecosystem services	Known challenges of plant systems, including plant diseases	Ecoregions selected
 **Banana and plantains** *Kifwebe mask; wood. Luba Kingdom, Democratic Republic of Congo.*	Banana and plantain (*Musa* spp.) are grown all over SSA for household consumption and local markets; only a small part of the banana production is internationally traded.	Banana and plantain productivity desperately low in SSA. Major diseases are chronic yield-reducers, and grave new diseases have developed recently.	SSA
 **Grapevine** *Dionysos in a ship, sailing among dolphins. Attic kylix, ca. 53 BCE. Vulci, Italy.*	Grapevine is at the heart of Western culture. Spain, France, and Italy are the world’s main grape-growing countries. Nearly 90% of the world’s organic grape area is located in Europe today.	Pesticide use in grapevine remains excessively high. Fewer effective chemicals are made available. Complex (especially wood) diseases are becoming harder to manage.	WE
 **Perennial fruits** *Reputed descendant of Newton’s apple tree at Trinity College, Cambridge.*	Fruit trees are important for human nutrition and generate important value chains. A wide range of species of fruit trees is grown worldwide. Apple (*Malus domestica*) and pecan (*Carya illinoinensis*) are keystone species in NAm.	Shifts in crop management and climate change alter growing patterns. Chronic foliage and fruit diseases remain challenges.	NAm
 **Coffee** *Sidamo coffee (*Coffea arabica*). Coffee originates from Ethiopia and the southern tip of Arabia.*	Arabica coffee (*Coffea arabica*) is one of the most traded agricultural products in the world. Coffee cultivation is especially important in CA, economically and environmentally.	The coffee-shade tree system, the largest agroforestry system of CA, is threatened by new practices and new plant material (*C. robusta*). The coffee rust crisis caused loss of income of many farm and field workers, aggravating poverty and food insecurity, and prompting migrations.	CA
 **Citrus** *O Meu Pé de Laranja Lima (My Sweet Orange Tree), by José Mauro de Vasconcelos in 1968, Brazil.*	Citrus fruits have high nutritional value. Most are consumed fresh, but citrus generates strong value chains. Main citrus-growing areas include EA, SA, MED, NAm, SAm, SSA, and AUS.	Very large, well organized, and industrialized production systems have shown their frailty in the New World. Successive pandemics have caused havoc in citrus plantations in NAm and SAm. Invasive diseases are threatening other production areas.	EA, SAm, NAm, MED, AUS, SSA

(*Continued on next page*)

Table 1. (*Continued from previous page*)

Plant systems and their meaning (society, cultural)	Importance of ecosystem services	Known challenges of plant systems, including plant diseases	Ecoregions selected
 **Peri-urban horticulture and household gardens** *Anna Purna. Hindu goddess of food and nourishment.*	Peri-urban horticultural systems are worldwide suppliers of perishable fruits and vegetables to urban centers. Household (home, kitchen, backyard) gardens are essential to family food and nutrition security and are foci of biological diversity and knowledge conservation.	Peri-urban agriculture has met the needs of accelerated urbanization but faces sustainability challenges (soils, water, nutrients). Pesticide usage is a persistent issue. These systems face numerous grave pathogens, many soilborne.	SSA, SA, SEA
 **Urban trees** *The Pulitzer Fountain, Manhattan's Grand Army Plaza, New York, U.S.A.*	Urban vegetation is a collective good of great ecological, sociological, psychological, spiritual, political, and ethical value. Plane tree (*Platanus* sp.), a keystone species of European urban forests, can live up to 2,000 years.	Urban trees are of extreme symbolic and environmental value. Numerous abiotic and biotic stresses occur in urban environments. Tree diseases can cause heavy losses in urban trees, such as Dutch Elm Disease (*Ophiostoma novo-ulmi*) in Europe.	WE
 **Oak forests** *The Big Oak. Painting by Gustave Courbet (1843).*	Oaks (*Quercus* spp.) are key components of deciduous forests of WE and NAm with major cultural, socio-economic, and environmental value. Oak was designated by U.S. Congress as the national tree in 2004.	Climate change and invasions are constant threats for oaks and the oak-based forests, especially in NAm. The causation of tree decline is still challenging. Effects of interactions between abiotic and biotic factors remain uncertain.	WE, NAm
 **Softwood forests** Pinus contorta *needles and cones and totem pole in Ketchikan, Alaska.*	The managed softwood forests of NAm ensure important cultural and provisioning roles. Key species include the loblolly pine, Douglas-fir, lodgepole pine, eastern white pine, and the red and white spruces.	Climate change has a large effect on the sustainability of softwood forests. Some species are threatened with extinction by diseases. Complex biotic-abiotic interactions exist.	NAm
 **Amazon forest** *World Tree, Izapa stela 5. Olmec art, 300–50 BCE. American ceibas are close to African fromagers and Asian Kapoks. All have profound spiritual value.*	The Amazon, the largest tropical rainforest in the world, supports an extraordinary biodiversity, and ensures key climate regulation globally (water, carbon). We focus on two commodities: *Hevea brasiliensis* and *Theobroma cacao,* which grow in the wild.	The Amazon is threatened by human activities in the short term. No known disease challenges identified in plants growing in the wild.	SAm
 **Eucalypt forests** *Eucalypts are important ceremonial elements for Australian aborigines. Aboriginal bark painting.*	Eucalypts (genera *Eucalyptus*, *Corymbia*, *Angophora*), remnants of Gondwana's biodiversity, have Australia as center of diversity. Their forests generate key provisioning and regulating service while having immense cultural significance.	Climate change, and its effect on complex abiotic-biotic stresses, is a concern. Pathogen invasions are a constant threat to a unique biodiversity hotspot.	AUS

revised their reports based on reviews. A total of 26 reports (two involving two plant systems, and one plant system addressed in six ecoregions in a single report) were thus assembled, constituting the basis of the GPHA Report (GPHA 2022) and of this article. This work was conducted by a number of teams and involved over 80 scientists across the world.

Main Results of the Global Plant Health Assessment

Overview of results

The GPHA includes 33 (Plant System × Ecoregion) combinations (Table 2), each considering one or several keystone plant species in one given ecoregion (Fig. 1). Among these (Fig. 4), the health of 15 are rated "good," but 19 are rated "fair" (13) or "poor" (6). In 21 cases, health is assessed as "declining," while it was assessed as "level" for 10 cases and "improving" in only 3 cases.

Not all three categories of ecosystem services (provisioning, regulating, and cultural) were assessed in each of the 33 (Plant System × Ecoregion) examples (Table 2; Fig. 4). With respect to provisioning (documented in 32 cases), states were assessed as "excellent," "good," "fair," and "poor" in 6, 13, 9, and 4 cases, respectively (Fig. 4). Only three trends of provisioning were assessed as "improving," while 19 and 10 were assessed as "stable" or "declining," respectively. As for regulating services (affected by plant diseases), assessed in 13 cases, states were assessed as "excellent," "good," "fair," and "poor" in 3, 2, 5, and 3 cases, respectively. A decline was declared in the majority (11) of the cases. With respect to cultural services (documented in 10 cases), states were assessed as "excellent," "good," "fair," and "poor" in 4, 3, 0, and 3 cases, respectively. In no case was an improvement reported, while cultural services were reported "stable" in six cases, and "declining" in four cases.

Assessments of the status and evolution of plant health and of ecosystem services, as impacted by disease, are displayed in Table 2 for all (Plant System × Ecoregion) considered. The main pathogens and diseases involved are listed in Supplementary File B. The assessments are described in more detail in Supplementary File C.

Pathogen invasions

The importance of invasions fueled by increasing human activities to the global state of plant health is compelling. The GPHA reported pathogen incursions sometimes leading to pandemics (Heesterbeek and Zadoks 1987) for wheat in South Asia; rice in South Asia and East Asia; potato in Western Europe; maize, cassava, and banana in sub-Saharan Africa; coffee in Central America; citrus in North America, South America, and Western Europe; urban trees in Western Europe; oaks in North America; softwood forests in North America; and eucalypts in Australia. In all, 15 of the 33 considered (Plant System × Ecoregion) examples refer to pathogen invasions as a factor, and sometimes the main cause, in poor plant health. The frequency of pathogen incursions in ecosystems has increased with exchanges (e.g., Stukenbrock and McDonald 2008) during the highly connected Anthropocene (Steiner 2020).

The GPHA documents numerous examples of invasions (Fig. 5A; Supplementary File C) in forest systems. In the softwood forests of North America, white pine blister rust (*Cronartium ribicola*) causes extensive mortality in five-needle pine species (Geils et al. 2010) and is a cause for threatening the whitebark pine (*Pinus albicaulis*) in the wild. Sudden oak death (Grünwald et al. 2019), caused by *Phytophthora ramorum*, a pathogen with a very wide host range that was first recognized in the mid-1990s in coastal evergreen forests of the San Francisco Bay Area, has killed an estimated 50 million oak and tanoak (*Notholithocarpus densiflorus*) trees along the Pacific Coast in California and southern Oregon. In Australia, the most significant pathogen of eucalypt forests, *Phytophthora cinnamomi* (one of the world's most invasive pathogen species), causes dieback and tree mortality. The pathogen is known to infect more than 150 species of eucalypts, and is recognized as a key threatening process (Cahill et al. 2008; Keane et al. 2000). Forest pathologists are extensively documenting the association of plant pathogens causing tree mortality worldwide, along with other organisms (e.g., insects) and abiotic stresses (e.g., drought, heat, and excess precipitation). Urban forests are vulnerable to pathogen invasions as shown by the epidemic of canker stain disease (Panconesi 1999), caused by *Ceratocystis platani*, which is decimating two-century-old plantations of London planes (*Platanus* × *acerifolia* (Aiton) Willd, syn.

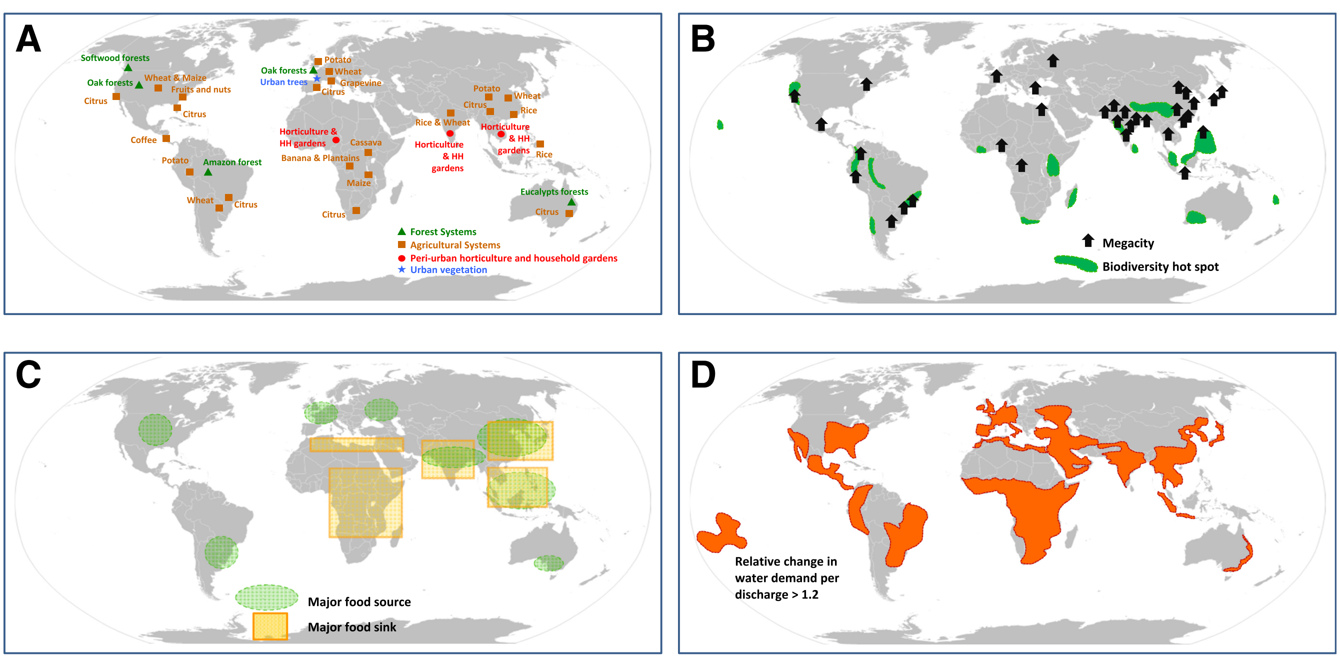


Fig. 1. Distribution of (Plant System × Ecoregion) systems considered in the Global Plant Health Assessment (GPHA), megacities, biodiversity hotspots, sources and sinks of food, and water resource. **A,** Approximate locations of the (Plant System × Ecoregion) systems considered in the GPHA. **B,** Megacities (https://en.wikipedia.org/wiki/Megacity): only megacities with more than 10 million inhabitants are shown. Biodiversity hotspots are approximately redrawn from Wilson (1992). **C,** Some major global food (cereal) sources and food sinks. **D,** Water discharge based on climate change and population. Approximately redrawn from Vörösmarty et al. (2000).

Platanus × hispanica Mill. Ex Münchh.) bordering the Canal du Midi in southern France.

Pathogen invasions in field crops are widely reported in the GPHA. This includes, for instance (Fig. 5A), the introduction of more aggressive strains of wheat stripe rust in Western Europe (Hovmøller et al. 2016); incursions and establishment of wheat stem rust in Western Europe (Saunders et al. 2019), especially in Italy; the introduction of the maize chlorotic mottle virus, first detected in 2011 in Kenya, causing the maize lethal necrosis epidemic in East Africa if associated with endemic potyviruses (Mahuku et al. 2015); the incursion of the wheat blast pathogen (Ceresini et al. 2018) in Bangladesh; or the spread of false smut of rice (*Ustilaginoidea virens*; Fan et al. 2016), a mycotoxinogenic flower disease, across the entire Asian ecoregions (Reddy et al. 2011). The latter appears to have been human-engineered, through the widespread attempts of hybrid rice cultivation rather than through transportation of inoculum (Reddy et al. 2011). The case of the viral diseases in rice in East Asia seems especially important as it concerns the food base of over a billion and half people (Fig. 1). There, a regional viral epidemic-climate system seems to have established, involving several viruses (Rice Black-Streaked Dwarf Fijivirus and Rice Stripe Virus) and their vectors (*Sogatella furcifera* and *Laodelphax striatellus*, respectively). Hotspots of these viruses seem established in Southeast Asia, where two or three rice seasons per year are practiced, and amplify the virus populations. As the summer monsoon progresses from Southeast Asia to South and Central China, the Koreas, and Japan, bringing the rains required for crop establishment, typhoons also transport viruliferous insect vectors laden with viruses acquired in older plantings, which infect young crop stands as they are being established (Supplementary File C; GPHA 2022).

Dramatic examples of past pathogen invasions include the destruction of North American chestnut forests by chestnut blight

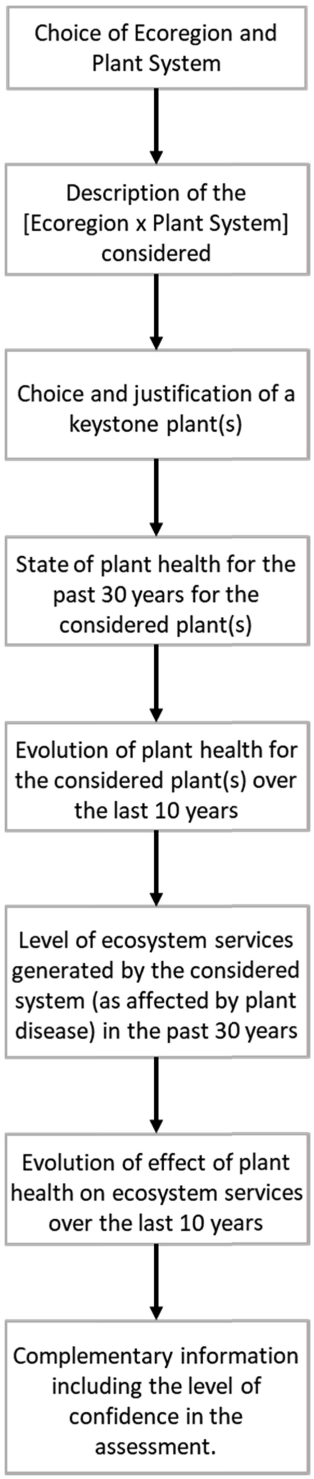
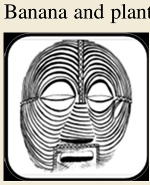


Fig. 2. Steps taken to assess plant health and ecosystem services of plant systems in world's ecoregions. The flowchart outlines the steps taken by each team of experts to develop reports according to a standardized format.

Fig. 3. Steps taken to review and edit reports from teams of experts. The flowchart outlines the steps taken in a process of internal peer review and editing of the reports developed by each team of experts.

Table 2. Overall state of plant health[a]

Plant system	World ecoregion	Overall state of plant health	Level of confidence in assessment; plant health	Main ecosystem services: Provisioning	Main ecosystem services: Regulating	Main ecosystem services: Culture	Level of confidence in assessment; services
Wheat 	Western Europe	G ↘	Very confident	G →			Reasonably confident
	North America	G →	Very confident	F ↘			Reasonably confident
	South America	G →	Very confident	G ↘			Reasonably confident
	East Asia	F ↗	Reasonably confident	G →			Reasonably confident
	South Asia	F ↘	Reasonably confident	F →			Reasonably confident
Rice 	Southeast Asia	G →	Reasonably confident	E →			Reasonably confident
	East Asia	G ↘	Reasonably confident	G →			Reasonably confident
	South Asia	F ↘	Reasonably confident	G ↘			Reasonably confident
Maize 	North America	G →	Reasonably confident	E →			Reasonably confident
	Sub-Saharan Africa	P ↘	Reasonably confident	P →			Reasonably confident
Potato 	South America	G →	Reasonably confident	F ↘	P ↘		Reasonably confident
	East Asia	P ↘	Reasonably confident	F →			Reasonably confident
	Western Europe	G ↘	Very confident	P ↘			Very confident
Cassava 	Sub-Saharan Africa	P ↘	Reasonably confident	P →	F ↘		Reasonably confident
Banana and plantains 	Sub-Saharan Africa	P ↘	Very confident	F →	F ↘		Reasonably to very confident

(*Continued on next page*)

[a] Color of boxes (green, yellow, orange) and letters (E, G, F, P) refer to levels of plant health over the past 30 years: "excellent," "good," "fair," or "poor." Directions of arrows indicate trends over the past 10 years (down: decline, level: stable, up: improving). The same scales are used for ecosystems services (see text for explanation): provisioning, regulating, culture. Levels of confidence are as indicated by experts in their reports. Icons for plant systems are explained in Table 1. Line drawings prepared from public domain sources (Wikipedia) and reprinted with permission from the GPHA, 2022.

Table 2. (*Continued from previous page*)

Plant system	World ecoregion	Overall state of plant health	Level of confidence in assessment; plant health	Main ecosystem services: Provisioning	Main ecosystem services: Regulating	Main ecosystem services: Culture	Level of confidence in assessment; services
Grapevine 	Western Europe	↘ G	Reasonably confident	→ E	↘ E	↘ E	Reasonably confident
Perennial fruits 	North America	→ G	Reasonably confident	→ G		→ G	Reasonably confident
Coffee 	Central America	↘ P	Very confident	↘ F	↘ G		Very confident
Citrus 	Global	↘ F	Reasonably confident	↘ G		↘ G	Reasonably confident
	East Asia	→ F	Reasonably confident	↗ G			Reasonably confident
	South America	↘ F	Reasonably confident	→ F		→ P	Reasonably confident
	North America	↘ F	Reasonably confident	↘ F		↘ P	Reasonably confident
	Mediterranean	↘ G	Reasonably confident	↘ G		→ G	Reasonably confident
	Australasia	→ G	Reasonably confident	→ G			Reasonably confident
	Sub-Saharan Africa	↗ G	Reasonably confident	↗ E			Reasonably confident
Peri-urban horticulture and household gardens 	Sub-Saharan Africa	↘ F	Reasonably confident	→ P	↘ P		Reasonably confident
	South Asia	↗ F	Reasonably confident	↗ G	↗ F	→ G	Uncertain to reasonably confident
	Southeast Asia	↘ G	Reasonably confident	→ G	↘ F	→ E	Uncertain to reasonably confident

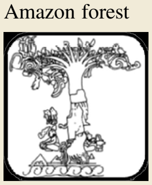
(*Continued on next page*)

(*Cryphonectria parasitica*), the decimation of European and American elms by the Dutch elm disease (*Ophiostoma ulmi* and *O. novo-ulmi*), the introduction of fire blight in Europe's rosaceous trees (Brasier 2008), or the introductions of potato late blight (*Phytophthora infestans*) into Europe starting in the 19th century. Weltzien's (1972) approach to predicting disease occurrence at a given location still holds: this requires information about (i) the pathogen's geographic distribution, (ii) the distribution of its host, and (iii) the ecological requirements of pathogen and host. Whether an intruder will ever become a true disease threat is hard to determine accurately. An issue for plant pathology concerns false positives; that is, cases where pandemics were predicted, but did not (or not yet) actually occur. It seems that, sometimes, Weltzien's third condition is not sufficiently considered.

Evolutionary biology of plant pathogens

Weltzien's (1972) suitable "environmental factors" for disease have often been taken to refer only to the local climate. However, this third condition concerns the whole biological life cycle of the pathogen, and therefore the plant population on which an epidemic is observed, as well as possible alternate hosts. The latter may enable sexual recombination and inoculum amplification, and may constitute the main reservoir of the pathogen. A so-called "alternate" host may well be the main one in the life strategy of the pathogen, which is only mirrored on the cultivated host of concern. This may occur with wheat blast in South America (Ceresini et al. 2018). Too little is known of the ecology of plant pathogens in natural or nonmanaged plant communities, especially with respect of their life cycles (Dinoor and Eshed 1984; Kranz 1990; but see also Jeger 2022). Knowledge of host jumps (from a given host species to another one), and speciation processes may also be insufficient. The introduction of wheat blast into South Asia does not seem to be causing the major pandemic some feared (Singh et al. 2021), perhaps because of the absence of alternate hosts. Rice blast is omnipresent in the rice-wheat system of South Asia, yet a blast-pathogen host jump from rice to wheat has never been observed, presumably because the rice blast pathogen is not adapted to wheat. From a biological speciation standpoint (Wilson 1992), there seems to be a barrier between the two entities—wheat blast and rice blast—which evolved separately on different hosts, possibly over millions of years. One species accomplishes its life cycle mainly on another host plant, and accidentally has become able to infect wheat in South America. In

Table 2. (*Continued from previous page*)

Plant system	World ecoregion	Overall state of plant health	Level of confidence in assessment; plant health	Main ecosystem services: Provisioning	Regulating	Culture	Level of confidence in assessment; services
Urban trees 	Europe	↘ P	Reasonably confident		↘ P	↘ P	Reasonably confident
Oak forests 	Western Europe	↘ F	Reasonably confident	→ E	↘ E	→ E	Reasonably confident
	North America	↘ F	Reasonably confident	↘ E	↘ E	↘ E	Reasonably confident
Softwood forests 	North America	↘ F	Reasonably confident	↘ G			Reasonably confident
Amazon forest 	South America	→ G	Reasonably confident	→ G	→ G		Uncertain to reasonably confident
Eucalypts 	Australasia	↘ G	Reasonably confident	→ G	↘ G	→ G	Reasonably confident

another example, the failure of soybean rust to invade most of North America (Goellner et al. 2010) may result from unsuitable environmental conditions, including cold winters or nonhost periods, and the absence of alternate host(s), i.e., the absence of a "green bridge" (Zadoks and Schein 1979).

The unique flora and fauna of Australasia evolved in nearly complete isolation for about 100 million years (Crisp and Cook 2013). With reference to the combined Africa-Europe continents, pathogens and plants coevolved on the comparatively smaller land mass of Australasia, under frequently glacial climatic conditions, and therefore under a relatively lower level of selection pressure from pathogens (Wilson 1992). This system is extremely vulnerable to introduced and polyphagous pathogens such as *P. cinnamomi*, which was presumably introduced at the beginning of the 20th century. Another forest system, the Amazon, has evolved on a larger land mass for a similar period of time, and under climatic conditions that remained almost constantly tropical. There, the botanical hyperdiversity (Cardenas et al. 2014) of the Amazon rainforest emerged, driven by a far more severe selection pressure of pathogens according to the Janzen–Connell hypothesis (Eck et al. 2019) over extensive geological time (Boyce and Lee 2017). This system appears impervious to the appearance of new pathogens because of the resilience of its plant community. We may assume that (i) (following Gilbert 2002) pathogens are strong contributors to plant evolution; and (ii) the larger the land mass (Wilson 1992), the longer-lasting the plant-pathogen coevolution, and the more resilient a forest system will be. Yet three other forest systems (softwood forests in North America and oaks in Western Europe and North America), which have also been exposed to selection pressure from pathogens, also appear very vulnerable to invasions. However, the forest systems of North America and Western Europe did not evolve under conditions similar to that of the Amazon rainforest.

Climate change and plant health

Climate change is a recurrent theme of many reports of the GPHA (Fig. 5B). The effects of climate change on plant diseases have been addressed in many studies and reviews (e.g., Chakraborty and Newton 2011; Garrett et al. 2011; Jeger 2022; Sturrock et al. 2011). In all, 17 of the 33 considered (Plant System × Ecoregion) case studies identify climate change as affecting the evolution of plant health. These reports, however, do not always provide specific detail on the processes involved. The effects of climate change on plant health are diverse, including: (i) direct effects on the life cycles of pathogens (e.g., rice and wheat in South Asia), (ii) direct effects on pathogen vectors (through increased vector activity; vegetables in sub-Saharan Africa), (iii) indirect effects via change in agricultural practices (maize in North America, wheat in South Asia), and (iv) indirect effects of disease combined with abiotic stresses such as drought and heat waves (wheat and rice in South Asia, oak-based forests in North America, eucalypt forests in Australia) or excessive rainfall (oak-based forests in North America). Except for the Amazon rainforest, all the reports on forest systems refer to complex interactions among pathogens, insects, and climate change. The causes for declining tree health in forest systems are complex (e.g., Desprez-Loustau et al. 2006).

Climate change refers to changes in temperature, precipitation, and atmospheric chemical composition on host plants and pathogens. These changes have effects at the hourly, daily, and yearly scales on complex systems, encompassing a host, a pathogen (interacting and producing disease), and a suite of micro-organismal components of the phytobiome (Leach et al. 2017). For instance, endophytes, which have a positive effect on plant physiology, could turn into or facilitate pathogens in response to abiotic stress (Busby et al. 2016). Little is still known of the dynamics triggered by climate change on the functioning and the communications among components of the phytobiome.

It has been suggested that necrotrophic plant pathogens would especially be favored in a context of changing climate, where abiotic stresses are more frequent and severe (Chakraborty and Newton 2011). This hypothesis concurs with the observations collected on rice brown spot (Barnwal et al. 2013) and wheat blotch (Sharma et al. 2007). Both diseases are on the rise where climate change is having a greater impact, and their causal pathogens have similar life strategies (survival between crop cycles, spore dispersal, or seed-transmission), population genetics, and host plant resistance patterns—and both pathogens are necrotrophs.

A reductionist approach to plant health

The GPHA is restricted to infectious plant diseases. Infectious plant diseases, however, depend on climate (in both their development and their effects on hosts), are influenced by the state of plant physiology and by crop development stages, and often develop in complex

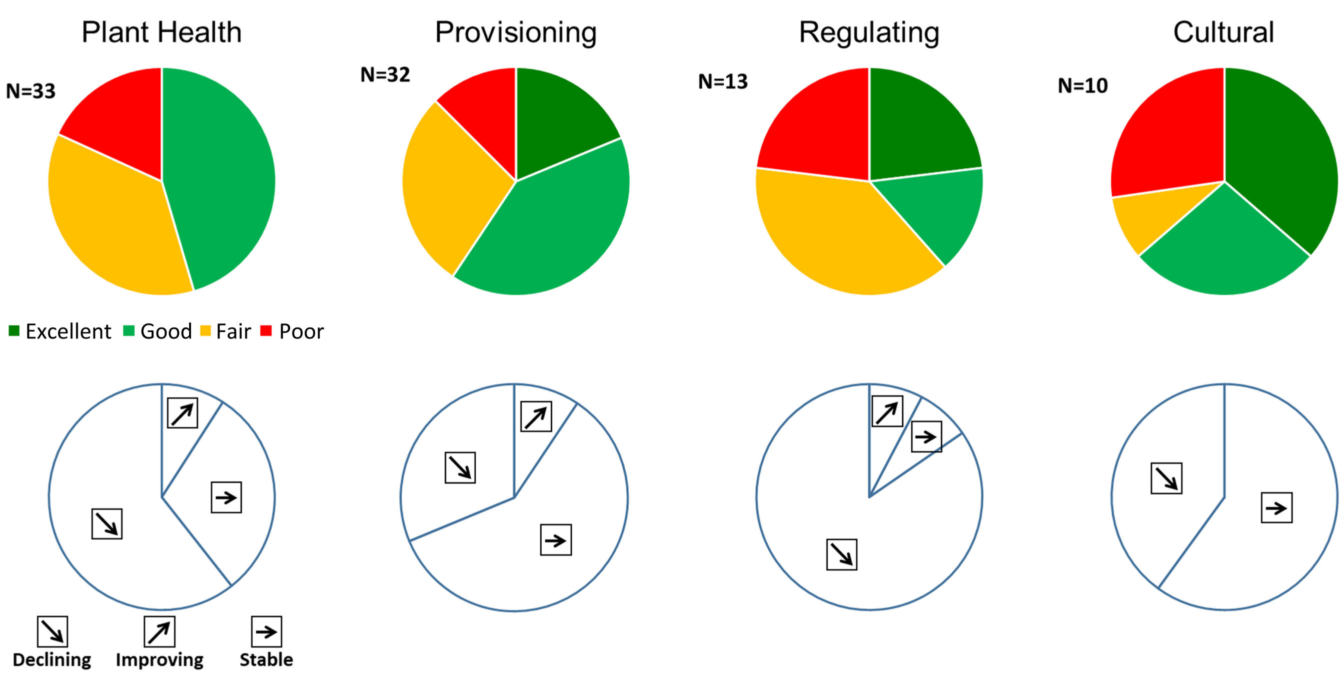


Fig. 4. Proportions of (Ecoregion × Plant System) cases with respect to plant health assessment and consequences of plant health on ecosystem services (provisioning, regulating, and cultural). Number (total 33) of (Ecoregion × Plant System) vary according to the attribute (plant health, provisioning services, regulating services, and cultural services) considered. Entries indicate the number of (Ecoregion × Plant System) considered.

interactions between pathogens and other microorganisms in the phytobiome and macroorganisms such as arthropods. As discussed in several reviews (e.g., Döring et al. 2012; Jeger 2022), "plant health" is a loose term with numerous angles. Considering infectious diseases was nevertheless judged an effective, concrete, and practical entry point to be addressed by plant pathologists.

Plant diseases in an ecological perspective

The GPHA encompasses a range of ecosystems where human intervention varies widely, from natural systems to intensive farming of the Old and New Worlds. This enables comparisons and an analysis of the inspiration from nature that prevails, or reappears, in some plant systems (Fig. 5C; Tables 1 and 2; and Supplementary File C).

Perennial, complex, and multi-species plant systems generate food, income, and material goods, along with biodiversity and soil conservation in several ecoregions of the Global South. These systems often demonstrate resilience to disturbances, including plant diseases. The agroforestry-coffee system of Central America is one such example (Avelino et al. 2018). Interspecific crop diversity (Boudreau 2013) is also widespread in many annual field crop systems of sub-Saharan Africa, reflecting farmers' adaptation to uncertain weather (erratic rainfall), poor soils, and disease risks (e.g., Savary et al. 1988). Diseased plane trees are replaced by nonsusceptible trees along the Canal du Midi, France, to generate botanical diversity and reduce epidemic spread (GPHA 2022). Biological control and integrated pest management have made headway in Europe's grapevines (Pertot et al. 2017), and environment-friendly technologies are being developed for the peri-urban vegetable production systems of sub-Saharan Africa and South and Southeast Asia (GPHA 2022). Inspiration from nature in crop and disease management may take many forms, involving age-old practices (field crops in sub-Saharan Africa) to the latest technological advances (grapevine or vegetable production).

The overall emerging picture from the GPHA is that ecosystems where chemical intervention is least, where human labor and care greatest, are often the least diseased, whereas those where chemical intervention is more frequent and human labor is the least are often the most vulnerable. This contrasts strikingly with the overall state of the world's ecosystems (MEA 2005), where the least anthropized systems are often the most at risk from human perturbations despite their resilience to disease, as a result of climate change, fires, roads and dams, and urbanization.

Agriculture itself is a root cause for epidemics in cultivated plants (Savary 2014). A crop is a cohort of individual plants growing in close proximity, of the same age and development stage, of similar or identical genetic make-up, under similar physiological stimulants (fertilizers), of similar physiology and similarly enhanced vulnerability to disease, and of similar shapes and sizes (Stukenbrock and

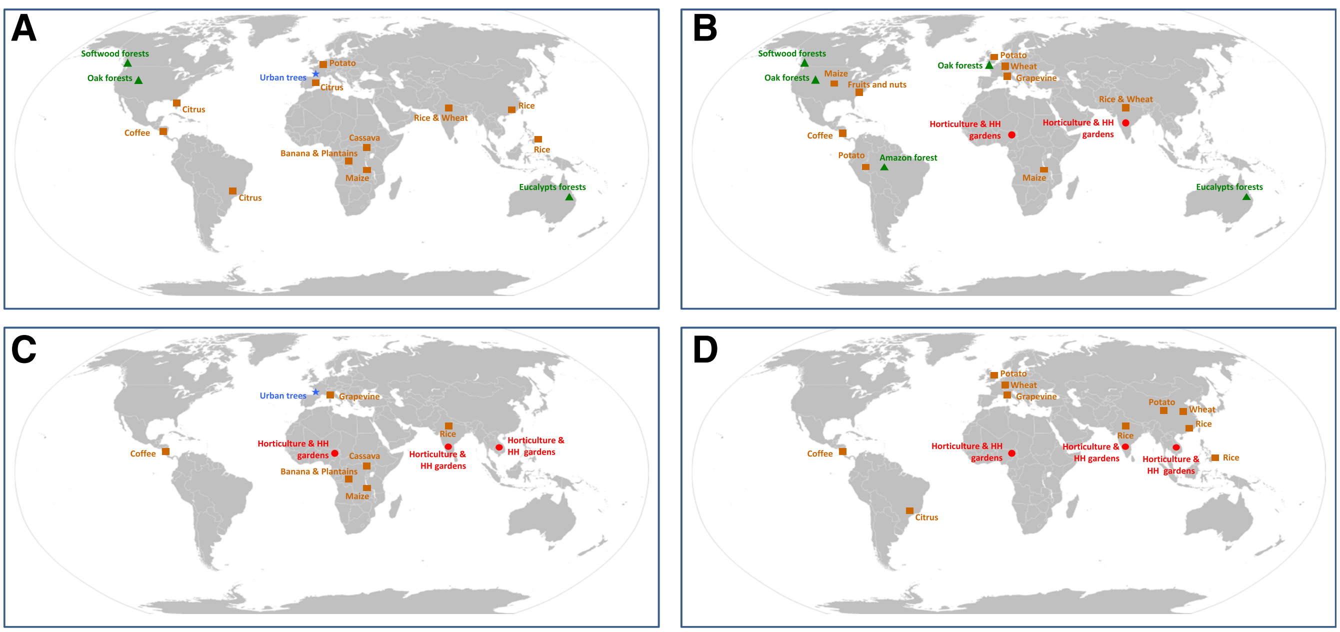


Fig. 5. Distribution of key challenges associated with plant health as reported in the Global Plant Health Assessment (GPHA). **A,** Pathogen invasions. Large scale polyetic disease expansions (i.e., pandemics, Heesterbeek and Zadoks 1987) are reported in several forest systems (oak and softwood forests in North America; eucalypt forests in Australia), with potentially severe consequences on biodiversity. Perennial plant systems (urban trees, citrus plantations in the New World and Europe) are also subjects of concern. Serious large-scale epidemics are reported in food crops of sub-Saharan Africa (banana and plantains, maize, and cassava). Field crops in Western Europe and South Asia (wheat, potato) have witnessed recurrent invasions of pathogens strengthened by strong pathogen evolution, exemplified especially by potato late blight. The expansion of false smut of rice across East, South, and Southeast Asia appears to have been associated with that of hybrid rice cultivation. In recent decades, a coupled regional climate–disease system has established yearly in Southeast Asia (where vectors multiply and acquire viruses) and East Asia (to which viruliferous vectors are transported as the summer monsoon progresses northward; see details in text and Supplementary File C). **B,** Climate change. The increased frequency of extended droughts and excessive rains is reported in the GPHA, especially in the softwood and oak forests of North America, where it is associated with increased insect and pathogen injuries. Climate change influence on plant health is reported in numerous field crops in a range of ecoregions, including maize in North America, potato in South America, maize in sub-Saharan Africa, wheat and potato in Western Europe, and rice and wheat in South Asia. These effects are often superimposed with pathogen spatial expansion (A). Vegetable production in peri-urban systems of sub-Saharan Africa and South Asia is also a subject of concern, as a result of increased pathogen vector activity. **C,** Inspiration of nature in human-made and -managed plant systems. Perennial, complex, and multi-species plant systems generate food, income, and material goods in several ecoregions of the Global South. In many cases, these systems demonstrate resilience to disturbances, including plant diseases. Such systems include the agroforestry-coffee systems of Central America, or banana and plantains in sub-Saharan Africa. Cultivated interspecific diversity prevails in many annual field crop systems of sub-Saharan Africa. Diseased plane trees are replaced by nonsusceptible trees along the Canal du Midi, France, to generate botanical diversity and reduce epidemic spread. Biological control and integrated pest management have made headways in Europe's grapevines. New environment-friendly technologies are also being developed for the peri-urban vegetable production systems of sub-Saharan Africa, South Asia, and Southeast Asia. **D,** Pesticide usage. An array of issues concerns the use of pesticides. Pesticide usage may be: (i) insufficient and/or inadequate (e.g., coffee, Central America); (ii) the sole alternative to disease control, leading to over-reliance (e.g., potato, Western Europe); (iii) inadequate for lack of chemical innovation in new compounds (e.g., grapevine, Western Europe); (iv) challenged by pathogen adaptation (e.g., wheat, Western Europe); (v) excessive, leading to multiple environmental problems (e.g., rice, wheat, and potato in East Asia; potato in Western Europe; citrus in South America; and vegetable production in sub-Saharan Africa, South Asia, and Southeast Asia); (vi) associated with the use of banned pesticides, or pesticides that are dangerous to human health (vegetables, sub-Saharan Africa).

McDonald 2008). Such similarities enable optimized pathogen dispersal and disease spread (extensification; Willocquet and Savary 2004) and local multiplication (intensification), which contribute to epidemic development. Then again, there are degrees to individual proximity, genetic similarity (e.g., intercropping), and physiological vulnerability. The differences in homogeneity—spatial, physiological, and host-genetic—between a maize field in the U.S. Midwest and a cassava plot in Côte d'Ivoire—are tremendous. Similarly, a wheat crop in northwestern Europe growing on a very large piece of land, with genetically uniform seed, tillage, fertilizers, herbicides, pesticides, and growth stimulators, differs profoundly from a small wheat plot in central Uttar Pradesh, India, with its genetically diverse seeds, limited water and manure inputs, hand-weeded, and with little or no pesticide. Weeds, an obstacle to wheat production in England, are turned into a benefit in Uttar Pradesh, where they serve as fodder for cows which in turn produce milk, cheese, and dung.

Taking inspiration from nature to better manage agroecosystems is an old and important idea (Wulf 2015; Zadoks and Schein 1979). A key attribute of natural systems is diversity: of genotypes within and across crops and landscape, and over vegetational successions. Another attribute is limited disruption, enabling biological regulations within an ecosystem to become established.

Disease management inspired by nature will not ensure total health, but it may ward off disasters in many cases. There is debate on how much agriculture should be renatured, including concerns about whether more natural agricultural systems could feed the world (Badgley and Perfecto 2007; Connor 2008; Muller et al. 2017). The present work supports the view that disappearance of ecological regulation through large-scale perturbations in agriculture can lead to disasters. Such disasters have occurred, for example, in the gigantic citrus plantations in North and South America with genetic homogeneity, intensive pesticide treatments, and successive waves of plant disease epidemics. Another example is the large-scale, mechanized, input-extensive cultivation of wheat on marginal wheat areas of South America where the crop often succumbs to wheat blast. Yet inspiration from nature may sometimes go astray: stopping the eradication of barberry triggered stem rust epidemics in Sweden (J. Yuen, personal observation), and a diversity of wild plants growing close to cultivated landscapes may constitute a reservoir of inoculum, especially for vector-transmitted pathogens (Chadwick and Marsh 1993).

Pesticide usage

Pesticide usage is addressed in numerous (Plant System × Ecoregion) reports (Supplementary File C; GPHA 2022; Fig. 5D). Reports indicate a range of diverse issues: inadequate pesticide usage (e.g., coffee in Central America); pesticide use as the sole alternative to disease control under given production contexts, leading to over-reliance (e.g., potato, Western Europe); chemical protection becoming inadequate for lack of chemical (new compounds) innovation, or because of regulations (e.g., grapevine, Western Europe); chemical protection being challenged by pathogen adaptation (e.g., wheat, Western Europe); excessive pesticide use leading to multiple environmental and/or health risks and problems (e.g., rice, potato, and wheat in East Asia; potato in Western Europe; citrus in South America; vegetable production in sub-Saharan Africa, South Asia, and Southeast Asia); and banned pesticides, or pesticides that are dangerous to human health, which are still commonly in use (vegetables in sub-Saharan Africa).

The state of plant health in sub-Saharan Africa

The reports of the GPHA indicate that plant health in sub-Saharan African agrosystems is in a poor state (five reports of six), and mostly (four reports) declining. Some of the African disease problems are formidable: mycotoxin-producing fungi and lethal necrosis in maize; viral diseases in cassava; viral and soil-borne fungal and bacterial diseases in banana and plantain. These diseases gravely damage the food base of the most food-insecure ecoregion in the world. They also have indirect, but devastating, impacts on the natural environment. Considerable efforts will be needed for their control. Labor-based disease control methods are unlikely to suffice. Chemicals often are too dangerous, too costly, fail in controlling such diseases, or do so only temporarily (e.g., Coyne et al. 2017). All possible options need consideration to improve plant health in sub-Saharan Africa, probably including the latest generation of genetic engineering instruments, since breeding for resistance to multiple diseases is a massive challenge, especially when no resistance sources are known. The use of dangerous or banned pesticides was commonplace in Africa 40 years ago (S. Savary, *unpublished data*). Sadly, the GPHA indicates no progress in reversing this trend. This problem requires immediate attention from policymakers.

A critique of the concept of ecosystem services

A critique of the concept of ecosystem service may be framed using three standpoints: agricultural (where the concept was born; Pingali and Heisey 1999), ecological, and evolutionary. The concept enables an effective and convenient accounting for the many benefits humans derive from nature, allowing comparisons and hypothesis-making, which can for instance be applied to the impacts of plant pathogens on plant systems (e.g., Cheatham et al. 2009; Paseka et al. 2020). Yet one cannot help seeing the concept of ecosystem service as a very strange way to see nature. Nature is not meant, or designed, to "serve" humans. Instead, humans contribute to the state of the environment to which they belong. Sadly, human services to nature are often negative. The concept of ecosystem services is anthropocentric and utilitarian. When applied to food supply or forestry, for example, the concept is particularly useful, but it becomes misplaced when applied to peace of mind or beauty. Yet the concept of ecosystem service guided the assessment, bearing in mind its limitations.

Lines of Thought for Future Research

Like part of the Millennium Ecosystem Assessment (MEA 2005), but unlike the IPCC (https://www.ipcc.ch), the Global Plant Health Assessment has been faced with a dearth of hard data. Assessing losses caused by diseases is costly, requiring trained experts and extensive field work (Savary et al. 2006; Teshome et al. 2020). Quantitative measurements of losses at the global scale do not exist; only expert assessments are available (e.g., Savary et al. 2019). Quantitative and qualitative data to describe the impacts of diseases on natural ecosystems and agrosystems are needed—in part to highlight the benefits of sustainable plant health management strategies. Data on plant disease impacts should for instance include the loss of natural vegetation due to crop abandonment and relocation because of crop diseases, and economic estimates of disease impacts on forests. We offer lines of thought to address these questions.

A first line of thought is that collective action (Nordman 2021; among scientists and with support of scientific societies) in support of a common good (e.g., plant health) may succeed in delivering wide-ranging, public information (global plant health). The overall result exceeds what an individual could possibly do and may be useful for further action (Nordman 2021), including the development of policy recommendations for plant health globally. Such data are also required for education, extension, and research prioritization, as well as for the development of disease management strategies under climate and global changes.

A second line of thought may concern specific ecoregions. The present study highlights the tragically poor overall status of plant health in sub-Saharan Africa, with massive crop losses, pathogen invasions, human health risks (e.g., from mycotoxins, along with dangerous pesticides), and dramatic collateral destruction of nature. This situation compounds the difficulties of the continent to feed itself (van Ittersum et al. 2016). Basic training in field work, together with the reconstruction of public advisory systems to farmers (i.e., extension services), are urgent in the Global South, and sub-Saharan Africa in particular.

Global change might perhaps be slowed, but it is inexorable because of the inertia of Earth's climate and its primary driver, human population. Resilience through botanical and genetic diversification seems essential to minimize the current and future impacts of global

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Banana and plantains: Lead: Leena Tripathi.[37] Experts: Altus Viljoen,[38] Lava Kumar,[28] George Mahuku,[35] and Jerome Kubiriba.[39]
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Softwood trees: Lead: Alex John Woods.[58] Experts: Isabel (Alvarez) Munck,[59] Anna Leon,[60] and Tod Ramsfield.[61]
Eucalypts: Lead: Angus J. Carnegie.[62] Experts: Emer O'Gara,[63] Robert O. Makinson,[64] and Giles E. St. J. Hardy.[65]
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change. This has applications in forestry (as in the softwoods in North America), urban trees (as on the plane trees of the Canal du Midi), and to global agriculture (Stukenbrock and McDonald 2008).

Despite accumulating evidence in a wide range of case studies (Jeger 2022), the impacts of climate change on plant diseases are still mostly unassessed and inadequately understood. The effects of climate variability combined with infection on plant physiology are complex. Much research is also needed to better understand tree decline (Delatour 1983). We still know too little of the effects of climate variability on the phytobiome, even for well-studied plants such as cereals, with the induced changes in physiology, resistance, or susceptibility on a stressed phytobiome-plant system (Jeger 2022).

Host plant resistance (HPR) remains the most reliable and environment-friendly disease management instrument. Because HPR is seed-based, resistant crop varieties can be accessible to farmers at an affordable cost with large benefits. HPR is pro-poor (if bred into varieties, not hybrids) and makes pesticide use superfluous when resistance genes are effective enough. Many domains of HPR are still open to further investigation; for instance, in multipathogen diseases, in the interaction of HPR with the phytobiome, and in the relations of HPR with crop physiology in agriculture.

The findings from the Global Plant Health Assessment exemplify the diversity in pathogens and diseases that impair plant health, the diversity of their consequences on ecosystem services, and the diversity of factors that impact or preserve plant health. Improving plant health, in turn, calls for multidisciplinary research (plant pathology, ecology, economics, and sociology) to develop cohesive and sustainable strategies involving diversity within and among plant systems. Challenges met with improving plant health echo challenges to uphold global common goods (Hardin 1968), which have to urgently be simultaneously addressed: climate (Skea et al. 2022), food (FAO et al. 2022), water, energy (Costanza et al. 2013), and biodiversity (Myers et al. 2000). This is because plant health is also a common good. As such, plant health needs to be investigated and nurtured through collective actions (Nordman 2021); the Global Plant Health Assessment is a step in this direction. Collective action to improve plant health requires changes in the way scientists work, from competing individuals to co-operative collectives, and from discipline-focused investigations to multidisciplinary-oriented science.

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Literature Cited

Avelino, J., Allinne, C., Cerda, R., Willocquet, L., and Savary, S. 2018. Multiple-disease system in coffee: From crop loss assessment to sustainable management. Annu. Rev. Phytopathol. 56:611-635.

Badgley, C., and Perfecto, I. 2007. Can organic agriculture feed the world? Renew. Agr. Food Syst. 22:80-86.

Bailey, R. 1996. Ecosystem Geography. Springer, New York.

Barnwal, M. K., Kotasthane, A., Magculia, N., Mukherjee, P. K., Savary, S., Sharma, A. K., Singh, H. B., Singh, U. S., Sparks, A. H., Variar, M., and Zaidi, N. 2013. A review on crop losses, epidemiology and disease management of rice brown spot to identify research priorities and knowledge gaps. Eur. J. Plant Pathol. 136:443-457.

Bond, W. J. 1994. Keystone species. Pages 237-253 in: Biodiversity and Ecosystem Function. E. D. Schulze, and H. A. Mooney, eds. Springer, Berlin, Heidelberg, Germany.

Boudreau, M. A. 2013. Diseases in intercropping systems. Annu. Rev. Phytopathol. 51:499-519.

Boyce, C. K., and Lee, J. E. 2017. Plant evolution and climate over geological timescales. Annu. Rev. Earth Planet. Sci. 45:61-87.

Brasier, C. M. 2008. The biosecurity threat to the UK and global environment from international trade in plants. Plant Pathol. 57:792-808.

Busby, P. E., Ridout, M., and Newcombe, G. 2016. Fungal endophytes: Modifiers of plant disease. Plant Mol. Biol. 90:645-655.

Cahill, D. M., Rookes, J. E., Wilson, B. A., Gibson, L., and McDougall, K. L. 2008. *Phytophthora cinnamomi* and Australia's biodiversity: Impacts, predictions and progress towards control. Aust. J. Bot. 56:279-310.

Cardenas, R. E., Valencia, R., Kraft, N. J. B., Argoti, A., and Dangles, O. 2014. Plant traits predict inter-and intraspecific variation in susceptibility to herbivory in a hyperdiverse Neotropical rain forest tree community. J. Ecol. 102:939-952.

Ceresini, P. C., Castroagudín, V. L., Rodrigues, F. Á., Rios, J. A., Aucique-Pérez, C. E., Moreira, S. I., Alves, E., Croll, D., and Maciel, J. L. N. 2018. Wheat blast: Past, present, and future. Annu. Rev. Phytopathol. 56:427-456.

Chadwick, D. J., and Marsh, J., eds. 1993. Crop Protection and Sustainable Agriculture. John Wiley & Sons, Chichester, U.K.

Chakraborty, S., and Newton, A. C. 2011. Climate change, plant diseases and food security: An overview. Plant Pathol. 60:2-14.

Cheatham, M. R., Rouse, M. N., Esker, P. D., Ignacio, S., Pradel, W., Raymundo, R., Sparks, A. H., Forbes, G. A., Gordon, T. R., and Garrett, K. A. 2009. Beyond yield: Plant disease in the context of ecosystem services. Phytopathology 99:1228-1236.

Connor, D. J. 2008. Organic agriculture cannot feed the world. Field Crops Res. 106:187-190.

Costanza, R., Alperovitz, G., Daly, H., Farley, J., Franco, C., Jackson, T., Kubiszewski, I., Schor, J., and Victor, P. 2013. Building a Sustainable and Desirable Economy-in-Society-in-Nature: Report to the United Nations for the 2012 Rio+ 20 Conference. ANU Press, Canberra, Australia.

Coyne, D. L., Dubois, T., and Daneel, M. S. 2017. Integrated pest management in banana and plantain. Pages 229-245 in: Integrated Pest Management in Tropical Regions. CABI, Wallingford, U.K.

Crisp, M. D., and Cook, L. G. 2013. How was the Australian flora assembled over the last 65 million years? A molecular phylogenetic perspective. Annu. Rev. Ecol. Evol. Syst. 44:303-324.

Delatour, C. 1983. Les dépérissements de chênes en Europe. Rev. For. Fran. 35: 303-324.

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.

Dinoor, A., and Eshed, N. 1984. The role and importance of pathogens in natural plant communities. Annu. Rev. Phytopathol. 22:443-466.

Dobbs, R. 2010. Prime numbers: Mega cities. Foreign Policy 181:132-135.

Döring, T. F., Pautasso, M., Finckh, M. R., and Wolfe, M. S. 2012. Concepts of plant health–reviewing and challenging the foundations of plant protection. Plant Pathol. 61:1-15.

Eck, J. L., Stump, S. M., Delavaux, C. S., Mangan, S. A., and Comita, L. S. 2019. Evidence of within-species specialization by soil microbes and the implications for plant community diversity. Proc. Natl. Acad. Sci. U.S.A. 116:7371-7376.

Fan, J., Yang, J., Wang, Y.-Q., Li, G.-B., Li, Y., Huang, F., and Wang, W.-M. 2016. Current understanding on *Villosiclava virens*, a unique flower-infecting fungus causing rice false smut disease. Mol. Plant Pathol. 17:1321-1330.

FAO, IFAD, UNICEF, WFP, and WHO. 2022. The State of Food Security and Nutrition in the World 2022. Repurposing Food and Agricultural Policies to Make Healthy Diets More Affordable. FAO, Rome. https://doi.org/10.4060/cc0639en

Garrett, K. A., Forbes, G. A., Savary, S., Skelsey, P., Sparks, A. H., Valdivia, C., van Bruggen, A. H. C., Willocquet, L., Djurle, A., Duveiller, E., Eckersten, H., Pande, S., Vera Cruz, C., and Yuen, J. 2011. Complexity in climate-change impacts: An analytical framework for effects mediated by plant disease. Plant Pathol. 60:15-30.

Geils, B. W., Hummer, K. E., and Hunt, R. S. 2010. White pines, *Ribes*, and blister rust: A review and synthesis. For. Pathol. 40:147-185.

Gilbert, G. S. 2002. Evolutionary ecology of plant diseases in natural ecosystems. Annu. Rev. Phytopathol. 40:13-43.

Goellner, K., Loehrer, M., Langenbach, C., Conrath, U., Koch, E., and Schaffrath, U. 2010. *Phakopsora pachyrhizi*, the causal agent of Asian soybean rust. Mol. Plant Pathol. 11:169-177.

GPHA. 2022. Global Plant Health Assessment. An International Peer-Reviewed Evaluation of the State of Plant Health across Ecoregions of the World, and of the Effects of Plant Disease on Ecosystem Services, 1st ed. L. Willocquet, M. Singh, S. Sah, F. Bove, S. Savary, and J. Yuen, eds. https://www.isppweb.org/about_gpha.asp

Grünwald, N. J., LeBoldus, J. M., and Hamelin, R. C. 2019. Ecology and evolution of the sudden oak death pathogen *Phytophthora ramorum*. Annu. Rev. Phytopathol. 57:301-321.

Hardin, G. 1968. The tragedy of the commons: The population problem has no technical solution; it requires a fundamental extension in morality. Science 162:1243-1248.

Heesterbeek, J. A. P., and Zadoks, J. C. 1987. Modelling pandemics of quarantine pests and diseases: Problems and perspectives. Crop Prot. 6:211-221.

Hovmøller, M. S., Walter, S., Bayles, R. A., Hubbard, A., Flath, K., Sommerfeldt, N., Leconte, M., Czembor, P., Rodriguez-Algaba, J., Thach, T., Hansen, J. G., Lassen, P., Justesen, A. F., Ali, S., and de Vallavieille-Pope, C. 2016. Replacement of the European wheat yellow rust population by new races from the centre of diversity in the near-Himalayan region. Plant Pathol. 65:402-411.

Hyatt-Twynam, S. R., Parnell, S., Stutt, R. O. J. H., Gottwald, T. R., Gilligan, C. A., and Cunniffe, N. J. 2017. Risk-based management of invading plant disease. New Phytol. 214:1317-1329.

Jeger, M. J. 2022. The impact of climate change on disease in wild plant populations and communities. Plant Pathol. 71:111-130.

Keane, P., Gile, G., Podger, F., and Brown, B. 2000. Diseases and Pathogens of Eucalypts. CSIRO Publishing, Melbourne, Australia.

Kranz, J. 1990. Tansley review no. 28 fungal diseases in multispecies plant communities. New Phytol. 116:383-405.

Leach, J. E., Triplett, L. R., Argueso, C. T., and Trivedi, P. 2017. Communication in the phytobiome. Cell 169:587-596.

Leffelaar, P. A., ed. 1993. On Systems Analysis and Simulation of Ecological Processes with Examples in CSMP and FORTRAN, Vol. 1. Springer Science & Business Media, Dordrecht, The Netherlands.

Mahuku, G., Lockhart, B. E., Wanjala, B., Jones, M. W., Kimunye, J. N., Stewart, L. R., Cassone, B. J., Sevgan, S., Nyasani, J. O., Kusia, E., Kumar, P. L., Niblett, C. L., Kiggundu, A., Asea, G., Pappu, H. R., Wangai, A., Prasanna, B. M., and Redinbaugh, M. G. 2015. Maize lethal necrosis (MLN), an emerging threat to maize-based food security in sub-Saharan Africa. Phytopathology 105:956-965.

MEA (Millennium Ecosystem Assessment). 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC.

Muller, A., Schader, C., El-Hage Scialabba, N., Brüggemann, J., Isensee, A., Erb, K.-H., Smith, P., Klocke, P., Leiber, F., Stolze, M., and Niggli, U. 2017. Strategies for feeding the world more sustainably with organic agriculture. Nat. Commun. 8:1290.

Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., and Kent, J. 2000. Biodiversity hotspots for conservation priorities. Nature 403:853-858.

Nordman, E. 2021. The Uncommon Knowledge of Elinor Ostrom – Essential Lessons for Collective Action. Island Press, Washington, DC.

Panconesi, A. 1999. Canker stain of plane trees: A serious danger to urban plantings in Europe. J. Plant Pathol. 81:3-15.

Paseka, R. E., White, L. A., Van de Waal, D. B., Strauss, A. T., González, A. L., Everett, R. A., Peace, A., Seabloom, E. W., Frenken, T., and Borer, E. T. 2020. Disease-mediated ecosystem services: Pathogens, plants, and people. Trends Ecol. Evol. 35:731-743.

Pertot, I., Caffi, T., Rossi, V., Mugnai, L., Hoffmann, C., Grando, M. S., Gary, C., Lafond, D., Duso, C., Thiery, D., Mazzoni, V., and Anfora, G. 2017. A critical review of plant protection tools for reducing pesticide use on grapevine and new perspectives for the implementation of IPM in viticulture. Crop Prot. 97:70-84.

Pingali, P., and Heisey, P. 1999. Cereal Crop Productivity in Developing Countries: Past Trends and Future Prospects. Economics Working Papers. CIMMYT, Mexico.

Reddy, C. S., Laha, G. S., Prasad, M. S., Krishnaveni, D., Castilla, N. P., Nelson, A., and Savary, S. 2011. Characterizing multiple linkages between individual diseases, crop health syndromes, germplasm deployment, and rice production situations in India. Field Crops Res. 120:241-253.

Rojstaczer, S., Sterling, S. M., and Moore, N. J. 2001. Human appropriation of photosynthesis products. Science 294:2549-2552.

Russell, R., Guerry, A. D., Balvanera, P., Gould, R. K., Basurto, X., Chan, K. M. A., Klain, S., Levine, J., and Tam, J. 2013. Humans and nature: How knowing and experiencing nature affect well-being. Annu. Rev. Environ. Res. 38:473-502.

Saunders, D. G., Pretorius, Z. A., and Hovmøller, M. S. 2019. Tackling the re-emergence of wheat stem rust in Western Europe. Commun. Biol. 2:51.

Savary, S. 2014. The roots of crop health: Cropping practices and disease management. Food Sec. 6:819-831.

Savary, S., Bosc, J.-P., Noirot, M., and Zadoks, J. C. 1988. Peanut rust in West Africa: A new component in a multiple pathosystem. Plant Dis. 72: 1001-1009.

Savary, S., Teng, P. S., Willocquet, L., and Nutter, F. W., Jr. 2006. Quantification and modeling of crop losses: A review of purposes. Annu. Rev. Phytopathol. 44:89-112.

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.

Sharma, R. C., Duveiller, E., and Ortiz-Ferrara, G. 2007. Progress and challenge towards reducing wheat spot blotch threat in the Eastern Gangetic Plains of South Asia: Is climate change already taking its toll? Field Crops Res. 103:109-118.

Singh, P. K., Gahtyari, N. C., Roy, C., Roy, K. K., He, X., Tembo, B., Xu, K., Juliana, P., Sonder, K., Kabir, M. R., and Chawade, A. 2021. Wheat blast: A disease spreading by intercontinental jumps and its management strategies. Front. Plant Sci. 12:710707.

Skea, J., Shukla, P. R., Reisinger, A., Slade, R., Pathak, M., Al Khourdajie, A., van Diemen, R., Abdulla, A., Akimoto, K., Babiker, M., and Bai, Q. 2022. Summary for policymakers. In: Climate Change 2022: Mitigation of Climate Change: Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. University Press, Cambridge, U.K.

Steiner, A. 2020. The Next Frontier: Human Development and the Anthropocene (Foreword). United Nations Development Program. https://www.undp.org/belarus/publications/next-frontier-human-development-and-anthropocene (accessed 9 Apr 2022).

Stukenbrock, E. H., and McDonald, B. A. 2008. The origins of plant pathogens in agro-ecosystems. Annu. Rev. Phytopathol. 46:75-100.

Sturrock, R. N., Frankel, S. J., Brown, A. V., Hennon, P. E., Kliejunas, J. T., Lewis, K. J., Worrall, J. J., and Woods, A. J. 2011. Climate change and forest diseases. Plant Pathol. 60:133-149.

Teshome, D. T., Zharare, G. E., and Naidoo, S. 2020. The threat of the combined effect of biotic and abiotic stress factors in forestry under a changing climate. Front. Plant Sci. 11:601009.

United Nations. 2019. World Population Prospects 2019. https://population.un.org/wpp/ (accessed 9 Nov 2019).

van Ittersum, M. K., van Bussel, L. G. J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., de Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., van Oort, P. A. J., van Loon, M. P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J. H. J. R., Ouattara, K., Tesfaye, K., and Cassman, K. G. 2016. Can sub-Saharan Africa feed itself? Proc. Natl. Acad. Sci. U.S.A. 113:14964-14969.

Vitousek, P. M., Ehrlich, P. R., Ehrlich, A. H., and Matson, P. A. 1986. Human appropriation of the products of photosynthesis. BioScience 36:368-373.

Vörösmarty, C. J., Green, P., Salisbury, J., and Lammers, R. B. 2000. Global water resources: Vulnerability from climate change and population growth. Science 289:284-288.

Weltzien, H. C. 1972. Geophytopathology. Annu. Rev. Phytopathol. 10:277-298.

Willocquet, L., and Savary, S. 2004. An epidemiological simulation model with three scales of spatial hierarchy. Phytopathology 94:883-891.

Wilson, E. 1992. The Diversity of Life. Belknap Press of Harvard University Press, Cambridge, MA, U.S.A.

Wulf, A. 2015. The Invention of Nature - The Adventures of Alexander von Humboldt, the Lost Hero of Science. John Murray, London, U.K.

Zadoks, J. C., and Schein, R. D. 1979. Epidemiology and Plant Disease Management. Oxford University Press, Oxford, U.K.

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The author list, "Serge Savary and the GPHA" below the article title did not give explicit credit to all authors involved. The article now lists every author individually in alphabetical order in the author list online. The article retains a complete list of authors and their roles within the GPHA on pages 3662-3663.